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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

September 1944 as
Memorandum Report

EFFECT OF WATER INJECTION ON KNOCK-LIMITED PERFORMANCE OF A V-TYPE 12-CYLINDER LIQUID-COOLED ENGINE

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WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Materiel Command

EFFECT OF WATER INJECTION ON KNOCK-LIMITED PERFORMANCE OF A V-TYPE 12-CYLINDER LIQUID-COOLED ENGINE

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SUMMARY

An investigation was conducted to determine the effect of water injection on the knock-limited performance of a V-type 12-cylinder liquid-cooled engine. The knock-limited performance tests were made at an engine speed of 3000 rpm with carburetor-air temperatures of 158°, 101°, and 50° F at water-fuel ratios of 0, 0.2, 0.4, and 0.6.

The following table summarizes the knock-limited data without water injection and with water injection at a water-fuel ratio of 0.6:

Carburetor-air temperature (°F) ↓ / Water-fuel ratio →	F/A = 0.08				F/A = 0.095			
	Brake horsepower		Manifold pressure (in. Hg abs.)		Brake horsepower		Manifold pressure (in. Hg abs.)	
	0	0.6	0	0.6	0	0.6	0	0.6
158	750	1560	36.5	65.8	990	1625	46.0	71.4
101	950	1735	42.5	68.5	1245	1785	53.6	73.8
50	1350	1965	54.4	75.0	1570	[a]1830	63.2	[a]73.0

[a]Water-fuel ratio of 0.4.

INTRODUCTION

At the request of the Army Air Forces, Materiel Command, tests were conducted at the NACA laboratory in Cleveland to evaluate several methods of improving the power output of a V-type 12-cylinder liquid-cooled engine. As a part of this general program knock-limited performance tests were made with a wide range of carburetor-air temperatures to determine the effects of aftercooling on the knock-limited power output of the test engine. The effect of water injection on the performance of a V-type 12-cylinder liquid-cooled engine was determined during December 1943 and January 1944 by tests with constant carburetor-air temperatures of 158°, 101°, and 50° F at water-fuel ratios from 0 to 0.6. A compilation of the data and a discussion of the results obtained in these water-injection tests are presented herein.

APPARATUS

The investigation was conducted on a V-type 12-cylinder liquid-cooled aircraft engine having a displacement of 1710 cubic inches. This engine has a compression ratio of 6.65 and is fitted with pistons having keystone upper compression rings. In order to decrease the possibilities of piston failure due to high temperatures and consequent overexpansion at the high power levels anticipated, the diametral clearances between the piston and the cylinder wall were increased 0.008 inch over the standard clearances. The engine is equipped with a double-venturi pressure-type carburetor and a single-speed, single-stage supercharger with an impeller diameter of $9\frac{1}{2}$ inches and a gear ratio of 9.6. Spark plugs, of the standard type installed by the manufacturer, were used. The tests were run with an AN-F-28, Amendment-2, fuel.

Engine installation. - The test engine was set up on a dynamometer stand with a 2000-horsepower eddy-current dynamometer. Oil and coolant (ethylene glycol) were supplied to the engine at specified conditions by auxiliary equipment. The installation provided for a variation of the combustion-air temperature from -40° to 200° F. The engine was fitted with special water-jacketed exhaust stacks with an inside diameter 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.

Water-injection equipment. - The water was continuously injected through 12 spray bars 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, as shown in figure 1. The spray bars (fig. 2) were 5/32-inch-diameter, stainless-steel tubing about $2\frac{1}{2}$ inches long with six holes, each 0.016 inch in diameter, arranged in two rows of three holes each to spray water directly into each intake port. Water was supplied to the spray bars by individual lines from a tank, which was kept under pressure with compressed air. Water flow was measured by calibrated rotameters in the individual water lines.

A water-injection system proposed for a flight investigation on a fighter airplane was installed on the test-stand engine for preliminary water-injection tests. This water-injection system differed from the one described in the preceding paragraph in that water was supplied to the spray bars from a common manifold and that water flow was measured by a calibrated orifice in the line to the manifold. The tests with this water-injection system are reported in the appendix.

Special equipment and instrumentation. - Magnetic-vibration-type pickup units were used for knock detection. Indication was by means of an amplifier-oscilloscope combination, using a commutator to reduce background interference. Previous tests showed that there was good correlation between the occurrence of knock as evidenced by exhaust-smoke puffs and the occurrence of knock as indicated by the oscilloscope.

Mixture control was facilitated by the use of a special air-bleed valve connected across the carburetor-air diaphragm. This device provided for mixture regulation between the automatic-rich and the automatic-lean control settings and also allowed leaning beyond automatic lean. The automatic-lean and the power-enrichment jets and the fuel-spray nozzle were enlarged to provide for the high fuel flows required for the high-power tests.

The carburetor-air temperature was measured by eight iron-constantan thermocouples connected in parallel and arranged to traverse the air stream immediately ahead of the carburetor face.

Mixture-temperature data reported herein were obtained using an unshielded thermocouple inserted to the middle of the central manifold pipe approximately $9\frac{1}{4}$ inches downstream from the flange of the supercharger outlet; thus, temperature measurements were made upstream from the point of water 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.

Cylinder-head temperatures were measured by iron-constantan thermocouples inserted in holes drilled from a position immediately above the exhaust-spark-plug recess on each cylinder to a point between the exhaust-valve seats. (See fig. 3.) These thermocouples measured temperatures in the critical region of the cylinder head where single-cylinder tests have shown that cracking may occur at high temperatures and high engine outputs.

OPERATING CONDITIONS AND PROCEDURE

The following operating conditions were maintained during the tests:

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

Carburetor-air pressure was held at approximately sea-level pressure.

Tests were run at carburetor-air temperatures of 158°, 101°, and 50° F, maintained to within ±2° F, at each of four water-fuel ratios (0, 0.2, 0.4, and 0.6). The tests covered a range of fuel-air ratios from about 0.07 to a fuel-air ratio slightly higher than that at which peak knock-limited power was obtained.

In order to obtain a knock point, the fuel flow necessary for the desired fuel-air ratio was first estimated on the basis of previous experience. From this fuel flow the water flow necessary to give the desired water-fuel ratio was calculated. The water flow was then set at the calculated value and the fuel flow was held at the estimated value while the knock point was obtained by increasing the manifold pressure until knock was observed.

The data were taken at a medium knock intensity; that is, when the oscilloscope indicated that three to five cylinders were knocking. Between knock points the engine was operated at conditions of low power and relatively rich mixture.

RESULTS AND DISCUSSION

Knock-limited performance. - Figure 4 presents knock-limited engine performance at a carburetor-air temperature of 158° F. The knock-limited brake-horsepower curves peak at successively leaner mixtures as the water-fuel ratio is increased. The curve for a water-fuel ratio of 0.6 shows a rapid decrease in knock-limited brake horsepower as the fuel-air ratio is increased beyond about 0.092. The knock-limited manifold pressure does not show a corresponding decrease. The decrease in knock-limited brake horsepower without a decrease in manifold pressure probably resulted from a decrease in thermal efficiency caused by too much liquid in the charge for proper vaporization and combustion.

Except at fuel-air ratios in excess of 0.092 the brake specific fuel and air consumptions were lower with water injection than without. The reduction was partly caused by the increased mechanical efficiency of the engine at the high power outputs attainable with water injection. Indicated specific fuel and air consumptions would be expected to remain nearly constant or increase slightly as the water-fuel ratio is increased.

The curves of knock-limited engine performance at a carburetor-air temperature of 101° F in figure 5 exhibit characteristics similar to those at 158° F in figure 4. The results at a carburetor-air temperature of 50° F shown in figure 6 are similar to those in figures 4 and 5. The brake specific fuel and air consumptions decrease less in the lean-mixture region and increase more in the rich-mixture region at a low carburetor-air temperature (fig. 6) than at the higher carburetor-air temperatures (figs. 4 and 5). The maximum knock-limited brake horsepower during these tests was 1965 at a fuel-air ratio of 0.08, a water-fuel ratio of 0.6, and a manifold pressure of 75 inches of mercury absolute. (See fig. 6.)

A comparison of figures 4, 5, and 6 shows that for a given water-fuel ratio the knock-limited brake-horsepower curves peak at successively leaner mixtures as the carburetor-air temperature is reduced. The same trend was shown in reference 1 for knock tests at several carburetor-air temperatures without water injection.

The data in figures 4, 5, and 6 are tabulated in table I and are cross-plotted as functions of water-fuel ratio in figure 7 and as functions of mixture temperature in figure 8.

Figure 9 presents the variation of knock-limited manifold pressure and brake specific fuel and liquid consumptions with knock-limited brake horsepower. The figures show the manifold pressures

and the brake specific fuel and liquid consumptions required for operation at the power levels attained in these tests with fuel-air ratios of 0.08 and 0.095 at three carburetor-air temperatures.

Carburetor inlet-air pressures. - All tests were run at carburetor inlet-air pressures approximately equal to sea-level pressure except when external boost was required to obtain the desired manifold pressures. When external boost was required, it was supplied at wide-open carburetor throttle, as shown in figure 10. The dashed portions of the curves of figure 10 indicate the minimum carburetor inlet-air pressures (or indirectly the maximum altitudes) that may be used to obtain the desired manifold pressures under the conditions of these tests. The carburetor inlet-air pressures shown in figure 10 are measured values of supercharger inlet-air pressures plus 1.4 inches of mercury, the assumed pressure drop through the carburetor at wide-open throttle.

Cylinder-head temperatures. - Figure 11 shows the cylinder-head-temperature patterns at fuel-air ratios of 0.08 and 0.095 for the runs represented by the curves in figures 4, 5, and 6. Temperature data from unpublished tests made with several engines of the same model as the test engine used in this investigation show that the cylinder-head-temperature pattern is not the same for any two engines. These differences in cylinder-head temperatures on several similar engines indicate that the differences in head temperatures from cylinder to cylinder are caused by small differences in the locations of the thermocouples. Therefore, the temperatures from cylinder to cylinder are not directly comparable, but comparison of the temperatures on any one cylinder of a given engine for different conditions is valid.

Cross plots from the data in figure 11 are presented in figure 12 and show the effect on the individual cylinder-head temperatures of water-fuel ratio at knock-limited conditions with a fuel-air ratio of 0.08. In general, the curves for the several cylinders are similar, but some differences in shape may be seen. These differences may have been caused by variations in the water spray from the individual spray bars and by possible forcing of some water from one spray bar into the intake port of an adjacent cylinder by the pulsating flow of the mixture in the manifolds.

The data in figure 11 were averaged and cross-plotted in figure 13 to show the effect of water-fuel ratio at knock-limited conditions at fuel-air ratios of 0.08 and 0.095 on average cylinder-head temperature. For convenience in analyzing the figure, the knock-limited brake horsepowers attained at the four water-fuel ratios are shown on the curves.

Figure 14 shows the knock-limited brake horsepowers at which the head temperatures in figure 13 were obtained. As the knock-limited power is increased by increasing the water-fuel ratio, the cylinder-head temperatures rise until a certain water-fuel ratio is reached and then begin to decrease as the water-fuel ratio is further increased. The water-fuel ratio at which the temperatures begin to decrease is approximately 0.5 at a fuel-air ratio of 0.08 and a carburetor-air temperature of 158° F and becomes lower as the carburetor-air temperature is reduced or as the fuel-air ratio is increased to 0.095. For a given knock-limited horsepower, the average cylinder-head temperature is very nearly the same whether the knock-limited power is attained with a high carburetor-air temperature and a high water-fuel ratio or with a low carburetor-air temperature and a low water-fuel ratio provided that the selected combinations of water-fuel ratio and carburetor-air temperature are on the rising parts of the cylinder-head-temperature curves. (See figs. 13 and 14.) If the high combination of carburetor-air temperature and water-fuel ratio is on the decreasing part of the cylinder-head-temperature curve, the desired power output will be accompanied by a lower average cylinder-head temperature at this point than at low carburetor-air temperatures and low water-fuel ratios.

SUMMARY OF RESULTS

The following results were obtained from knock-limited performance tests of a V-type 12-cylinder liquid-cooled engine at an engine speed of 3000 rpm with carburetor-air temperatures of 158°, 101°, and 50° F and with several water-fuel ratios:

1. The maximum knock-limited brake horsepower attained was 1965 at a fuel-air ratio of 0.08, a carburetor-air temperature of 50° F, and a water-fuel ratio of 0.6.

2. The curves of knock-limited brake horsepower against fuel-air ratio peak at successively leaner mixtures as the carburetor-air temperature is reduced and as the water-fuel ratio is increased.

3. In general, water injection became progressively less effective in increasing the knock-limited performance as the carburetor-air temperature was reduced, as the mixture was enriched, or as the water-fuel ratio was increased.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, September 9, 1944.

APPENDIX

PRELIMINARY TESTS USING EXPERIMENTAL WATER-INJECTION SYSTEM

Preliminary tests were run with a V-type 12-cylinder liquid-cooled engine to determine the effect of water injection on the knock-limited power output of the engine and to test a water-injection system that had been proposed for experimental use on a fighter airplane at Cleveland.

The water-injection system used in these preliminary tests was similar to that described in the body of this report except that the water was fed to the individual spray bars by single lines from a common manifold and that the water flow was measured by a calibrated orifice in the line to the manifold. Calibration of the system indicated that the variation of flow between nozzles was less than ±3 percent of the flow through one nozzle.

The fuel used was AN-F-28, Amendent-1. Unpublished data from single-cylinder tests conducted at Cleveland show that this fuel and the AN-F-28, Amendment-2, fuel used for the tests presented in the body of this paper are very nearly alike in knock-limited performance. Tests were run at carburetor-air temperatures of 158° and 101° F. All other engine conditions were the same as those given in the body of this report.

Figure 15 presents curves of knock-limited engine performance and mixture temperature at a carburetor-air temperature of 158° F without water injection and with water injected to give water-fuel ratios of 0.215 and 0.41 at the knock point. These data agree well with those obtained in subsequent tests (fig. 4) except that the subsequent tests showed higher knock-limited horsepowers and manifold pressures at water-fuel ratios of 0.2 and 0.4 and slightly higher mixture temperatures. Better water distribution, owing to the use of individual rotameters in each spray-bar feed line, is considered the cause of the higher knock-limited horsepowers and manifold pressures obtained in the subsequent tests.

Data for knock-limited engine performance and mixture temperature at a carburetor-air temperature of 101° F and water-fuel ratios of 0, 0.2, and 0.4 (fig. 16) agree well with those obtained in subsequent tests (fig. 5). A slightly lower knock-limited horsepower and a slightly higher brake specific air consumption at 0.2 water-fuel ratio is again shown. These differences are probably caused by better water distribution in the subsequent tests.

TABLE I. - SUMMARY OF KNOCK-LIMITED PERFORMANCE WITH AND WITHOUT WATER INJECTION

[V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2.]

Fuel-air ratio	Water-fuel ratio	Brake horse-power	Increase over bhp when W/F = 0 (percent)	Manifold pressure (in. Hg abs.)	Increase over manifold pressure when W/F = 0 (percent)
Carburetor-air temperature, 158° F					
0.08	0	750	----------	36.5	----------
	.2	1080	43.0	48.0	31.5
	.4	1350	80.0	58.0	58.9
	.6	1560	108.0	65.8	80.3
0.095	0	990	----------	46.0	----------
	.2	1355	36.9	59.7	29.8
	.4	1530	54.6	66.7	47.2
	.6	1625	64.1	71.4	55.2
Carburetor-air temperature, 101° F					
0.08	0	950	----------	42.5	----------
	.2	1350	42.2	56.0	31.8
	.4	1575	65.8	64.0	50.7
	.6	1735	82.7	68.5	61.1
0.095	0	1245	----------	53.6	----------
	.2	1570	26.1	65.0	21.3
	.4	1695	36.1	70.2	31.0
	.6	1782	43.2	73.0	36.2
Carburetor-air temperature, 50° F					
0.08	0	1350	----------	54.4	----------
	.2	1695	25.5	65.0	19.5
	.4	1850	37.0	71.1	30.7
	.6	1965	45.6	75.0	37.9
0.095	0	1570	----------	63.2	----------
	.2	1720	9.6	68.0	7.6
	.4	1830	16.6	73.0	15.5
	.6	1800	14.6	72.9	15.3

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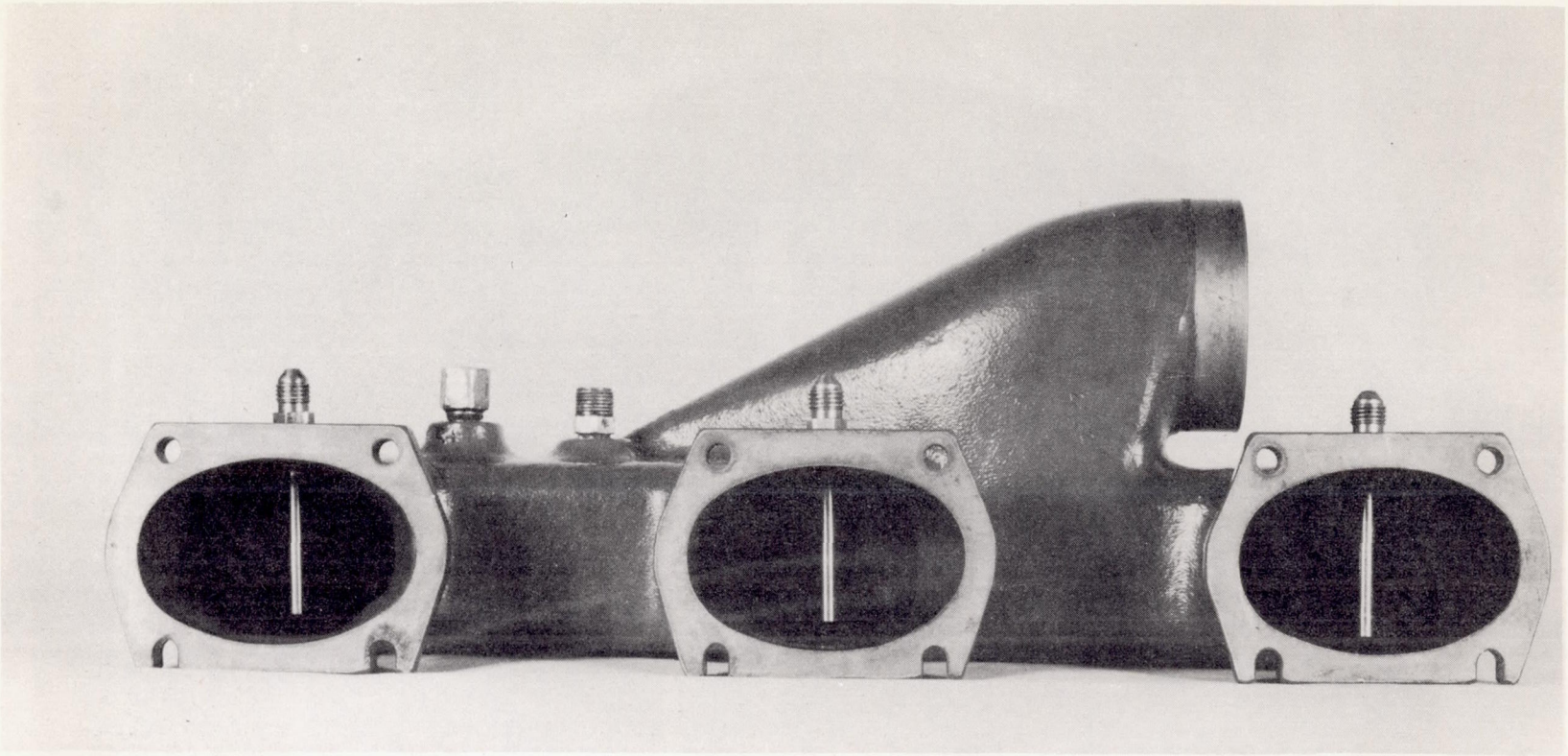

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Figure 1. - Intake manifold with water spray bars in position.

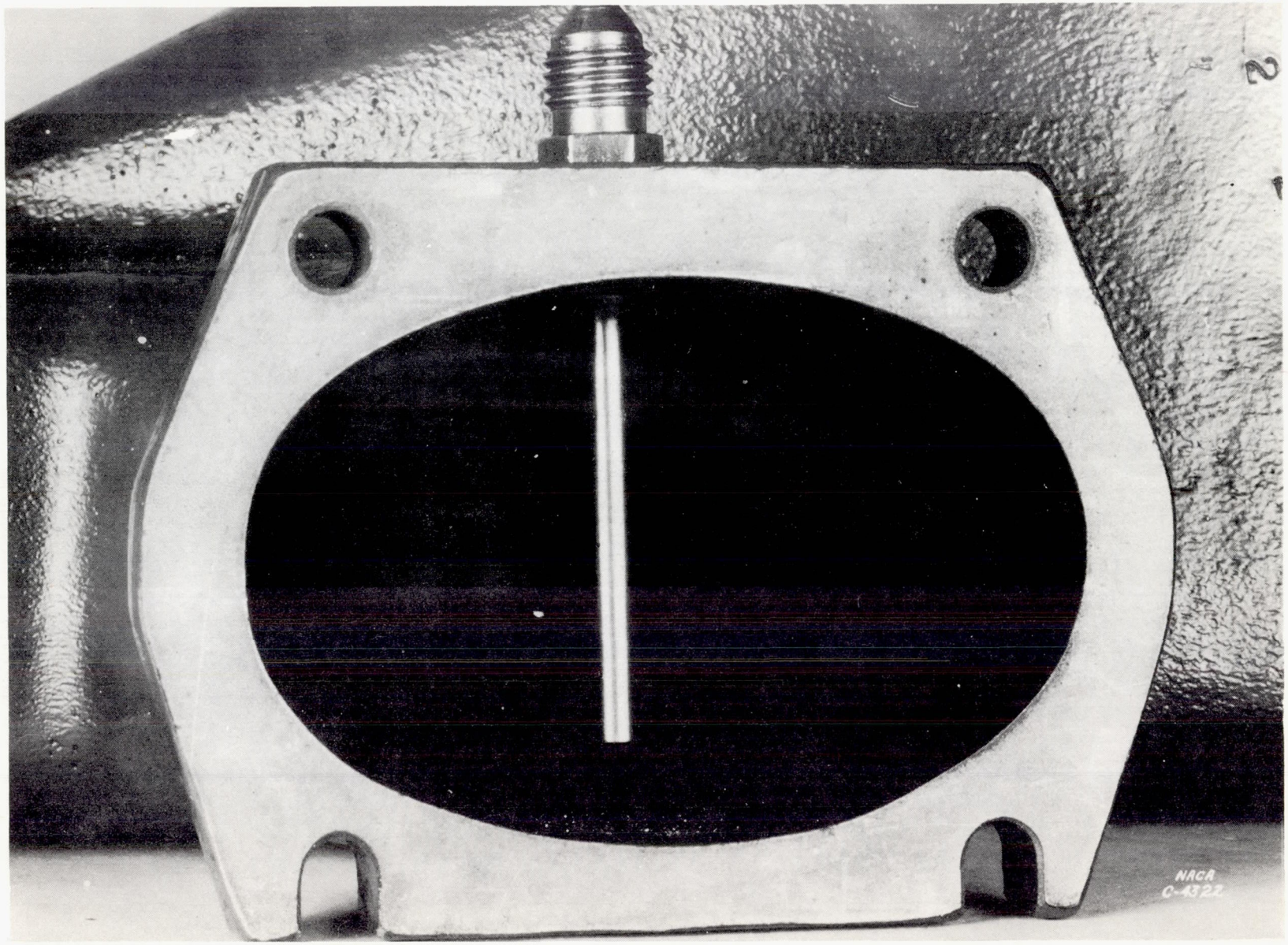

Figure 2. - Close-up of water spray bar inserted in intake manifold.

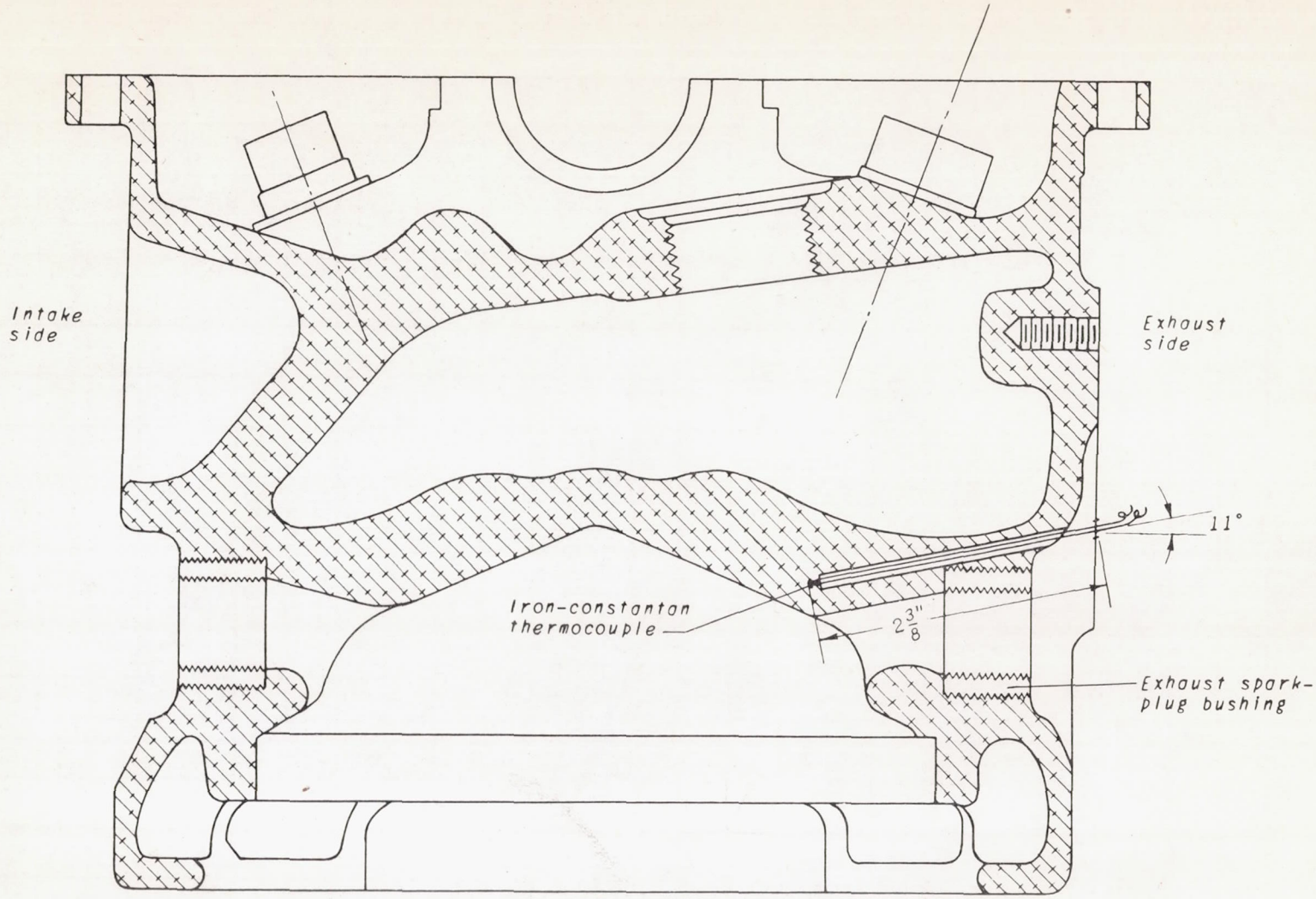

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Figure 3. - Location of thermocouple in cylinder head.

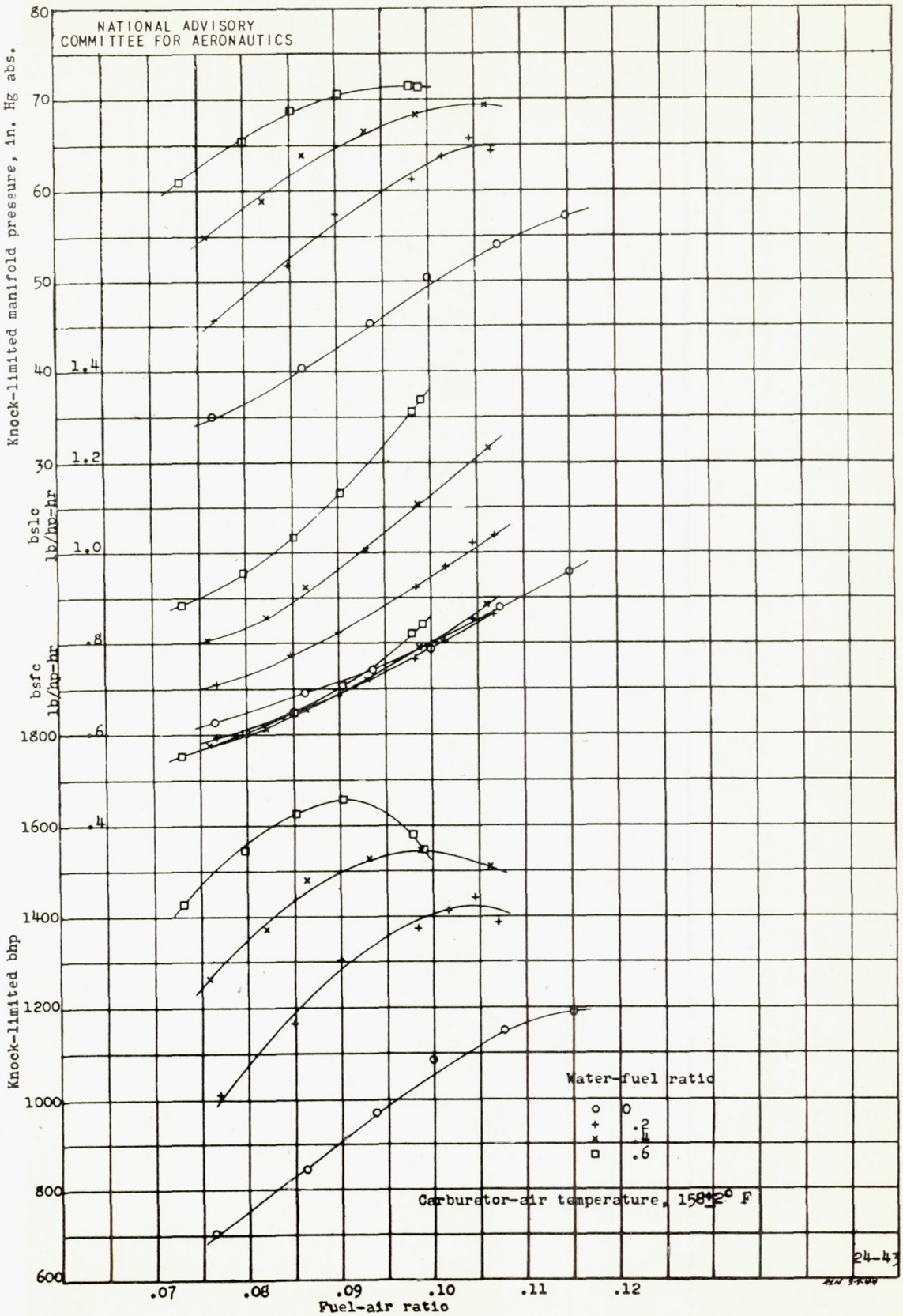

Figure 4. - Knock-limited performance with water injection at carburetor-air temperature of 158° F. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2.

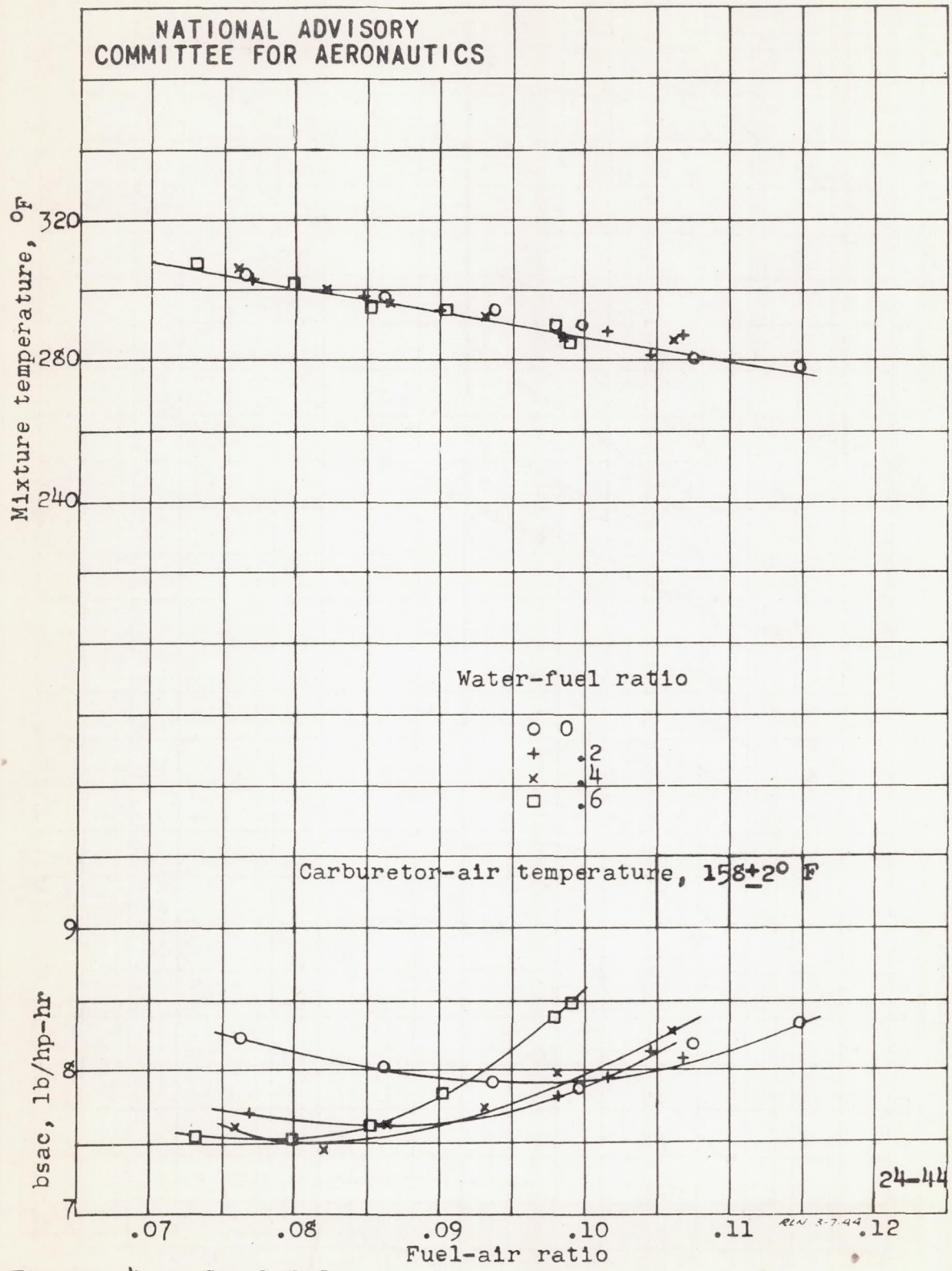

Figure 4. - Concluded.

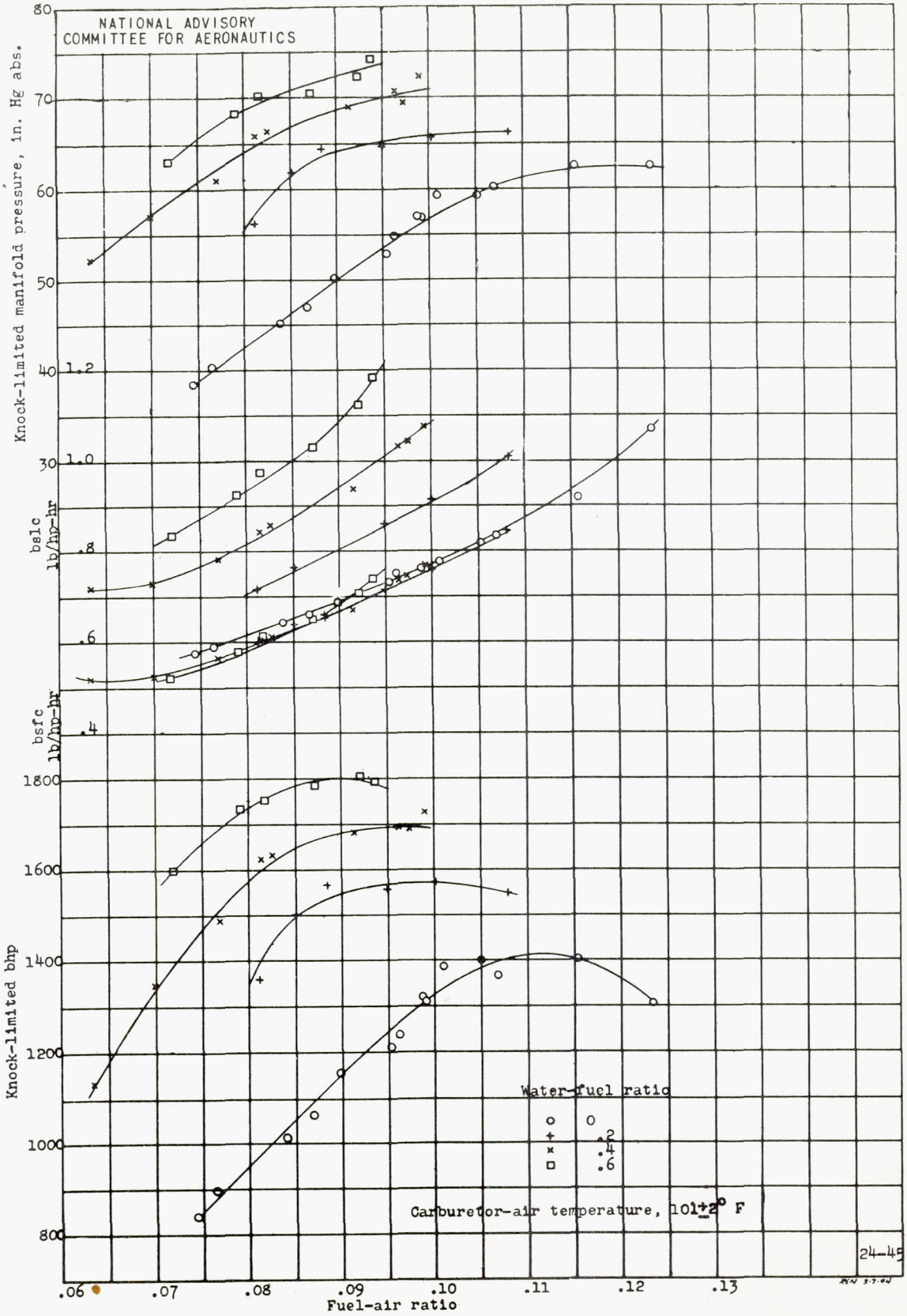

Figure 5. - Knock-limited performance with water injection at carburetor-air temperature of 101° F. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2.

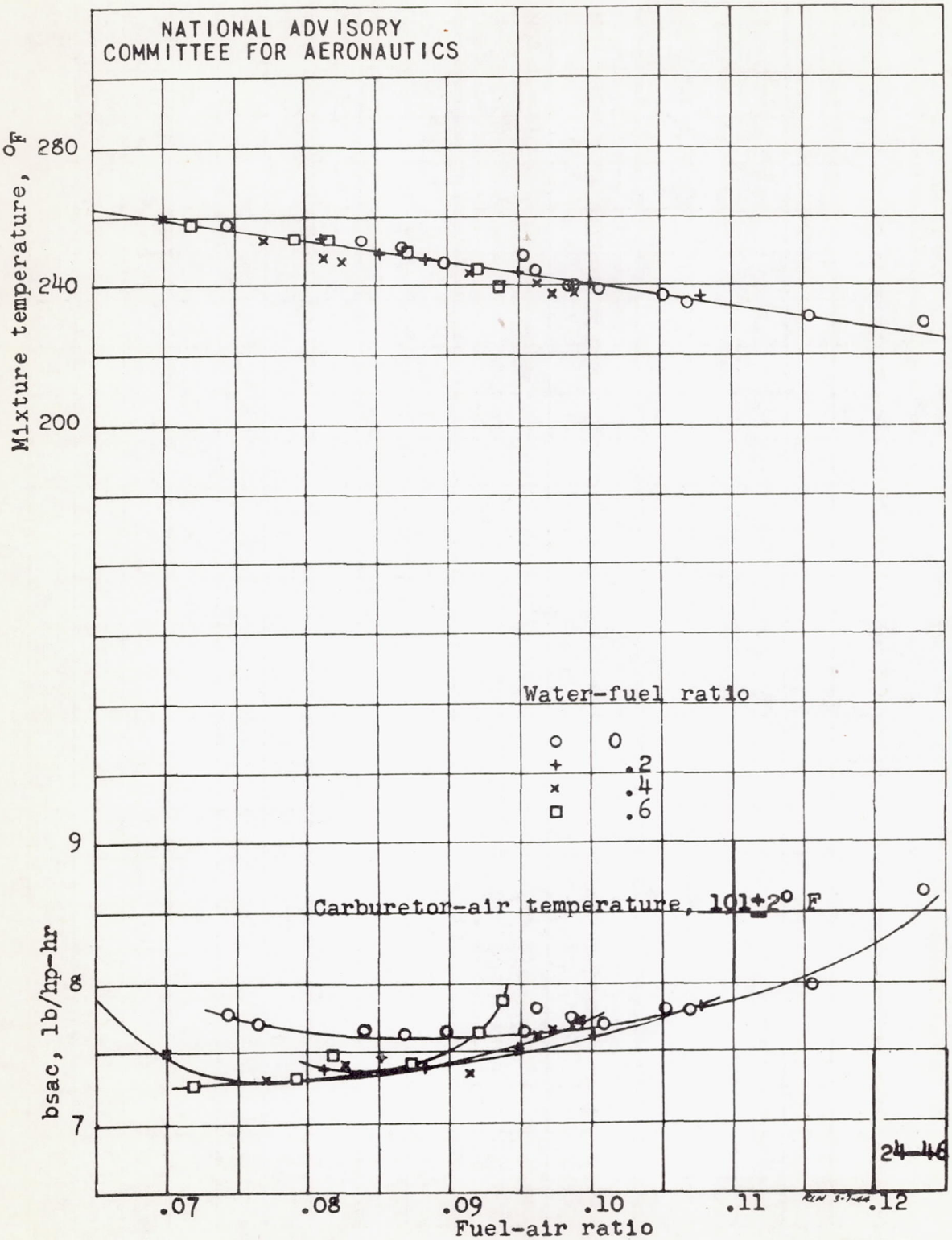

Figure 5. - Concluded.

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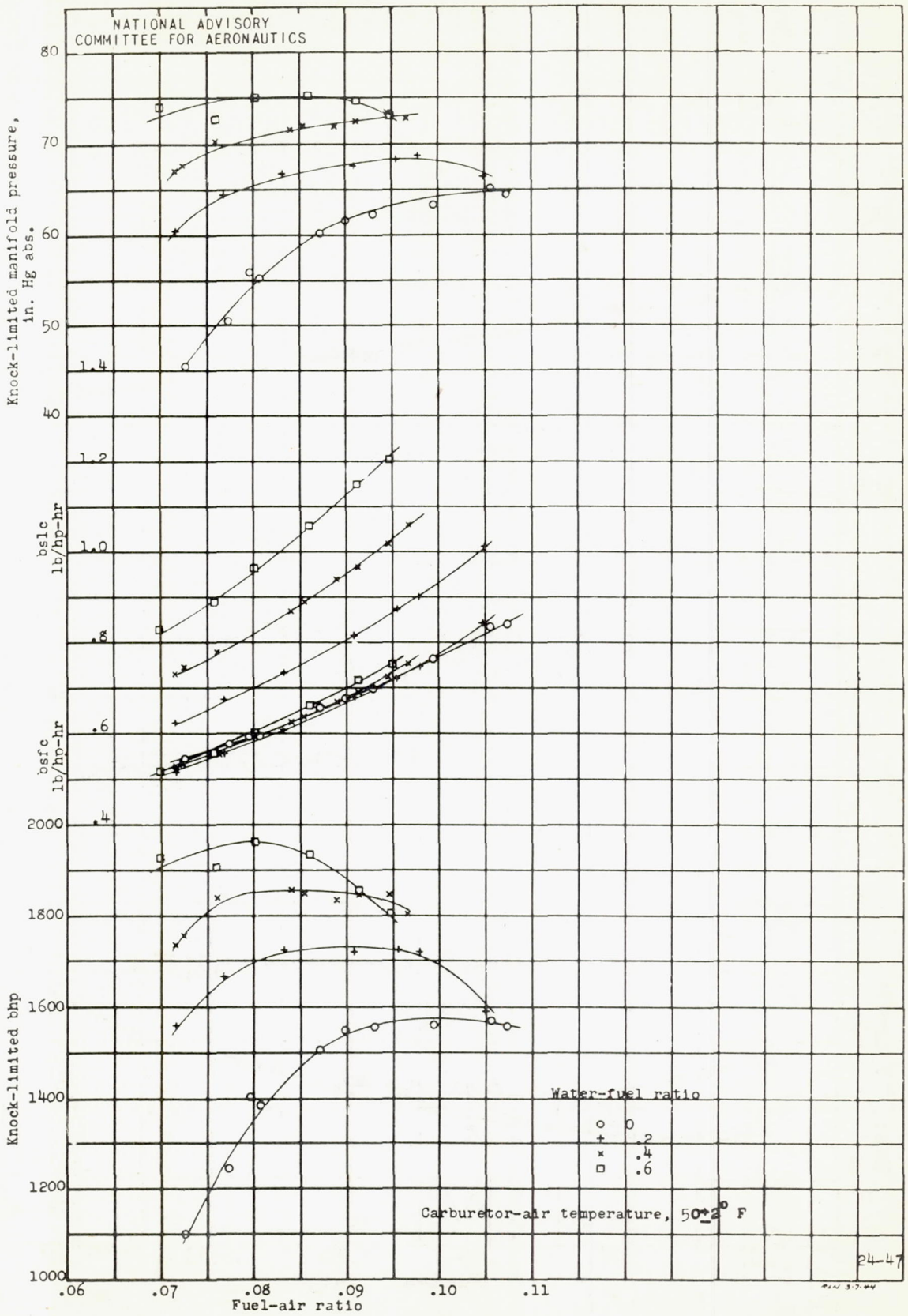
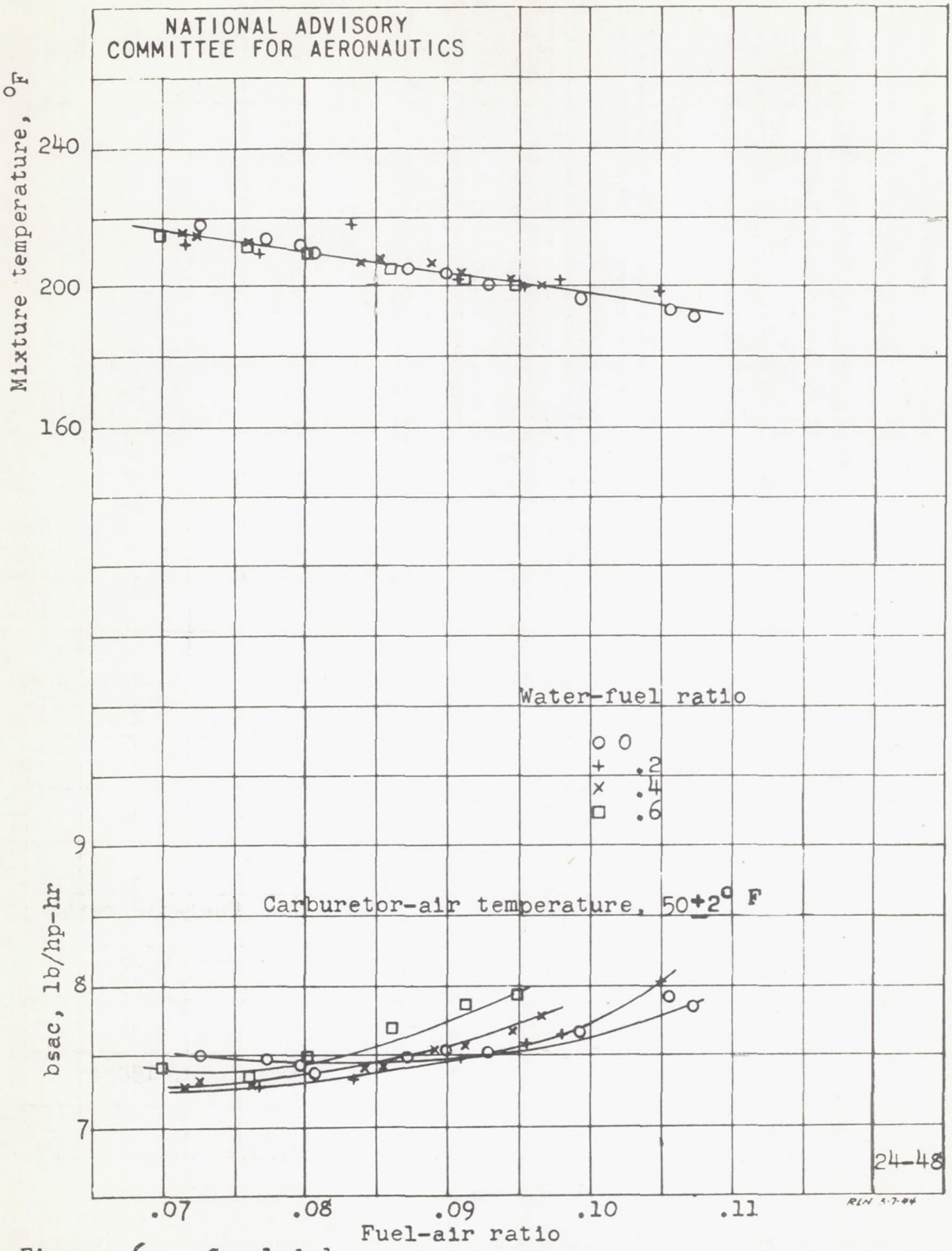


Figure 6. - Knock-limited performance with water injection at carburetor-air temperature of 50° F. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2.



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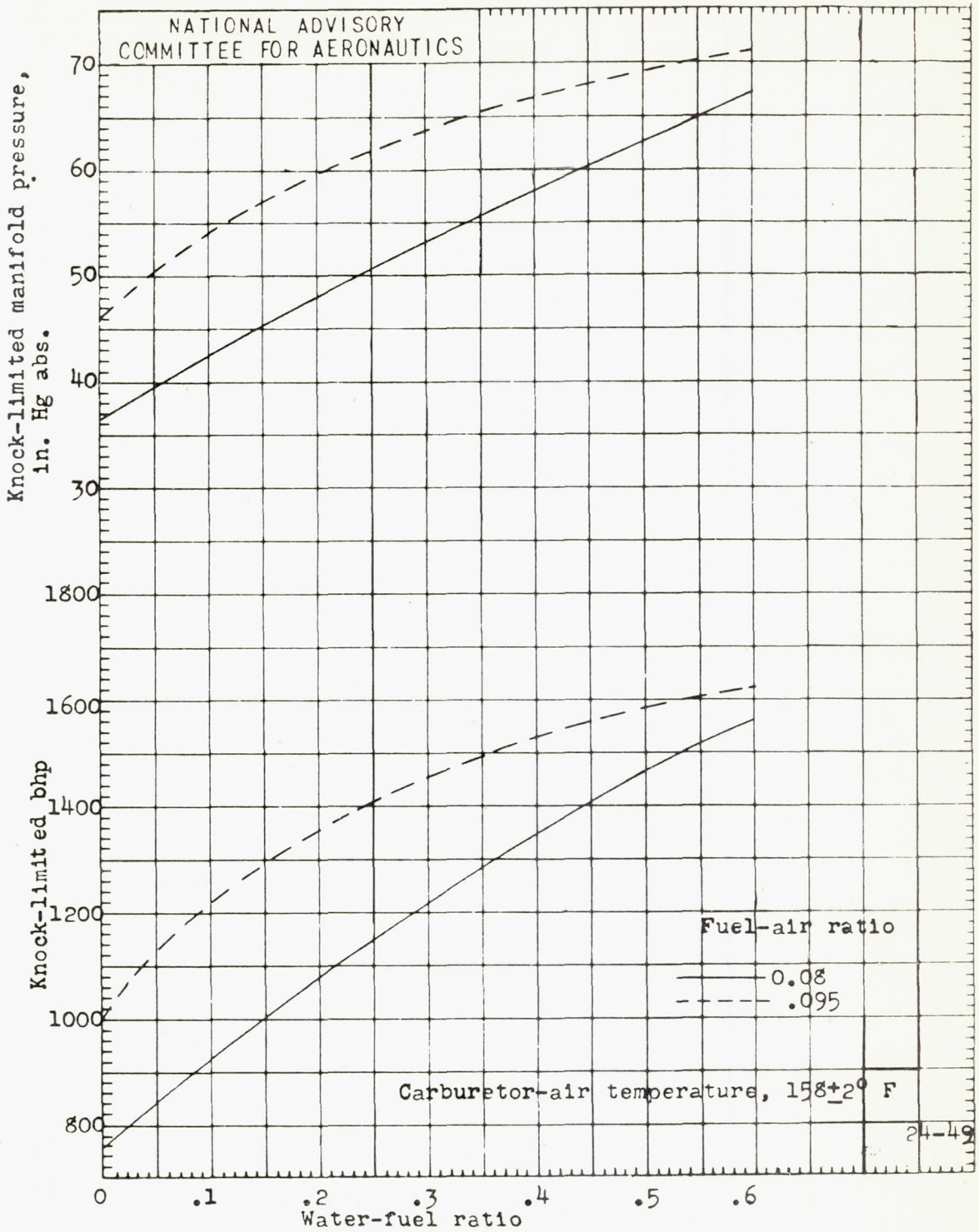
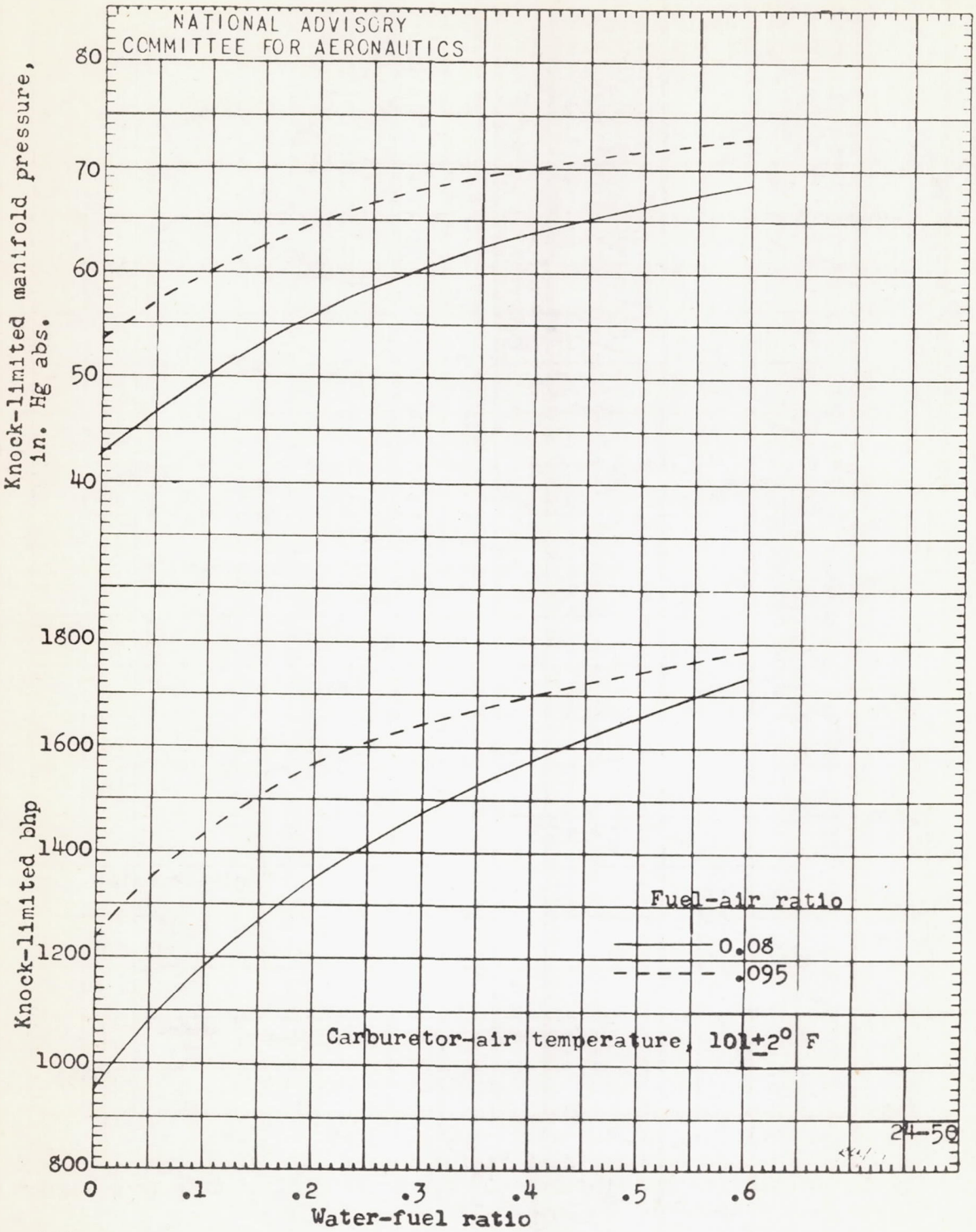


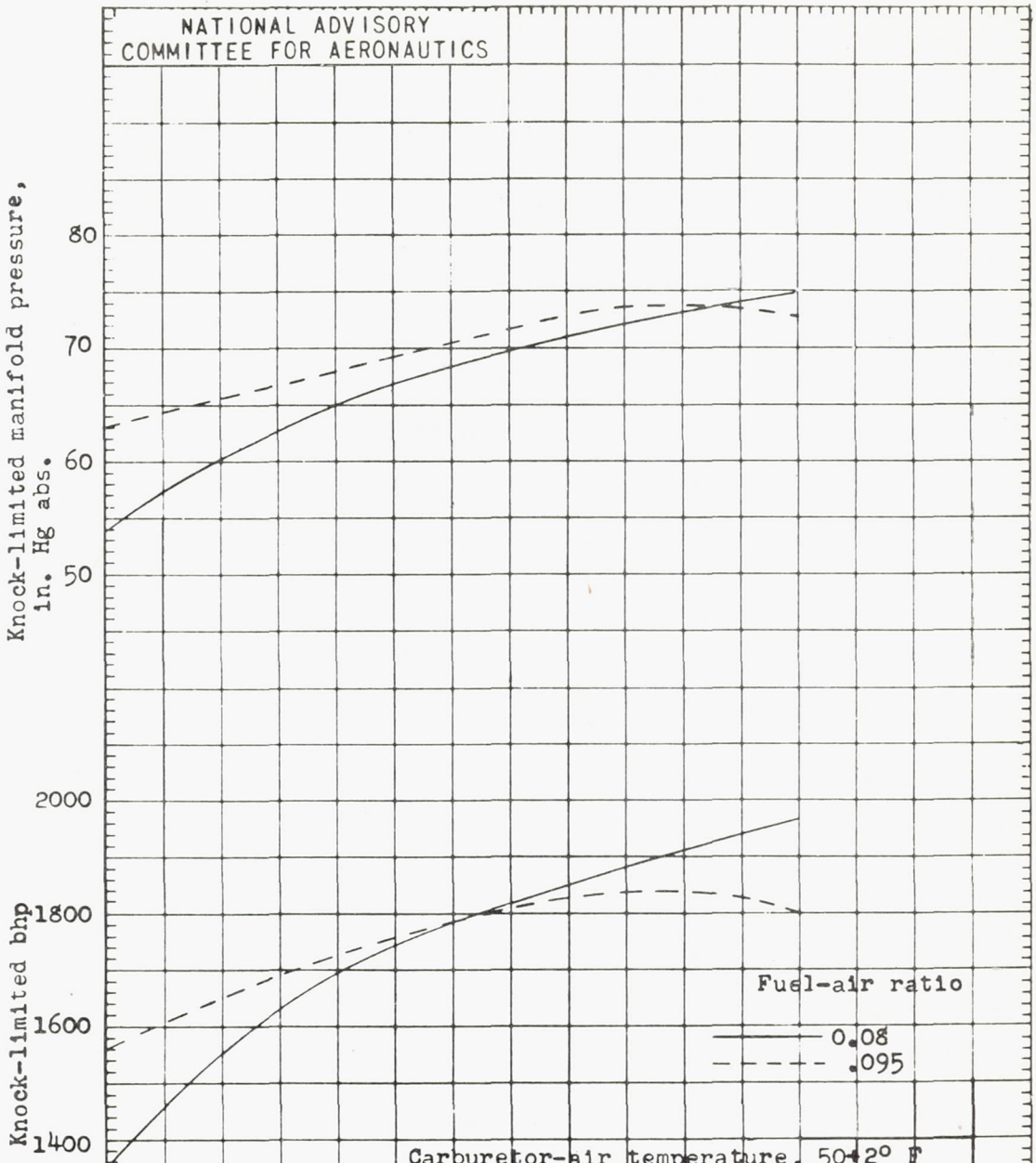
(a) Carburetor-air temperature, 158° F. Cross plot of data from figure 4.

Figure 7. - Variation of knock-limited brake horsepower and manifold pressure with water-fuel ratio. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2.

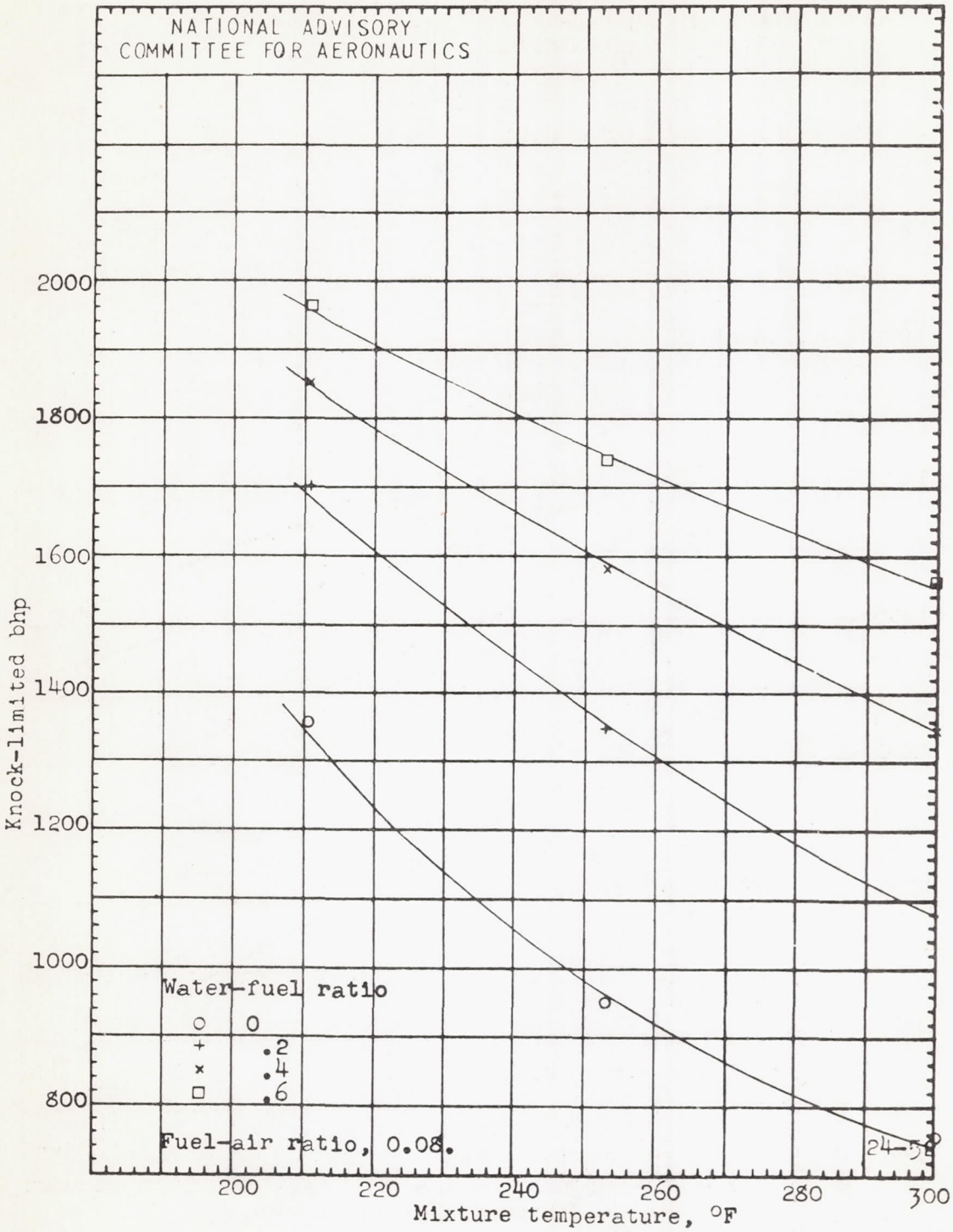


(b) Carburetor-air temperature, 101° F. Cross plot of data from figure 5.

Figure 7. - Continued.

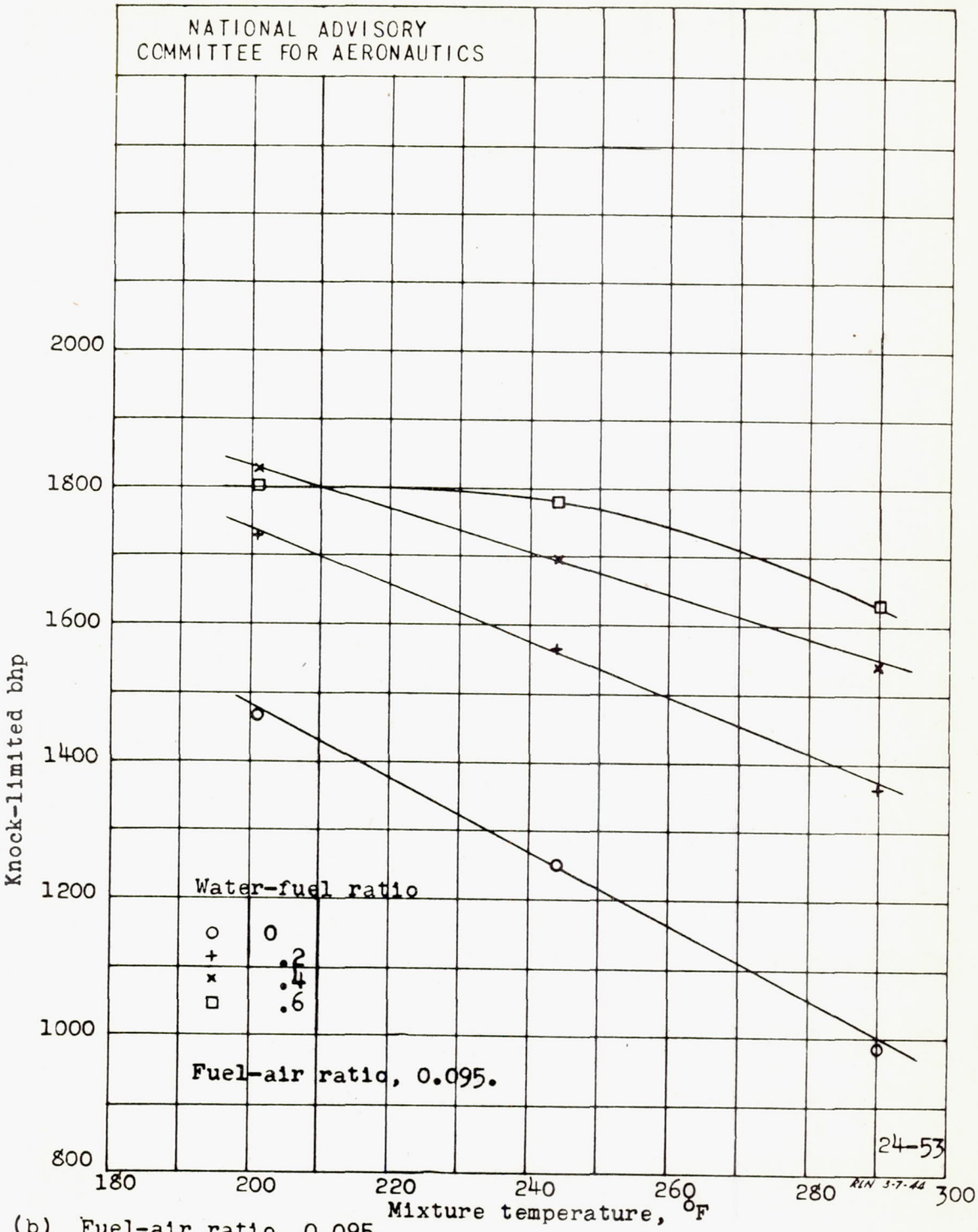


(c) Carburetor-air temperature, 50° F. Cross plot of data from figure 6.
Figure 7. - Concluded.

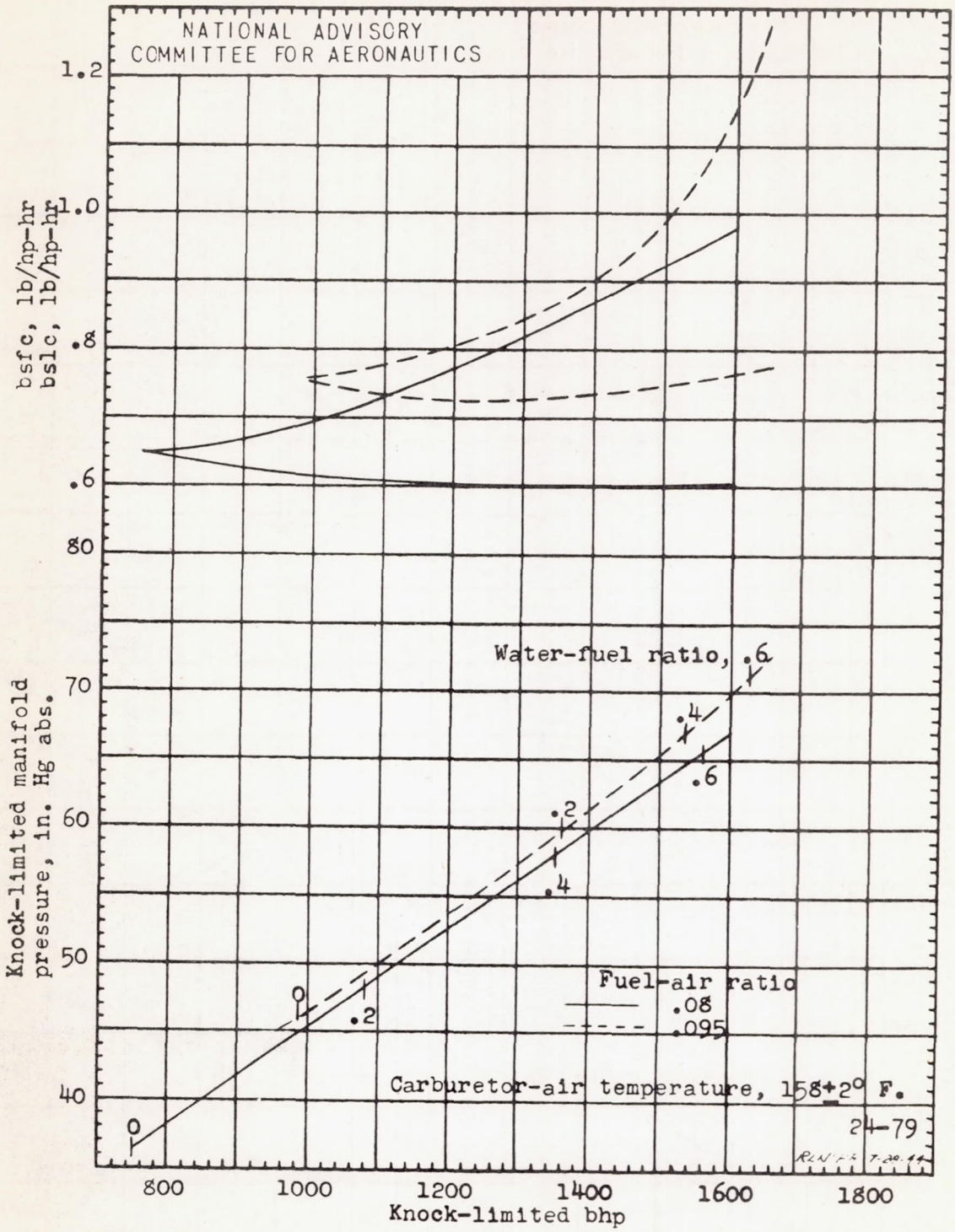


(a) Fuel-air ratio, 0.08.

Figure 8. - Variation of knock-limited brake horsepower with mixture temperature. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2. Cross plot from figures 4, 5, and 6.

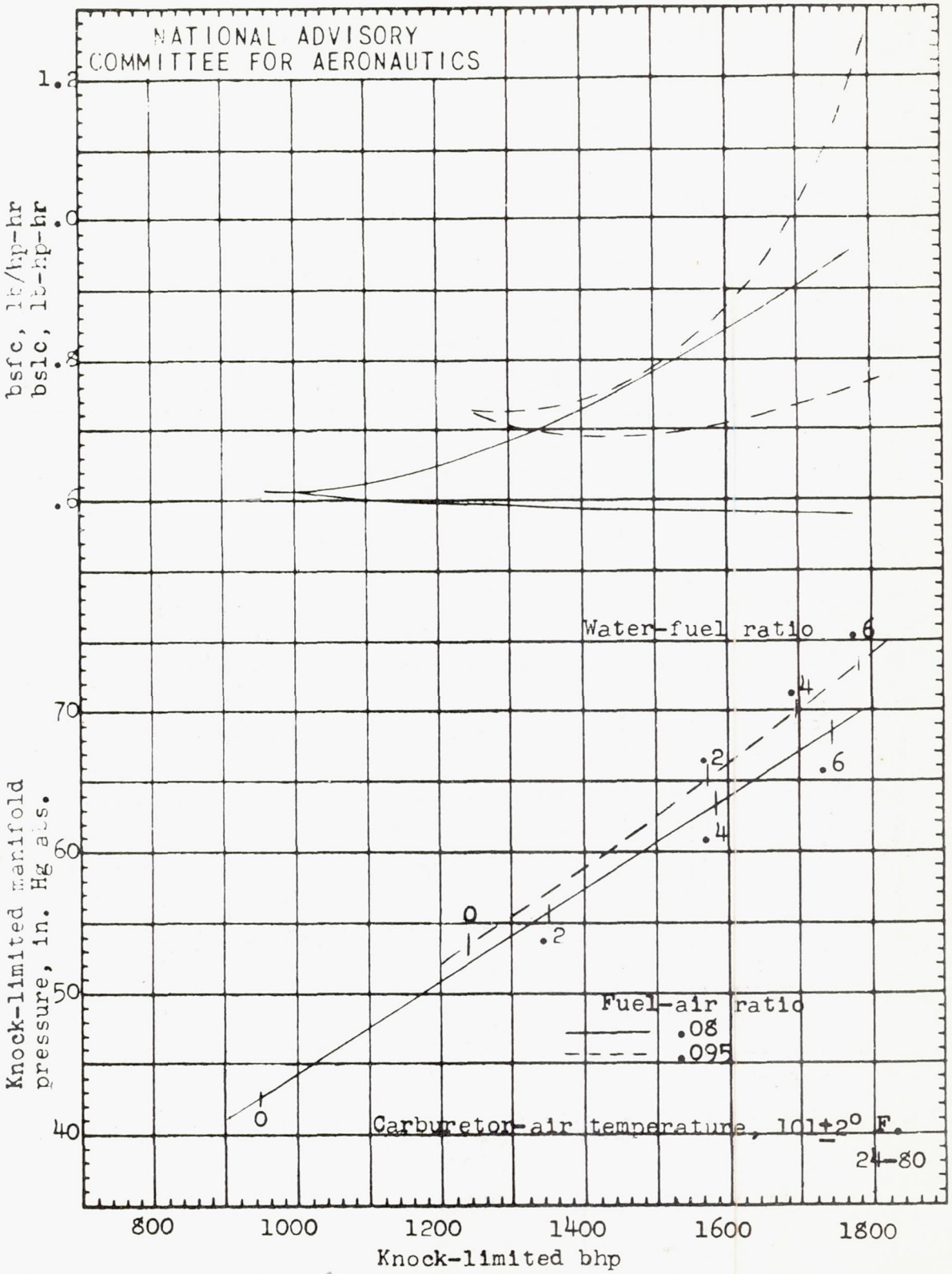


(b) Fuel-air ratio, 0.095.
Figure 8. - Concluded.



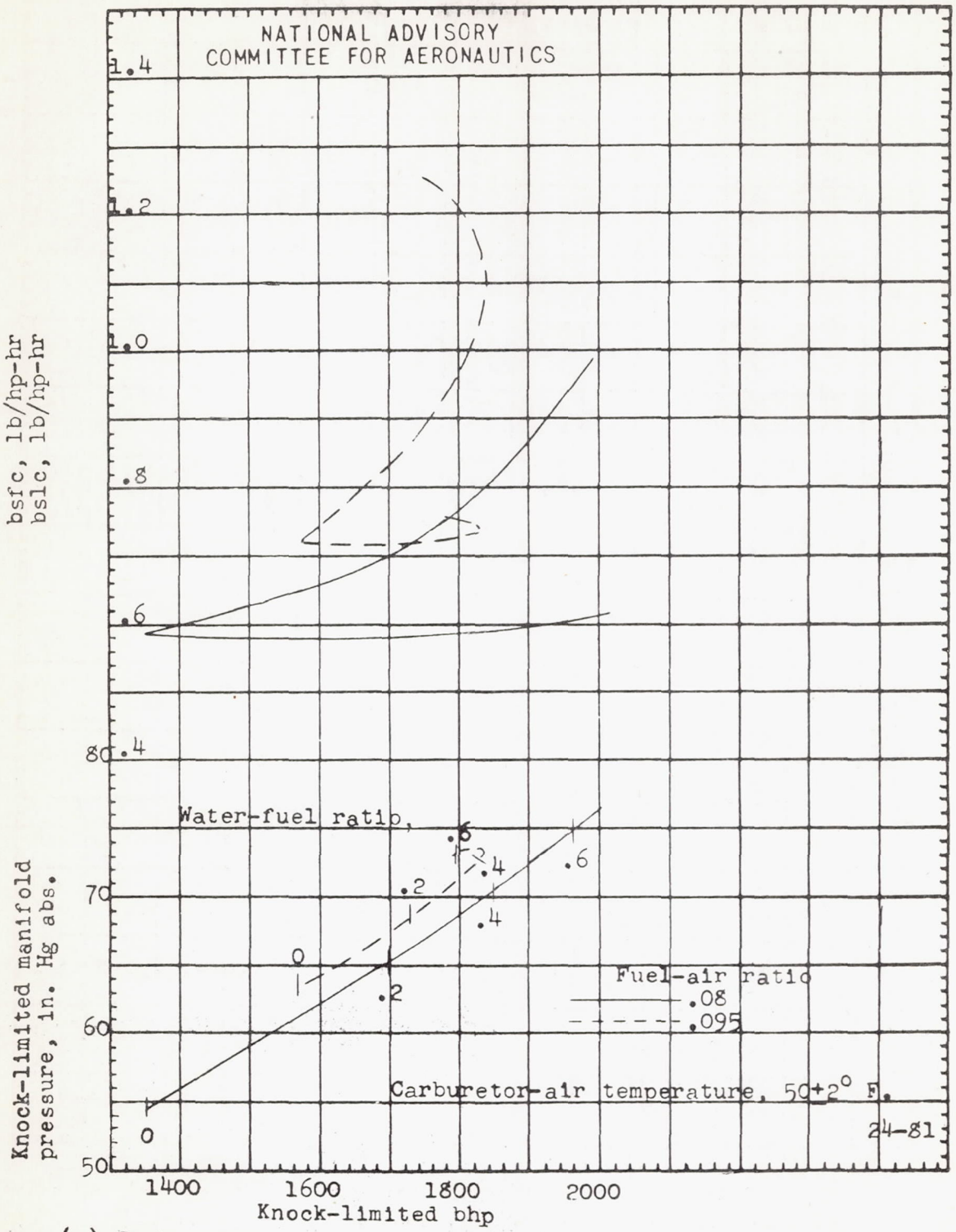
(a) Carburetor-air temperature, 158° F. Cross plot of data from figure 4.

Figure 9. - Variation of knock-limited manifold pressure, brake specific fuel consumption, and brake specific liquid consumption with knock-limited brake horsepower using water injection. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2.



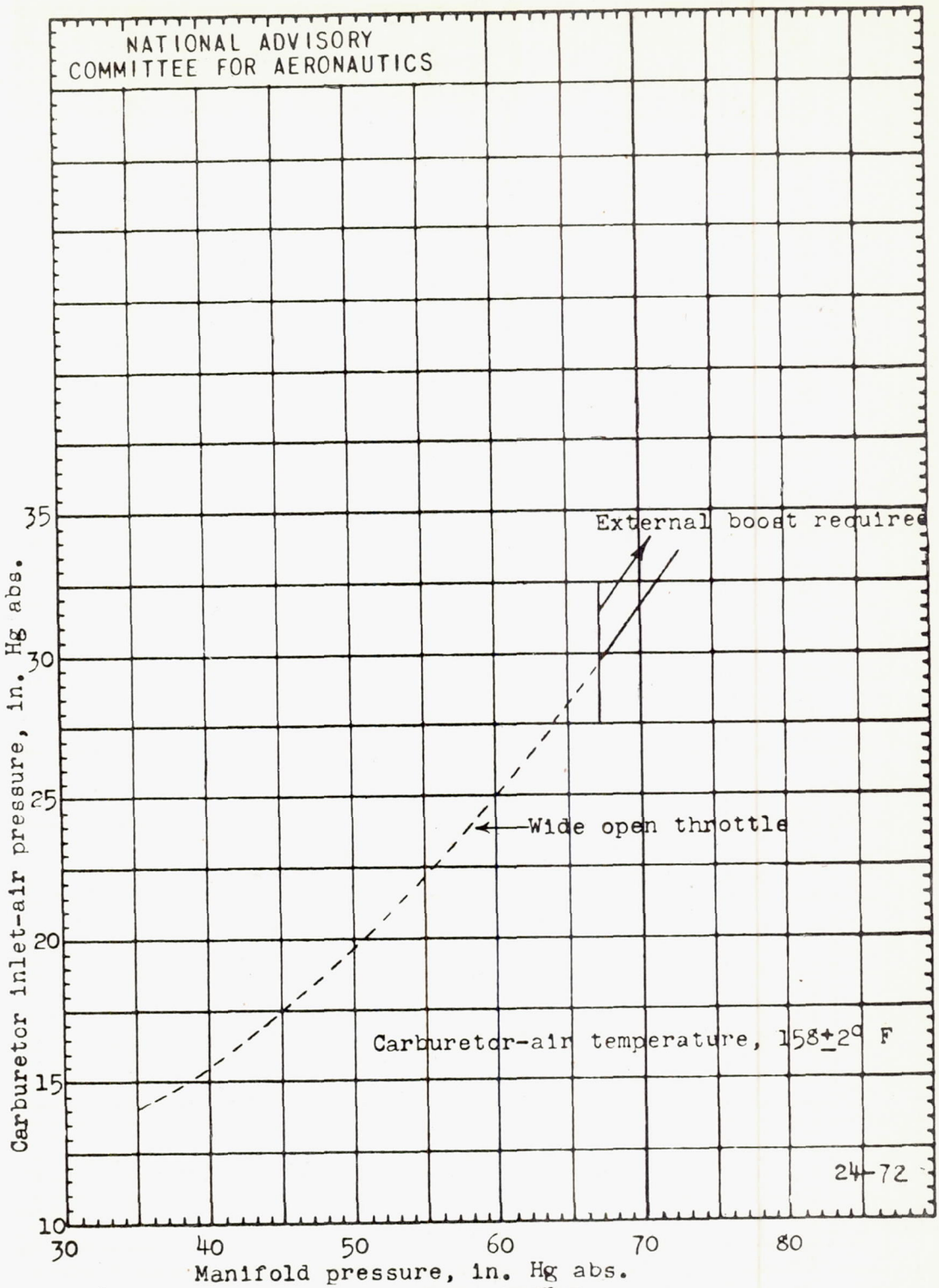
(b) Carburetor-air temperature, 101° F. Cross plot of data from figure 5.

Figure 9. - Continued.



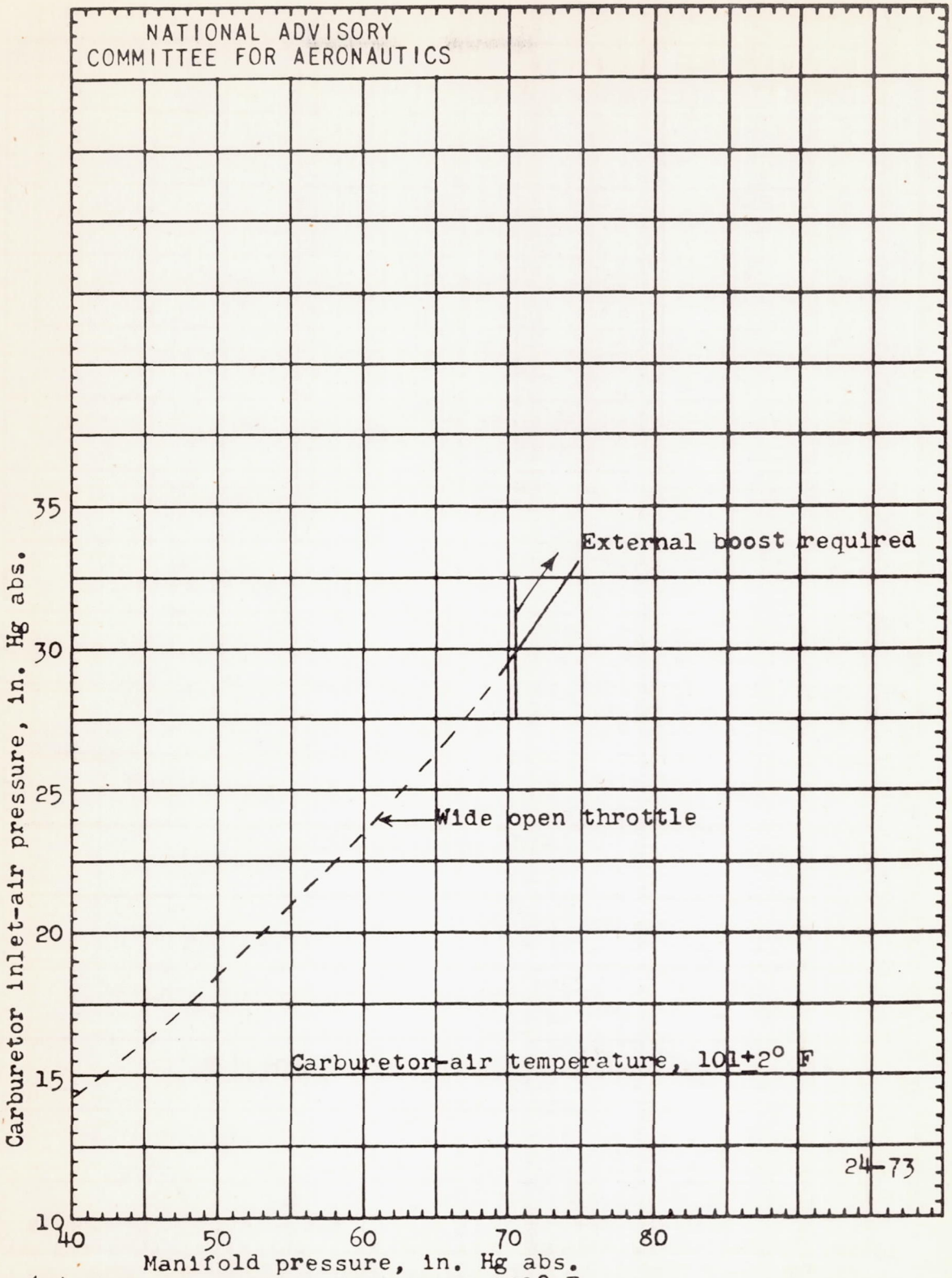
(c) Carburetor-air temperature, 50° F. Cross plot of data from figure 6.

Figure 9. - Concluded.



(a) Carburetor-air temperature, 158° F.

Figure 10. - Variation of required carburetor inlet-air pressure with manifold pressure at wide open throttle. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; supercharger-gear ratio, 9.6.



(b) Carburetor-air temperature, 101° F.
Figure 10. - Continued.

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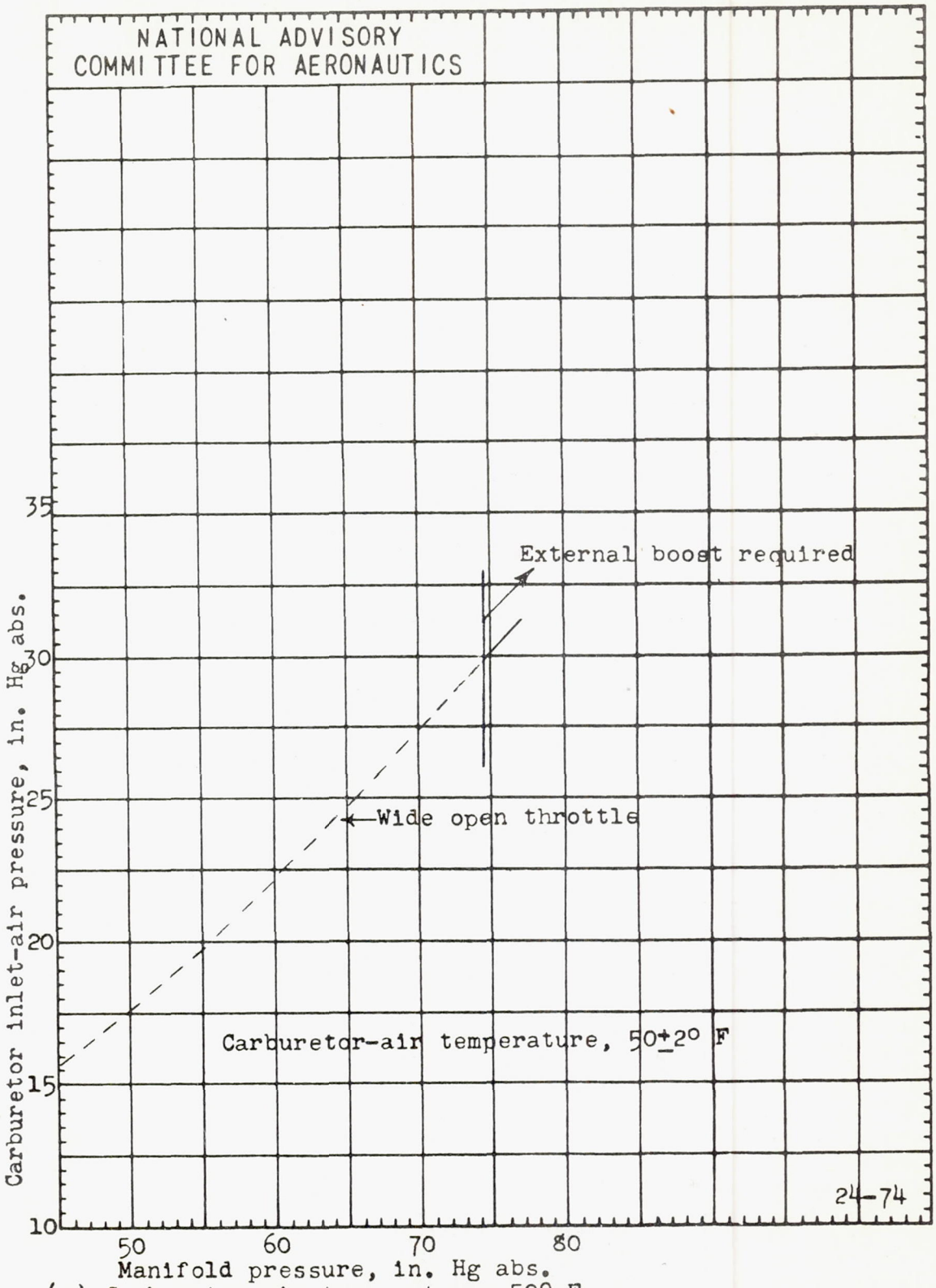
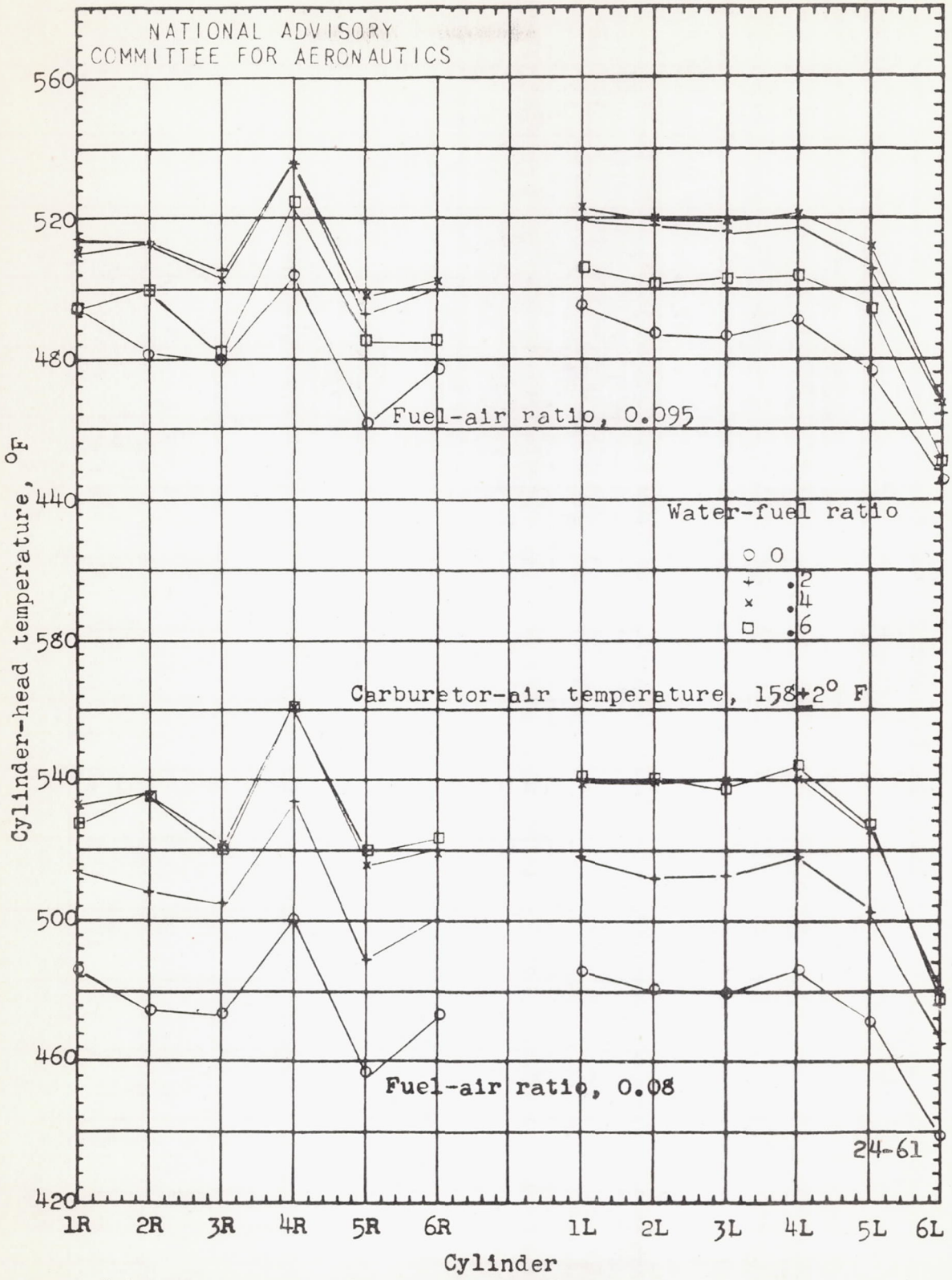
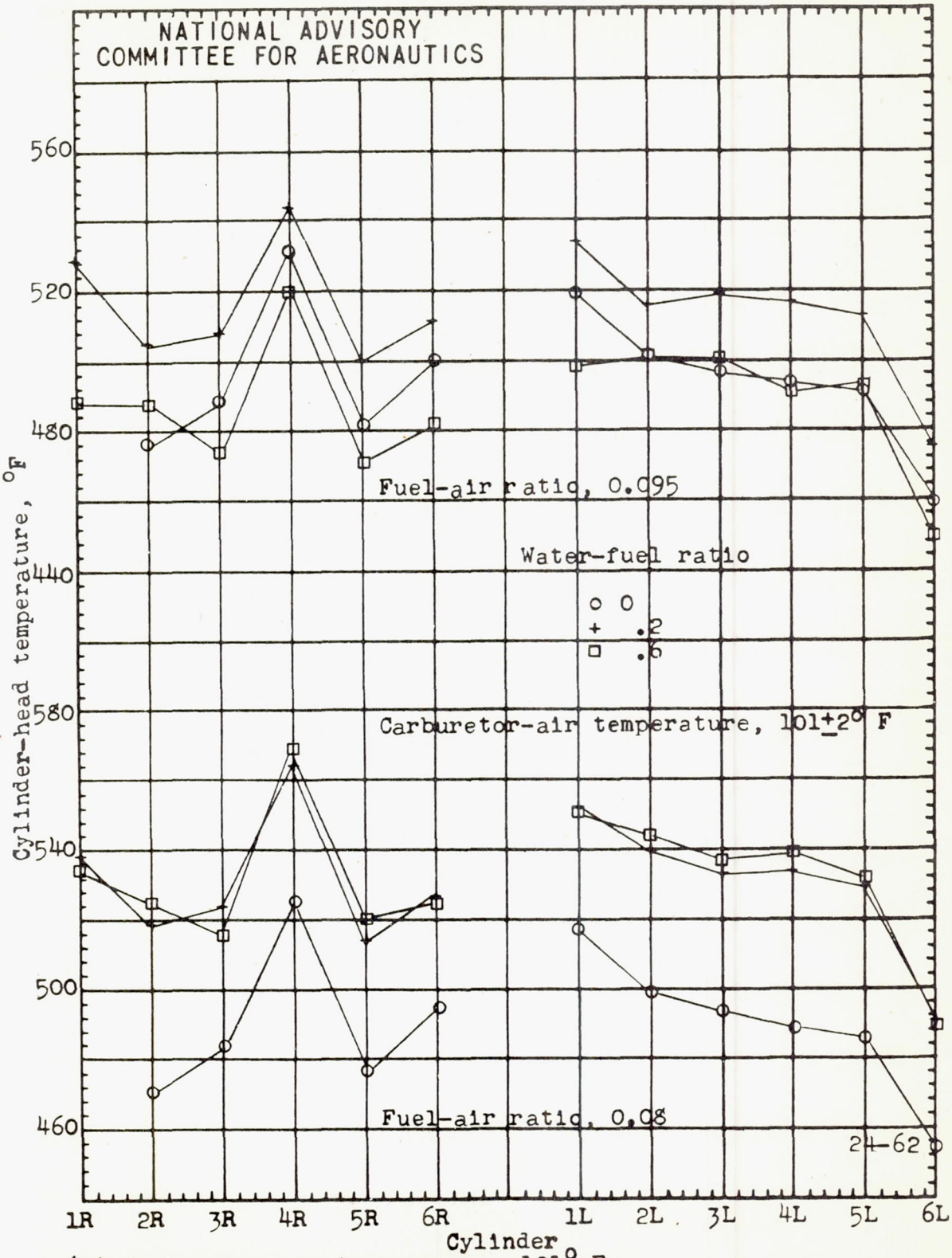


(c) Carburetor-air temperature, 50° F.
Figure 10. - Concluded.

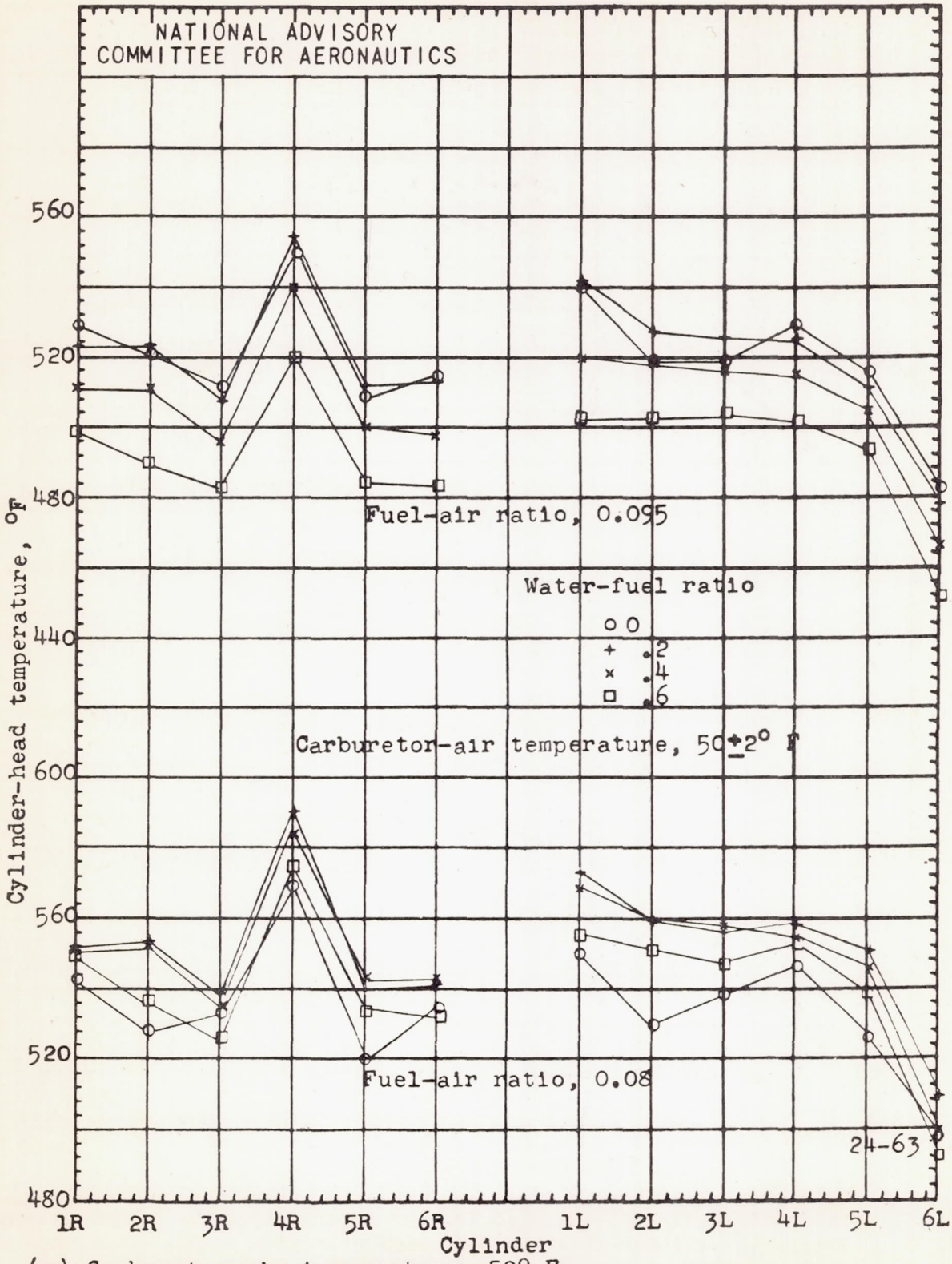


(a) Carburetor-air temperature, 158° F.

Figure 11. - Cylinder-head temperatures at knock-limited power with several water-fuel ratios and two fuel-air ratios. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2. Cross plot from original data.



(b) Carburetor-air temperature, 101° F.
Figure 11. - Continued.



(c) Carburetor-air temperature, 50° F.
Figure 11. - Concluded.

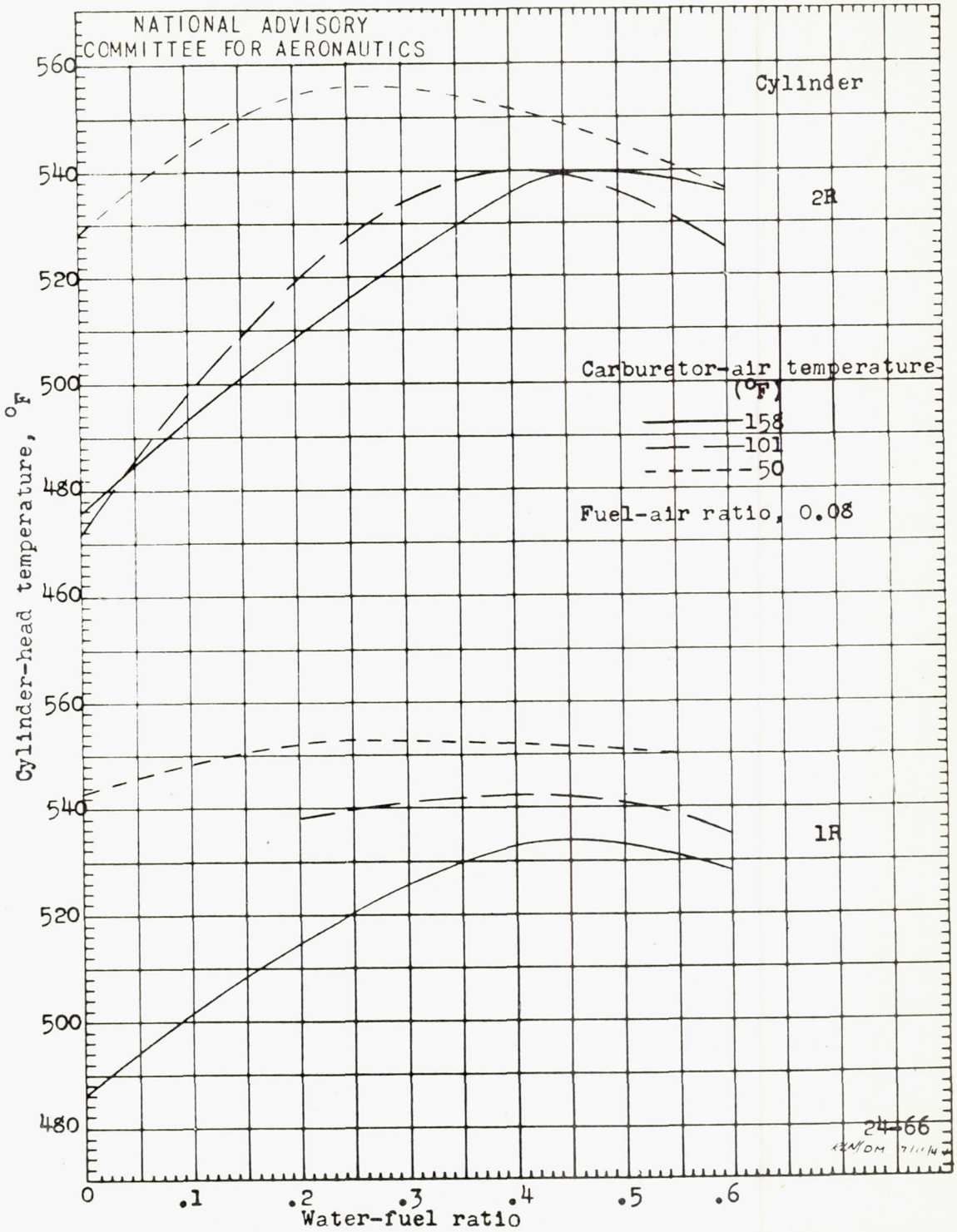


Figure 12. - Variation of cylinder-head temperatures with water-fuel ratio at knock-limited power for three carburetor-air temperatures. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2; fuel-air ratio, 0.08. Cross plot of data from figure 11.

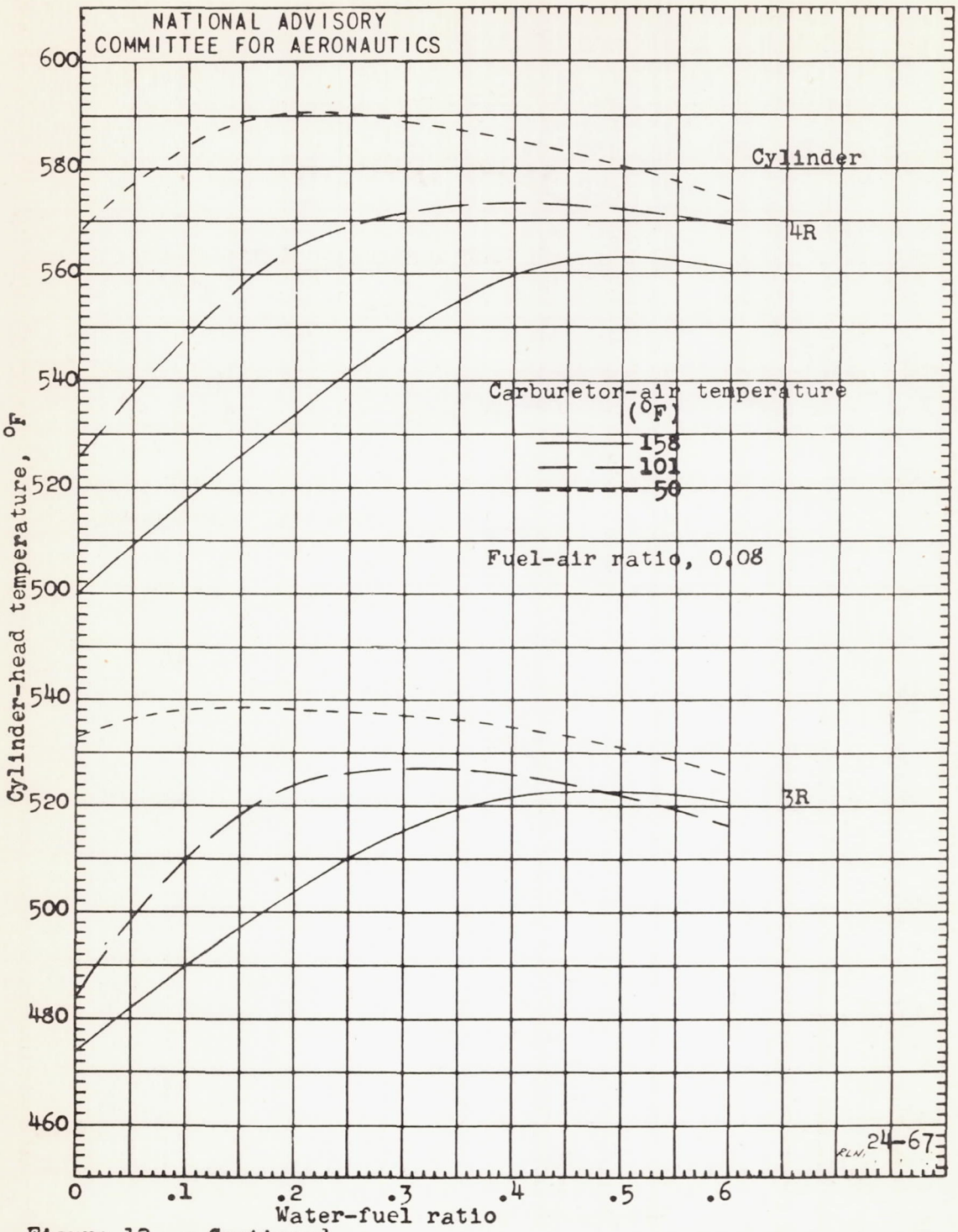


Figure 12. - Continued.

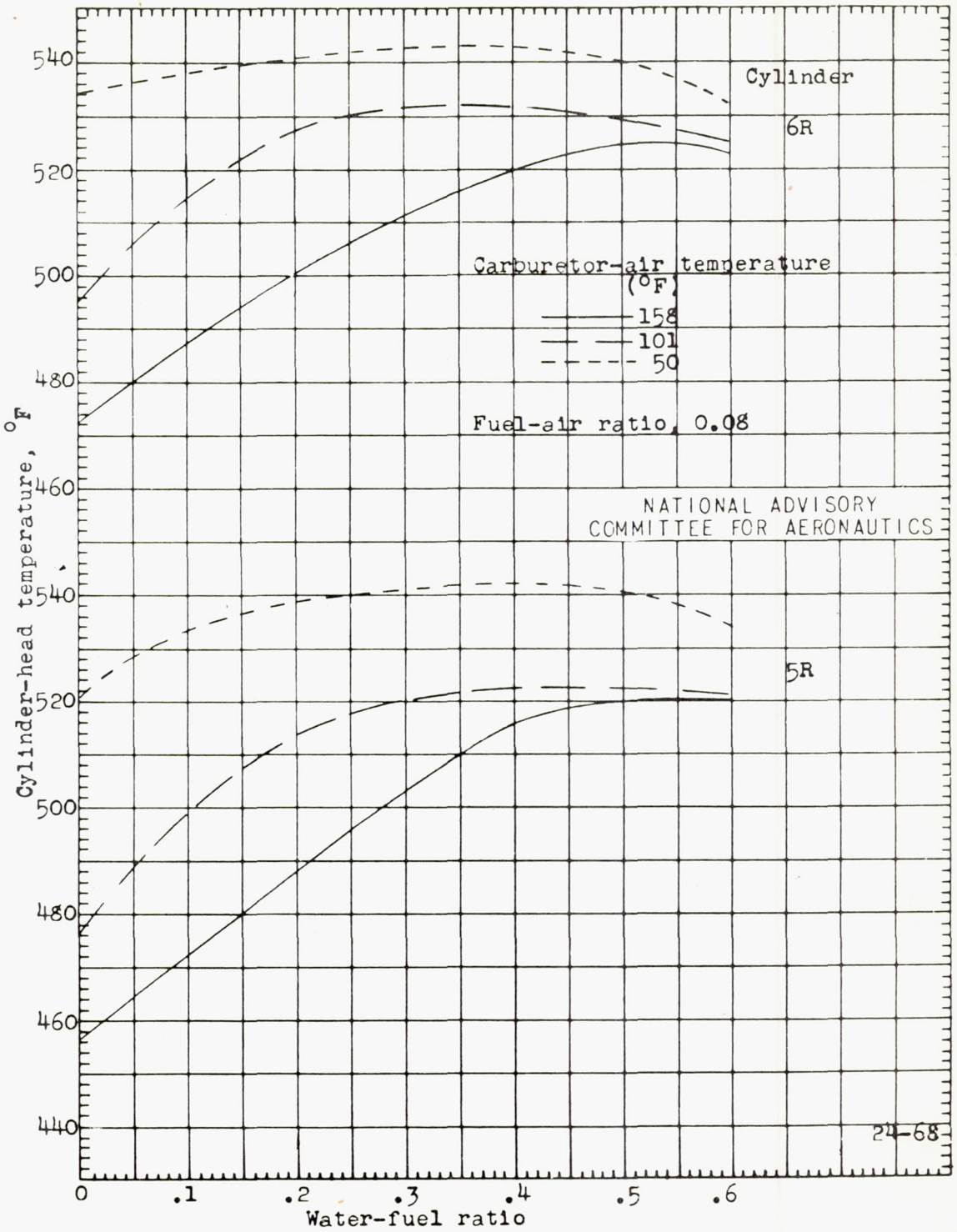


Figure 12. - Continued.

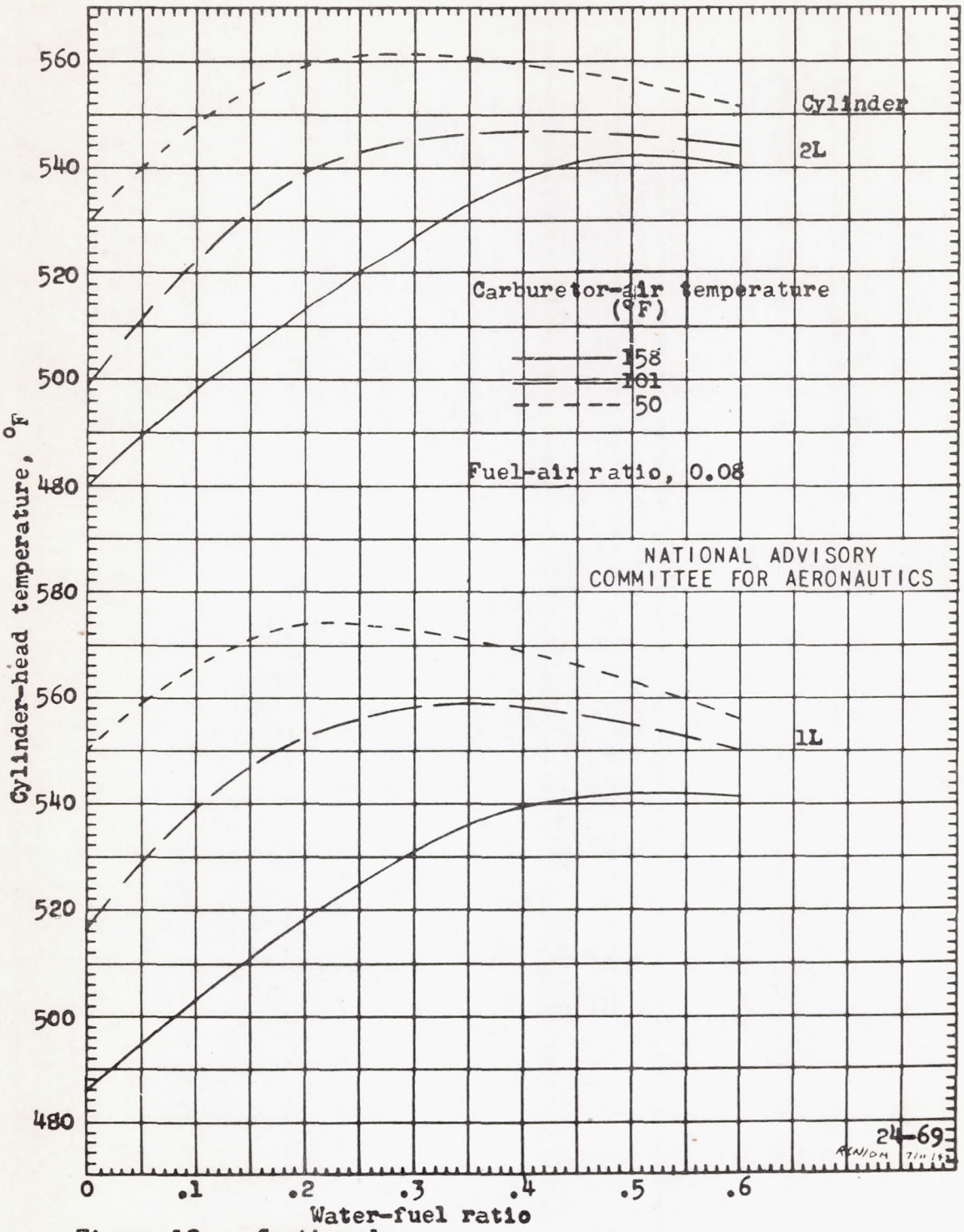


Figure 12. - Continued.

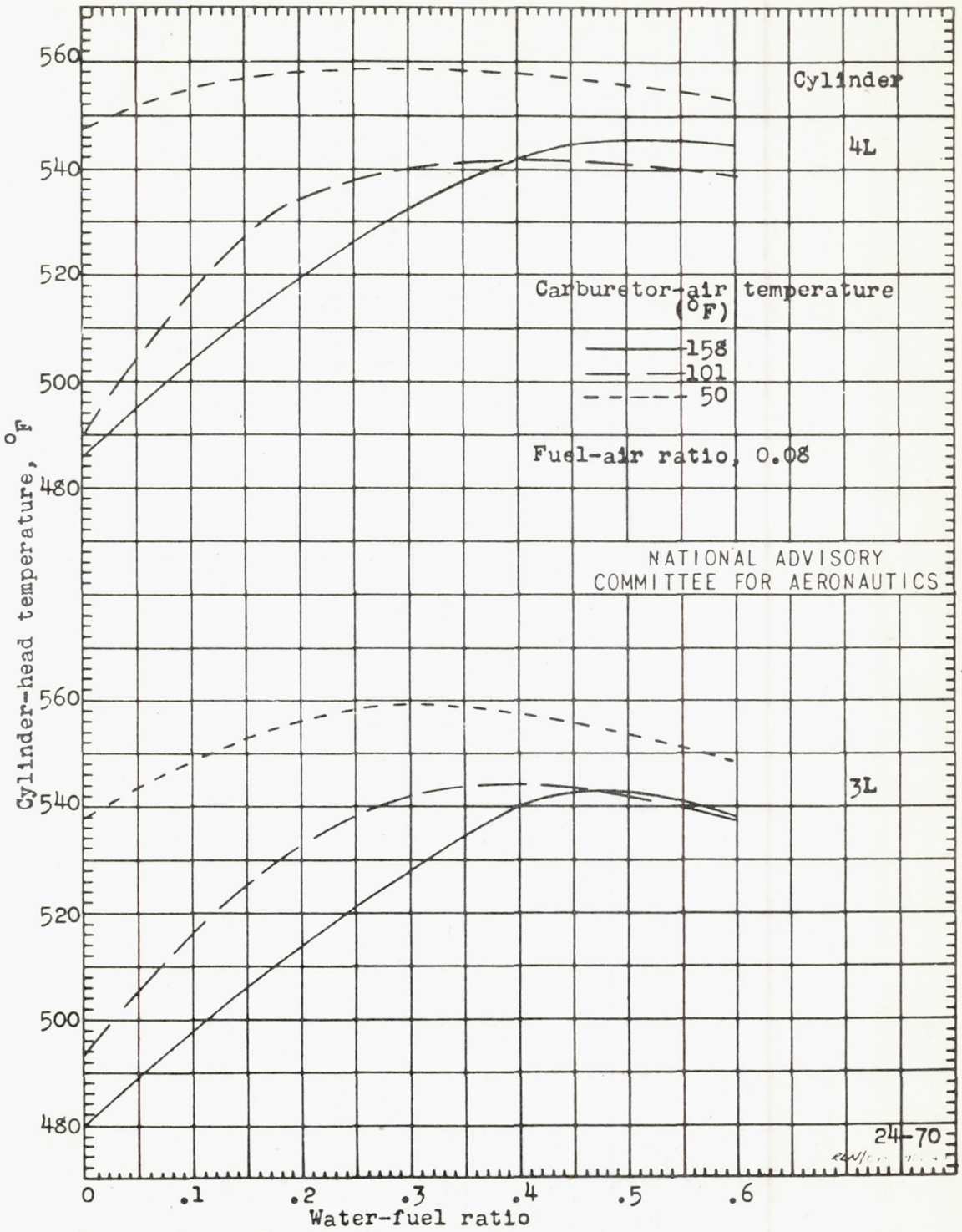


Figure 12. - Continued.

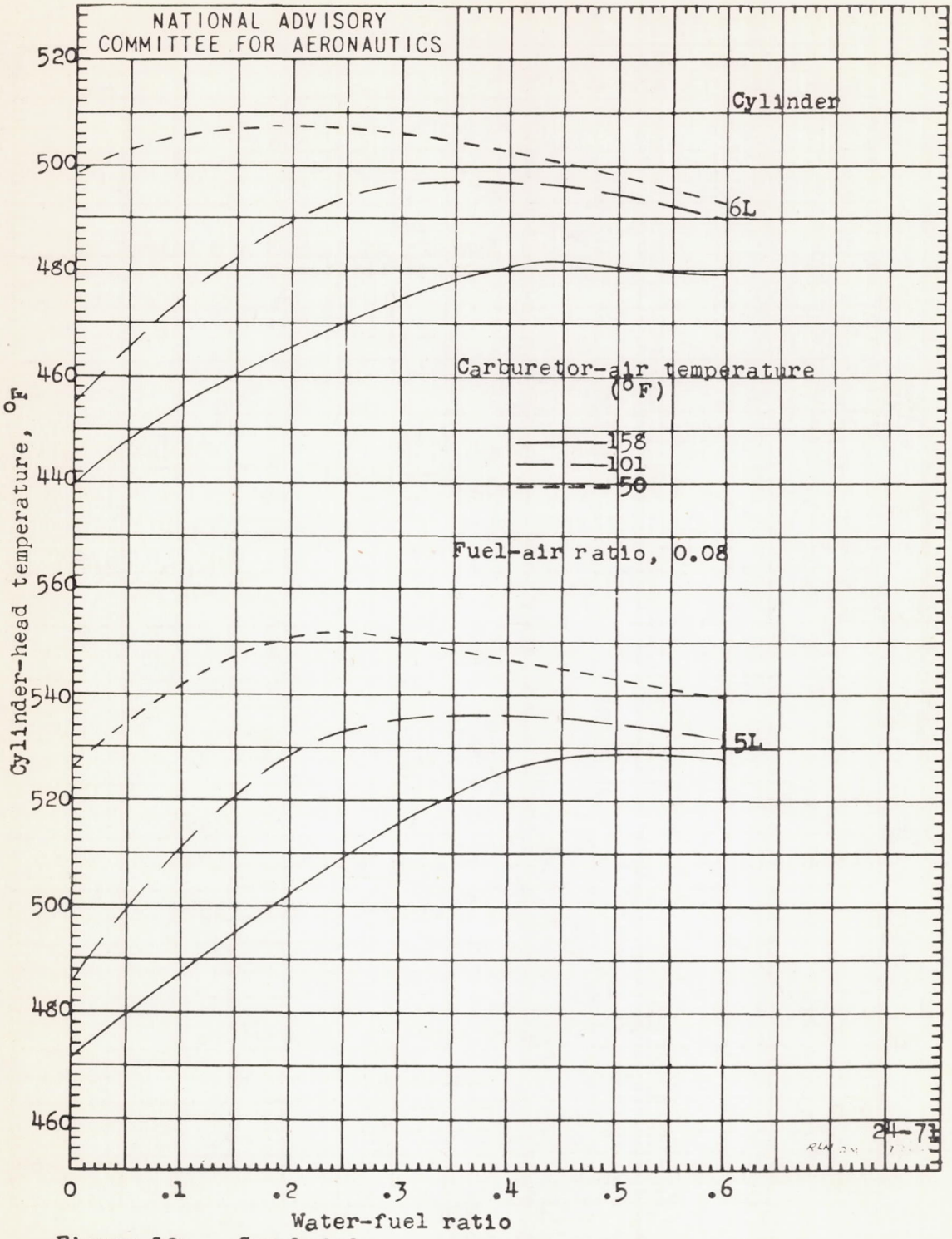


Figure 12. - Concluded.

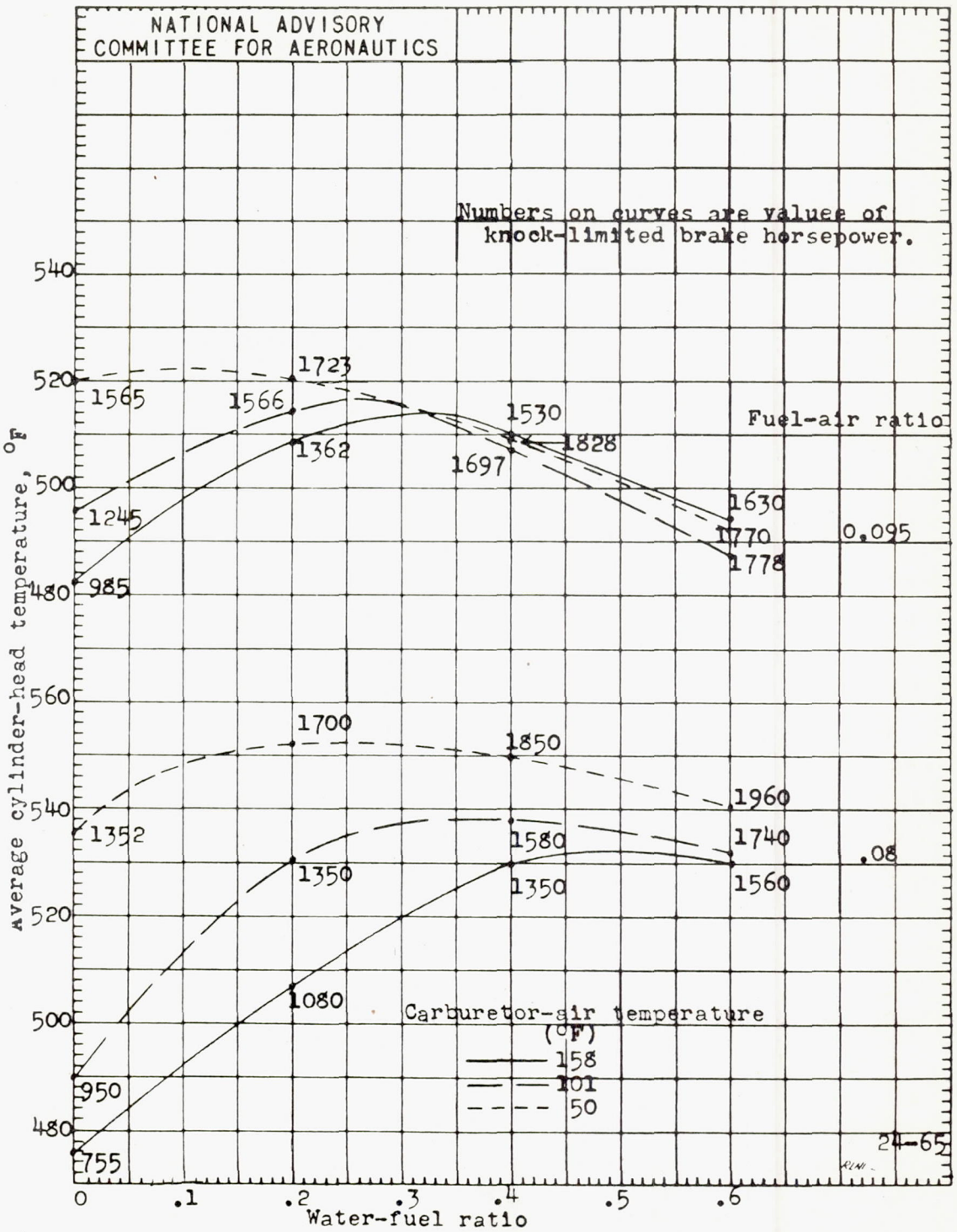


Figure 13. - Variation of average cylinder-head temperature with water-fuel ratio at knock-limited power for three carburetor-air temperatures. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2.

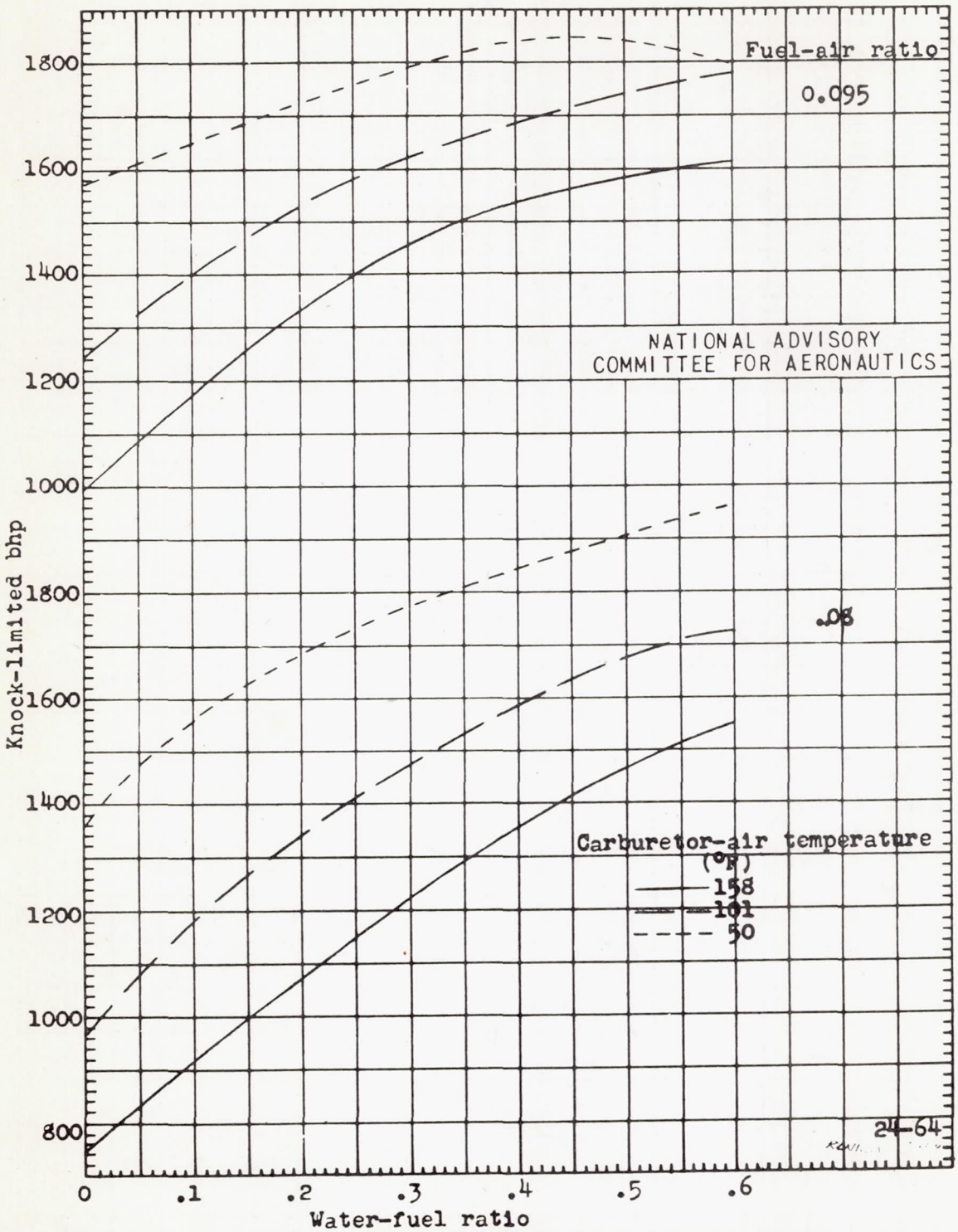


Figure 14. - Variation of knock-limited brake horsepower with water-fuel ratio for three carburetor-air temperatures and two fuel-air ratios. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-2. Cross plot from figures 4, 5, and 6.

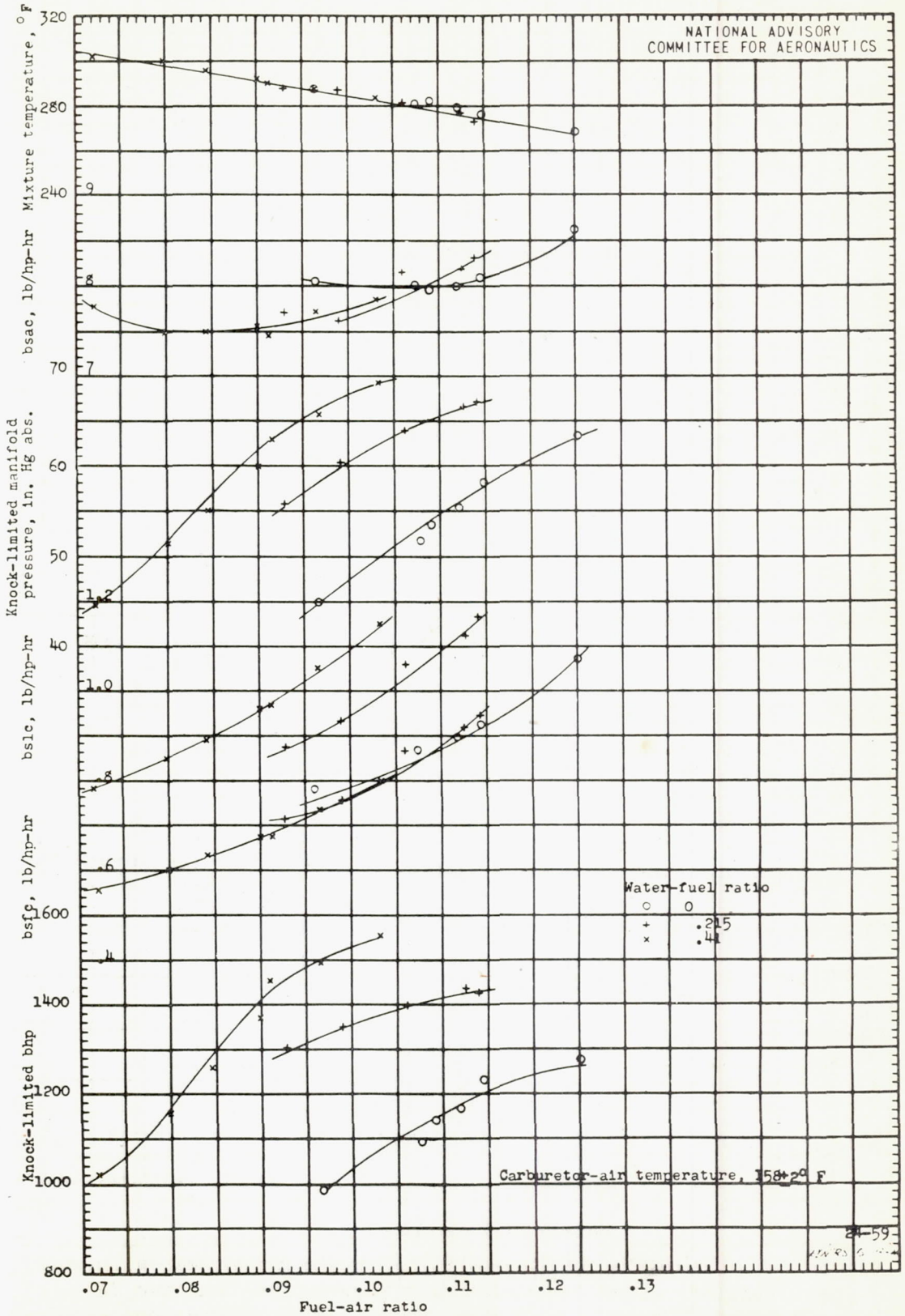


Figure 15. - Knock-limited performance with water-injection system proposed for fighter airplane at carburetor-air temperature of 158° F. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-1.

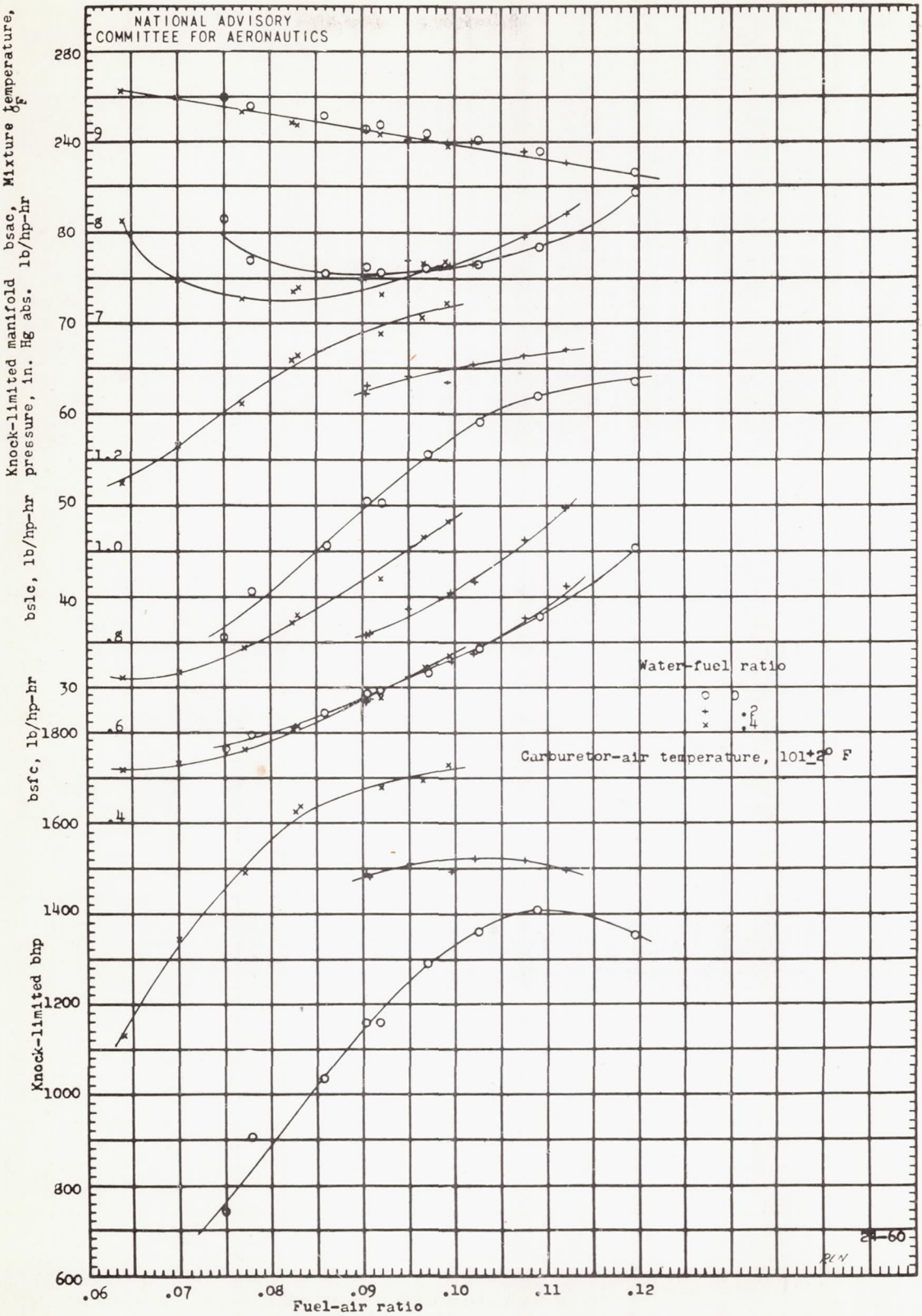


Figure 16. - Knock-limited performance with water-injection system proposed for fighter airplane at carburetor-air temperature of 101° F. V-type 12-cylinder liquid-cooled engine; engine speed, 3000 rpm; fuel, AN-F-28, Amendment-1.