REPORT No. 45

EFFECT OF COMPRESSION RATIO, PRESSURE, TEMPERATURE, AND HUMIDITY ON POWER

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Part I.—VARIATION OF HORSEPOWER WITH ALTITUDE AND COMPRESSION RATIO

By H. C. DICKINSON, W. S. JAMES AND G. V. ANDERSON

Part II.—VALUE OF SUPERCHARGING

By H. C. DICKINSON AND G. V. ANDERSON

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By V. W. BRINKERHOFF

REPORT No. 45.

PART I.

VARIATION OF HORSEPOWER WITH ALTITUDE AND COMPRESSION RATIO.[1]

By H. C. Dickinson, W. S. James and G. V. Anderson.

RÉSUMÉ.

Among many other factors which affect the horsepower of an airplane engine are the atmospheric pressure, and consequently the altitude at which the engine is working, and the compression ratio, or cylinder volume divided by clearance volume.

The tests upon which this report is based were selected from a large number of runs made during the intercomparison of various gasolines to determine the variation of horsepower with altitude at three different compression ratios and the following conclusions have been reached:

(1) The total power of the engine decreases rapidly with increase in altitude, being only 71 per cent of the power on the ground at 10,000 feet, 49 per cent at 20,000 feet, and 32.5 per cent at 30,000 feet.

(2) The gain in power due to increase in compression does not bear a constant relation to the total power of the engine at different altitudes, being greater at high than at low altitudes. The curves on plot 8 illustrate this variation in horsepower for the three compressions considered at different altitudes.

VARIATION OF HORSEPOWER WITH ALTITUDE AND COMPRESSION RATIO.

The following report is based upon the results of a series of tests conducted at the altitude laboratory at the Bureau of Standards for the National Advisory Committee for Aeronautics. In this laboratory the engine under test is installed in a concrete chamber from which the air may be partially exhausted by means of a blower, thus reducing the barometric pressure within the chamber to a point corresponding to the pressure at any desired altitude. At the same time, by passing the air, as it enters the chamber, over a series of refrigerating coils and heating grids, the temperature may be regulated during the tests. The power of the engine is absorbed by an electric dynamometer placed outside the chamber and connected to the engine through a flexible coupling. Measurements of power are made by weighing the torque on the dynamometer field at measured engine speeds. A complete description of this apparatus and methods of observation is contained in Report No. 44.

A stock Hispano-Suiza, 8-cylinder engine, rated at 150 horsepower, and built by the Wright-Martin Aircraft Corporation, New Brunswick, N. J., was used in making these experiments. This engine is furnished with three sets of pistons, designated as "low," "high," and "extra high" compression, the ratios of compression, that is $\frac{\text{cylinder volume}}{\text{clearance volume}}$, being approximately 4.7, 5.3, and 6.2, respectively. All of the tests were run on a single grade of gasoline designated as "X," with a Claudel carburetor which was adjusted by hand in each case to give the least fuel consumption consistent with maximum power. All the results are based upon an engine speed of 1,500 revolutions per minute. In the earlier tests the horsepowers were corrected to 0° C., while in the later ones they were corrected to standard temperatures for given barometric pressures, as will be described in a subsequent paragraph.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 7.

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Tables I, II, and III give the results of a number of tests, using the three different sets of pistons, the horsepowers deduced from these tests having been corrected to 0° C. The data contained in these tables are plotted on curve sheet 1.

As it is desirable to obtain the relations existing between barometric pressure and horsepower developed under the actual conditions of flight, the observed horsepower must be corrected from the temperature during the test to the mean temperature encountered in actual flight at the given barometric pressure. To obtain this relation between temperature and barometric pressure, use was made of the information contained in Aeronautic Instruments Circular No. 3, issued by the Bureau of Standards, resulting in the temperature-altitude curves marked "B" on plots 2 and 3. The curve on plot 2 is in metric and that on plot 3 in English units.

To correct a given horsepower, HP_o, at a given barometric pressure from 0° to some temperature t at the same barometric pressure we may make use of the following relation:

$$HP_o = HP_t \times F_o \tag{1}$$

In which HP_o = Horsepower at 0° C., at the given barometic pressure.
In which HP_t = Horsepower at temperature t degrees centigrade at the given barometric pressure.
In which F_o = Correction factor to reduce horsepower from t degrees to 0° C.

Values of F_o for any given temperature t may be obtained from curve B, or its equation, both of which are given on plot 4, which is a mean curve of correction factors obtained from the results of a number of tests performed at the altitude laboratory with two different carburetors and at various altitudes.

We may obtain an expression for HP_t in terms of HP_o by transposing equation (1), as follows:

$$HP_t = \frac{HP}{F_o} \text{ or } HP_t = HP_o \times \frac{1}{F_o} \tag{2}$$

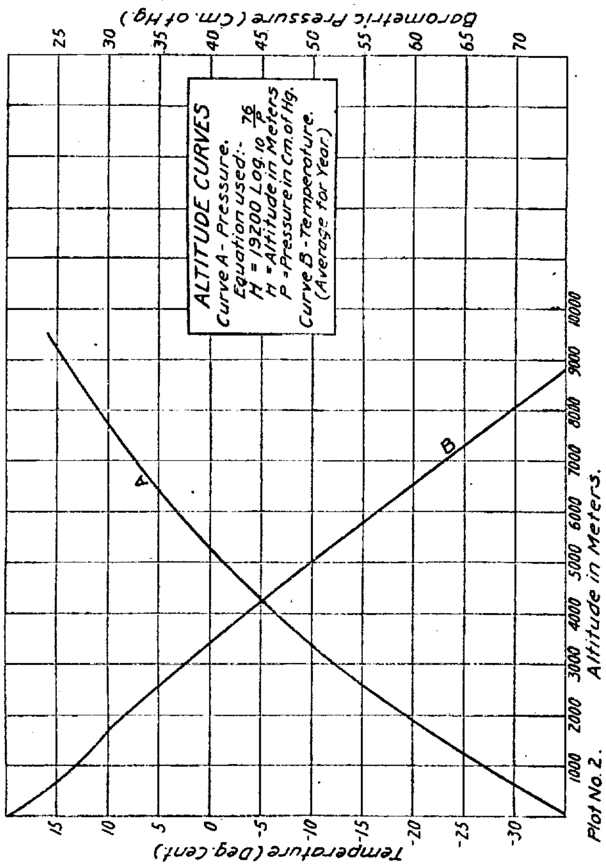
in which $\frac{1}{F_o}$ is a factor to correct from 0° C., to the given temperature t.

In the tests performed in the altitude laboratory the runs were conducted at four barometric pressures, which were adopted as standards for comparing the results of different tests and also to facilitate computations. In the later tests, series 99 to 111, carried out with the high compression pistons, the horsepowers were corrected to the mean temperatures corresponding to the observed barometric pressures, consequently it was necessary to establish a set of standard temperatures corresponding to the different standard barometric pressures. The mean values of these four "standard" temperatures obtained from curve on plot 2, together with the corresponding approximate altitudes, are as follows:

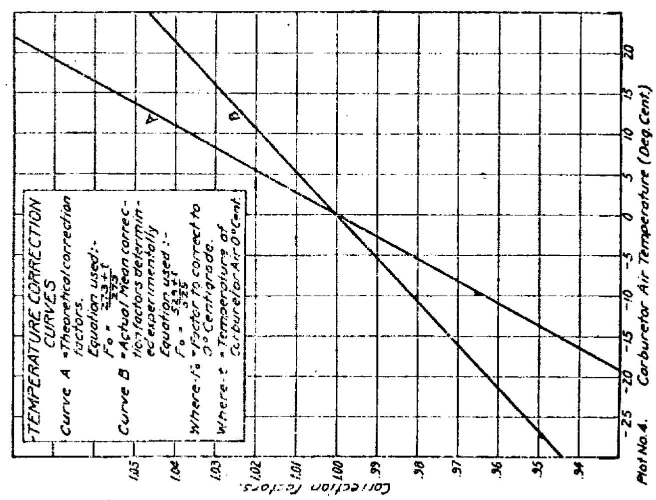
Barometric pressure in centimeters of mercury.	Temperatures in degrees centigrade.	Approximate altitude in feet.
62.1	10.1	5,500
49.8	− 0.1	11,500
37.6	−15.1	19,200
25.6	−36.6	29,600

Values of horsepower for the three compression ratios were obtained from curve on plot 1 at the standard barometric pressures and tabulated in Table IV. These were corrected from 0° C. to the standard temperatures by use of equation (2), giving the values of horsepower corrected to standard temperatures for the three earlier series, as tabulated in the last column of Table IV.

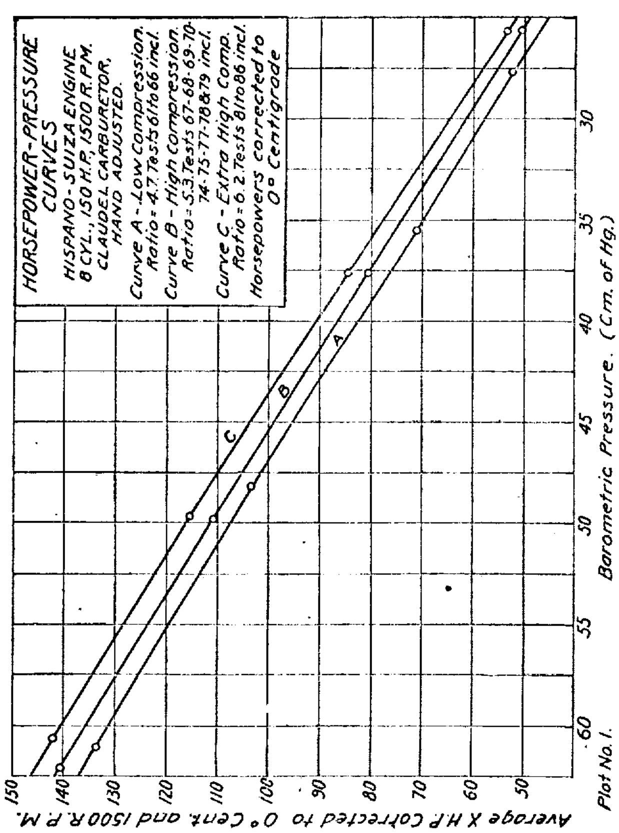
The runs in series 99 to 111 were made at various speeds. Table V gives the observed values of speed and horsepower at the different altitudes for this series. These data are averaged and plotted on sheet 5 and the values of horsepower at 1,500 revolutions per minute



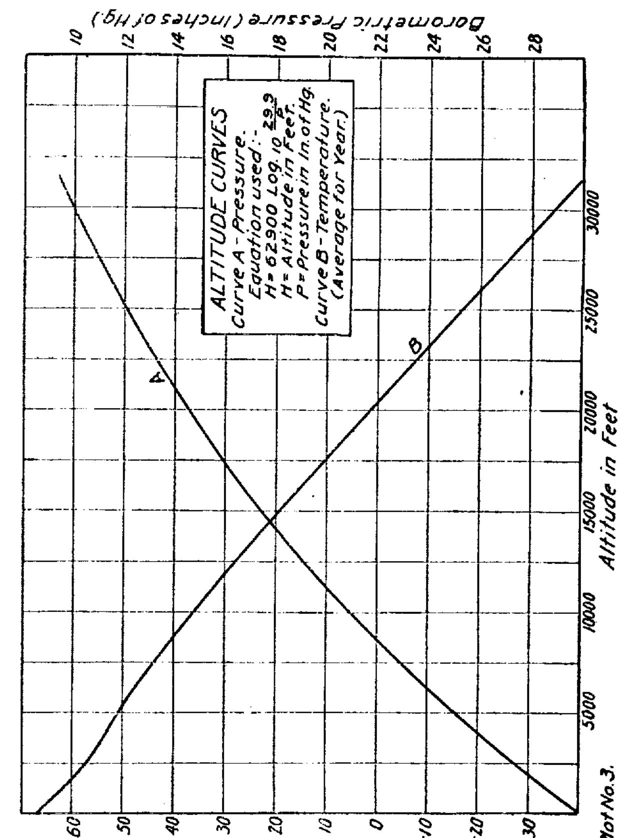
Plot No. 2.



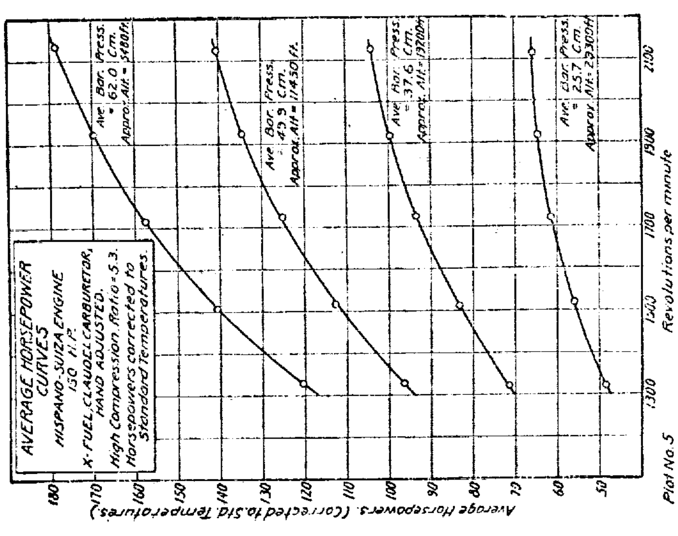
Plot No. 4.

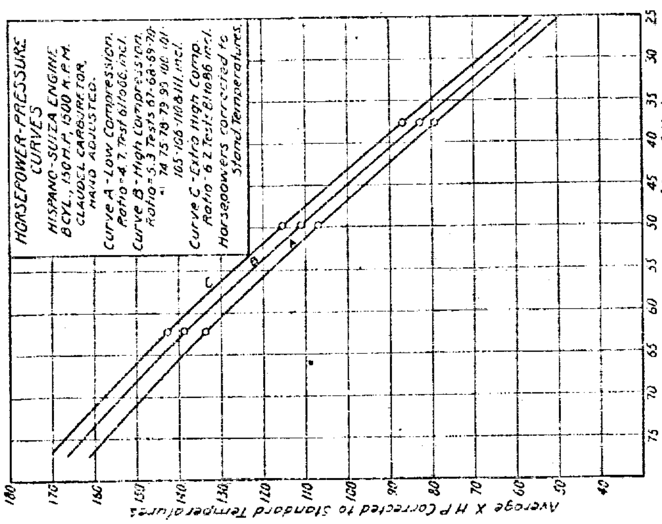


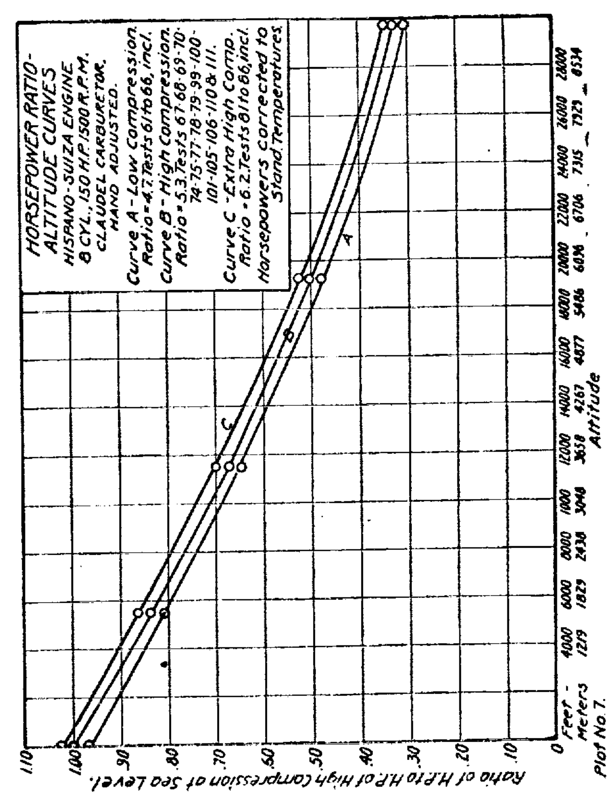
Plot No. 1.

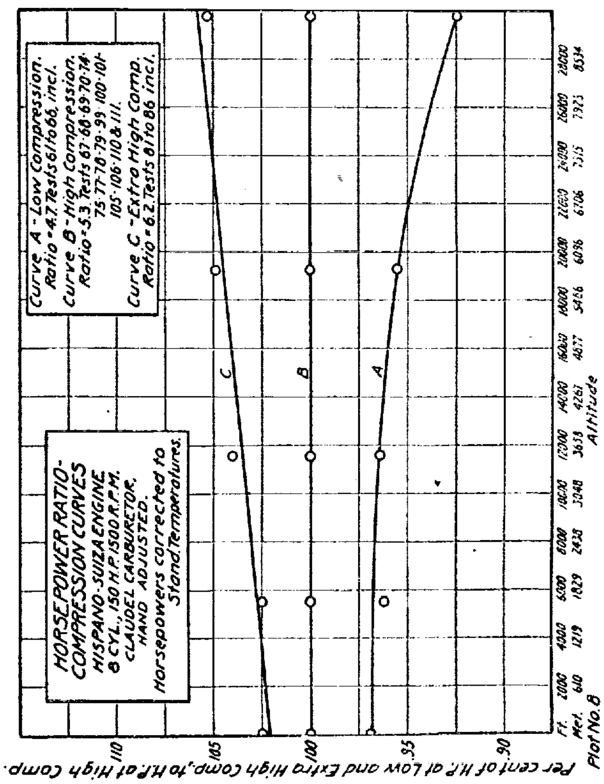


Plot No. 3.


AVERAGE HORSEPOWER CURVES
HISPANO-SUIZA ENGINE 150 H.P.
X-FUEL, CLAUDEL CARBURETOR, HAND ADJUSTED.
High Compression. Ratio = 5.3.
Horsepowers corrected to Standard Temperatures.
Ave. Bar. Press. = 62.0 Cm. Approx. Alt. = 5480 ft.
Ave. Bar. Press. = 49.9 Cm. Approx. Alt. = 11450 ft.
Ave. Bar. Press. = 37.6 Cm. Approx. Alt. = 19200 ft.
Ave. Bar. Press. = 25.7 Cm. Approx. Alt. = 29300 ft.
Average Horsepowers. (Corrected to Std. Temperatures.)
Revolutions per minute
Plot No. 5


HORSEPOWER-PRESSURE CURVES
HISPANO-SUIZA ENGINE 8 CYL., 150 H.P. 1500 R.P.M.
CLAUDEL CARBURETOR, HAND ADJUSTED.
Curve A - Low Compression. Ratio = 4.7. Tests 61 to 66 incl.
Curve B - High Compression. Ratio = 5.3. Tests 67-68-69-70-71-74-75-78-79-99-100-101-105-106-110 & 111 incl.
Curve C - Extra High Comp. Ratio = 6.2. Tests 81 to 86 incl.
Horsepowers corrected to Stand. Temperatures.
Average X H P Corrected to Standard Temperatures.
Barometric Pressures. (Cm. of Hg.)
Plot No. 6


HORSEPOWER RATIO-ALTITUDE CURVES
HISPANO-SUIZA ENGINE 8 CYL., 150 H.P. 1500 R.P.M.
CLAUDEL CARBURETOR, HAND ADJUSTED.
Curve A - Low Compression. Ratio = 4.7. Tests 61 to 66, incl.
Curve B - High Compression. Ratio = 5.3. Tests 67-68-69-70-74-75-77-78-79-99-100-101-105-106-110 & 111.
Curve C - Extra High Comp. Ratio = 6.2. Tests 81 to 86, incl.
Horsepowers corrected to Stand. Temperatures.
Ratio of H.P. to H.P. of High Compression at Sea Level.
Altitude
Feet - Meters
Plot No. 7.


HORSEPOWER RATIO-COMPRESSION CURVES
HISPANO-SUIZA ENGINE 8 CYL., 150 H.P. 1500 R.P.M.
CLAUDEL CARBURETOR, HAND ADJUSTED.
Horsepowers corrected to Stand. Temperatures.
Curve A - Low Compression. Ratio = 4.7. Tests 61 to 66, incl.
Curve B - High Compression. Ratio = 5.3. Tests 67-68-69-70-74-75-77-78-79-99-100-101-105-106-110 & 111.
Curve C - Extra High Comp. Ratio = 6.2. Tests 81 to 86 incl.
Per cent of H.P. at Low and Extra High Comp. to H.P. at High Comp.
Altitude
Ft. - Met.
Plot No. 8

taken from the resulting curves are tabulated and averaged in Table VI with series 67 to 79, both series being on the high compression ratio 5.3. The averaged data are plotted on plot 6, together with the corresponding data for the other two compressions (4.7 and 6.2) obtained from the last column of Table IV, giving curves of horsepower at 1,500 revolutions per minute, corrected to standard temperatures versus barometric pressure for the three compressions.

From these curves the ratios of the different horsepowers for each compression to the horsepower at sea level for the high (5.3) compression were computed. These ratios were plotted on plot 7 against altitudes in feet corresponding to the different barometric pressures. The altitudes were computed from the formula:

$$h = 62{,}900 \log_{10} \frac{76}{P}$$

obtained from the Smithsonian Meteorological Tables for 1907, page 100, in which h is the altitude in feet and p is the atmospheric pressure in centimeters of mercury.

The curves on plot 8 illustrate the variation in horsepower with compression ratio at different altitudes. The horsepower developed with the 5.3 or "high" compression ratio at the different altitudes was taken as 100 per cent and the other two compression ratios were plotted as percentages of this curve. As will be seen upon examination, the gain in horsepower due to "extra-high" over "high" compression amounts to but 2.8 per cent at 5,000 feet, while it increases to nearly 5.8 per cent at 30,000 feet. Likewise the decrease in horsepower due to "low" compression, while only 3.3 per cent at 5,000 feet, amounts to about 7.3 per cent at 30,000 feet.

It is evident, therefore, that the value of high compression is more apparent at high than at low altitudes.

It should be pointed out that any comparison of absolute horsepowers for the different compression ratios may be misleading as the engine conditions, such as fit of piston and rings, condition of valves, etc., were not the same in each case. However, the manner in which the horsepower varies with barometric pressure in each case may be taken as characteristic for the given combination of engine, carburetor, and fuel with a given compression ratio.

In conclusion, it may be stated that practically all the tests conducted in the altitude laboratory show nearly the same relation between horsepower and altitude. Any given set of conditions which affect the operation of the engine may be held approximately constant during one test and the variation of horsepower with altitude determined for these conditions. Only a small amount of this information has been collected in this report, as the tests upon which it is based were chosen particularly to show the power-altitude relation at different compression ratios.

TABLE I.—*Average horsepowers and barometric pressures for tests on X fuel.—Low compression ratio=4.7; horsepowers corrected to 0° C. and 1,500 R. P. M.*

Test No.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.
61	61.1	135.6	48.0	106.0				
62	61.5	134.8	48.5	104.6	35.4	71.8	27.7	51.4
63	61.5	133.1	48.5	102.4	35.7	70.0	27.7	52.7
64	60.8	131.8	48.0	102.7	35.4	70.9	27.7	52.7
65			48.3	103.0	35.4	72.1	27.8	54.0
66	60.7	131.0	48.0	101.0	35.4	70.1	27.7	51.0
Average	61.1	133.3	48.2	103.3	35.5	71.0	27.7	52.4

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TABLE II.—*Average horsepowers and barometric pressures for tests on X fuel.—High compression ratio=5.3; horsepowers corrected to 0° C. and 1,500 R. P. M.*

Test No.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.
67	62.2	144.0	49.9	111.4	37.7	80.5	25.7	50.3
68	62.1	140.4	49.9	111.2	37.7	79.5	25.7	51.0
69	61.9	141.5	49.6	112.8	37.2	80.5	24.9	51.3
70	62.0	142.1	49.8	112.1	37.6	80.5	25.7	51.2
74	62.2	141.1	50.1	110.2	37.8	80.6	25.7	48.8
75	62.3	138.0	48.8	109.1	37.6	80.4	25.7	50.6
77	62.0	135.8	50.1	115.0	37.7	80.7	25.7	52.2
78	61.9	142.0	49.8	106.5	37.6	79.8	25.6	50.3
79	62.0	138.7	49.9	108.5	37.7	81.5	25.8	49.4
Average	62.1	140.4	49.8	110.8	37.6	80.4	25.6	50.6

TABLE III.—*Average horsepowers and barometric pressures for tests on X fuel.—Extra high compression ratio=6.2; horsepowers corrected to 0° C. and 1,500 R. P. M.*

Test No.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.	Barometric pressure.	Horse-power.
81	60.6	145.9	49.7	117.6	37.6	85.7	25.7	53.7
82	60.6	142.5	49.7	114.4	37.6	85.4	25.7	53.7
83	60.6	139.4	49.7	115.9	37.6	85.5	25.7	53.0
84	60.6	143.1	50.0	116.7	37.6	85.4	25.7	53.1
85			49.7	112.9	37.6	82.8	25.7	52.5
86	60.5	138.9	49.6	113.9	37.5	84.1	25.7	53.9
Average	60.6	142.0	49.7	115.2	37.6	84.8	25.7	53.3

TABLE IV.—*Table of data for reducing horsepowers from 0° C. to standard temperatures.*

Barometric pressure in Cms. of Hg.	Average temperature from curve on sheet 2, 0° C.	Correction factor from curve B on sheet 3 $=(F_o)t$.	Factor to correct from 0° C. to standard temperatures $=\frac{1}{(F_o)t}$.	Horsepower from curves on sheet 1 $=HP_o$. Compression.	Horsepower from curves on sheet 1 $=HP_o$. Horse-power at 1,500 R.P.M.	Horse-powers corrected to standard temperatures and 1,500 R.P.M.
62.1	10.1	1.019	0.981	Ratio—low =4.7	136.0	133.5
				Ratio—high =5.3	140.4	137.7
				Ratio—extra high=6.2	145.3	142.5
49.8	− 0.1	1.000	1.000	Ratio—low =4.7	106.9	106.9
				Ratio—high =5.3	110.8	110.8
				Ratio—extra high=6.2	115.2	115.2
37.6	−15.1	.972	1.029	Ratio—low =4.7	76.9	79.1
				Ratio—high =5.3	80.3	82.6
				Ratio—extra high=6.2	84.4	86.8
25.6	−36.6	.931	1.074	Ratio—low =4.7	46.9	50.4
				Ratio—high =5.3	50.3	54.0
				Ratio—extra high=6.2	53.5	57.5

TABLE V.—*Observed horsepowers, revolutions per minute, and barometric pressures for X fuel.—Series 99 to 111; horsepowers corrected to standard temperatures.*

Test No.	Barometric pressure.	Speed.	Horsepower.	Speed.	Horsepower.	Speed.	Horsepower.	Speed.	Horsepower.	Speed.	Horsepower.
Approximate altitude=5,500 feet.											
99	62.0	1,310	119.7	1,504	141.9	1,710	158.3	1,923	168.7	2,110	174.2
100	61.9	1,325	126.1	1,515	147.1	1,715	162.7	1,935	173.4	2,140	181.0
101	62.1	1,300	114.2	1,518	135.0	1,715	154.0	1,920	165.1	2,155	177.1
105	62.3	1,375	124.0	1,525	141.7	1,725	158.0	1,965	173.2	2,140	179.3
106	62.1	1,365	122.8	1,536	140.4	1,763	153.4	1,925	165.8	2,140	174.2
110	61.9	1,305	118.9	1,480	139.9	1,695	159.2	1,890	171.4	2,120	182.0
111	61.9	1,315	116.3	1,485	137.2	1,700	157.0	1,910	171.0	2,156	181.1
Average	62.0	1,328	120.3	1,509	140.5	1,718	157.5	1,924	169.8	2,137	178.4
Approximate altitude=11,500 feet.											
99	49.9	1,310	96.2	1,517	114.0	1,715	127.0	1,907	134.9	2,105	139.5
100	49.8	1,315	96.5	1,500	113.0	1,725	126.7	1,930	138.6	2,115	143.0
101	49.9	1,315	93.9	1,505	109.9	1,730	118.7	1,925	127.9	2,107	133.2
105	50.2	1,340	95.8	1,515	110.8	1,715	124.0	1,910	134.0	2,135	140.5
106	49.8	1,370	96.8	1,540	111.2	1,750	120.7	1,945	130.5	2,150	135.0
110	49.8	1,327	101.2	1,540	119.8	1,710	130.2	1,915	138.7	2,120	144.8
111	49.95	1,305	92.9	1,500	111.0	1,737	126.9	1,927	137.2	2,130	144.5
Average	49.9	1,326	96.2	1,517	112.8	1,726	124.9	1,923	134.5	2,123	140.1
Approximate altitude=19,200 feet.											
99	37.6	1,300	71.2	1,500	84.6	1,715	95.2	1,920	100.6	2,100	103.3
100	37.5	1,310	71.7	1,500	83.3	1,720	95.0	1,920	99.5	2,135	107.0
101	37.8	1,310	69.4	1,520	81.0	1,725	88.9	1,940	95.6	2,120	98.5
105	37.7	1,355	71.4	1,528	82.3	1,725	90.6	1,923	98.4	2,140	105.4
106	37.5	1,360	72.8	1,515	82.6	1,745	91.7	1,925	98.6	2,140	102.5
110	37.55	1,289	74.0	1,513	88.3	1,718	96.7	1,896	99.4	2,100	105.7
111	37.6	1,310	71.1	1,487	82.8	1,717	94.2	1,910	101.9	2,125	105.2
Average	37.6	1,319	71.7	1,509	83.6	1,724	93.2	1,919	99.1	2,123	103.9
Approximate altitude=29,600 feet.											
99	25.7	1,303	47.7	1,535	56.6	1,730	61.4	1,930	62.6	2,105	65.1
100	25.5	1,330	48.4	1,505	55.8	1,725	61.8	1,930	64.4	2,105	64.1
101	26.0	1,314	45.1	1,512	52.9	1,707	58.3	1,924	62.4	2,120	63.1
105	25.9	1,310	47.3	1,505	55.8	1,705	61.4	1,914	65.9	2,115	68.8
106	25.7	1,370	47.6	1,560	54.4	1,735	59.6	1,885	60.8	2,085	60.8
110	25.7	1,290	48.2	1,510	57.2	1,723	63.6	1,900	64.8	2,120	63.2
111	25.7	1,310	51.2	1,505	59.1	1,710	65.7	1,937	69.9	2,130	72.0
Average	25.7	1,318	47.9	1,519	56.0	1,719	61.7	1,917	64.4	2,112	65.3

TABLE VI.—*Table of data for averaging horsepowers for high compression from series 67 to 79 and 99 to 111; horsepowers corrected to standard temperatures and 1,500 R. P. M.*

A=averages from Table IV.			B=average from Tables V.			C=averages from A and B.		
	Barometric pressure.	Horsepower.		Barometric pressure.	Horsepower.		Barometric pressure.	Horsepower.
Average of 9 tests, series from 67 to 79	62.1	137.7	Average of 7 tests, series from 99 to 111	62.0	140.0	Average of 16 tests, series from 67 to 79 and 99 to 111	62.05	138.9
	49.8	110.8		49.9	111.0		49.85	110.9
	37.6	82.6		37.6	82.8		37.60	82.7
	25.6	54.0		25.7	55.3		25.65	54.65

REPORT No. 45.

PART II.

VALUE OF SUPERCHARGING.[1]

By H. C. Dickinson and G. V. Anderson.

RÉSUMÉ.

A test was carried out at the altitude laboratory of the Bureau of Standards to investigate the results obtained by increasing the carburetor air inlet pressure above the exhaust back pressure of an airplane engine, and to evaluate the effect of this upon the horsepower output. In practice, supercharging may be accomplished by means of a blower driven from the engine by gearing, or connected to an exhaust turbine.

The results of this test show what gain in horsepower may reasonably be expected through supercharging, and indicate that a net gain in horsepower will result even if considerable power is required to drive the blower.

Curves showing this increase in power for different carburetor inlet pressures and exhaust back pressures are given on plots 1 and 2.

VALUE OF SUPERCHARGING.

The following report is based upon a test made in the altitude laboratory of the Bureau of Standards to determine the effect produced upon the horsepower output of an airplane engine by the introduction of air to the carburetor at a higher pressure than the exhaust or back pressure. Such a condition is easily produced in this laboratory, as the engine under test is inclosed in a chamber in which the air pressure may be controlled, independently of that on the carburetor inlet, by means of suitable pipes and valves leading to a suction blower. A more complete description of this method of controlling the barometric pressure is given in Technical Report No. 44.

A stock 150-horsepower Hispano-Suiza engine, built by the Wright-Martin Aircraft Corporation, New Brunswick, N. J., having a compression ratio of 5.3 to 1, was used in making the test. The Claudel carburetor, with which the engine is equipped, was adjusted in each case to give minimum fuel consumption consistent with maximum power.

Two runs were made with approximately a constant pressure on the carburetor, and with varying exhaust back pressures in each case. The first run was made with the valve on the intake wide open, so that the highest pressure could be obtained at the carburetor. The pressure within the chamber, which is the same as the exhaust back pressure, was adjusted, and readings taken at values of approximately 62, 50, 38, and 34 cm. Hg. The data obtained are tabulated in Table I, and the results are plotted as curve A on plot 1.

In the second run, the valve on the intake was partially closed, so that the pressure on the carburetor was the equivalent of 20 cm. Hg below the prevailing atnospheric pressure, and readings taken at approximately the same points as before. The results of this run are given in the second half of Table I and are plotted as curve B on plot 1.

In the first run the pressure of the intake air was not constant throughout, varying from 72.67 to 70.22 cm. Hg, so that it was necessary to correct the results to some constant pressure. The correction was made to a pressure of 70 cm. Hg by interpolation, which is based on

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 9.

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the assumption that the increment of horsepower developed at a given back pressure is proportional to the increment of pressure of the carburetor air. This correction gave curve C on plot 1. All horsepowers were corrected to 1,500 revolutions per minute and 0° C.

This temperature correction was made in accordance with the results of a series of tests performed at this laboratory to determine the variation of horsepower with temperature, and more complete information on this subject may be obtained from Part III of this report.

In order to determine the engine performance under different conditions of carburetor pressure and exhaust back pressure, a family of curves at carburetor pressures of 76, 70, 65, 60, and 55 cm. Hg were plotted against the exhaust back pressures. These were derived from the two experimental curves by interpolation based on the assumption as mentioned above.

As it is desirable for the purpose of design to know the engine output under different conditions as a function of the maximum output on the ground, the ratio of horsepower taken from the above mentioned curves to the horsepower at a carburetor and exhaust pressure of 76 cm. Hg, taken from curve D, is computed and plotted on plot 2. These curves give the engine performance under the different conditions on the basis of a constant temperature of air at the carburetor.

To compute the horsepower that would be developed by an engine equipped with a supercharging device under a given set of conditions of altitude, carburetor air pressure, and exhaust back pressure, knowing the engine performance on the ground, we may make use of the above mentioned curves in connection with the following relations:

$$HP = HP_1 \times R \times (F_2)_1 \qquad (1)$$

in which HP = horsepower developed with supercharging apparatus at the given altitude, and HP_1 = the observed horsepower on the ground at the observed carburetor air temperature of t_1, and R = horsepower ratio at the given conditions of exhaust and carburetor pressures produced by the supercharging device at the given altitude (obtained from curves on plot 2) and $(F_2)_1$ = temperature correction factor to correct from observed temperature on the ground, t_1, to temperature at the carburetor, t_2, under the given conditions.

The use of any form of supercharging device involves a compression of the air from the prevailing atmospheric pressure at the given altitude to some higher pressure, before entering the carburetor. This results in a heating of the air above the prevailing temperature of the atmosphere, and a consequent reduction of the available output of the engine. (For average temperatures of atmosphere at various altitudes see curve B on plot 5). The temperature resulting from such a compression may be computed by use of the equation:

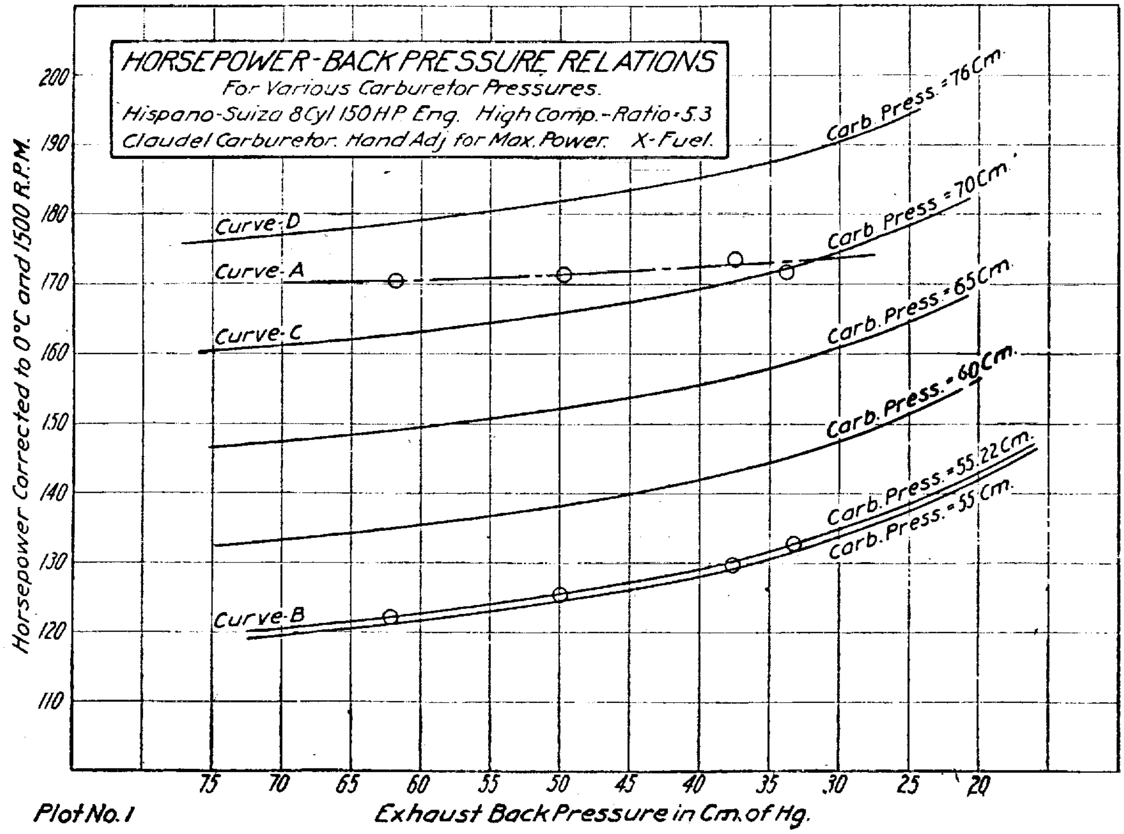
$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \qquad (2)$$

in which T_2 = temperature at carburetor after compression (absolute) and T_1 = the temperature of the atmosphere before compression (abs.); P_2 = pressure at the carburetor after compression; P_1 = atmospheric pressure at the given altitude (pressure before compression); and n = compression exponent (1.41 for an adiabatic compression).

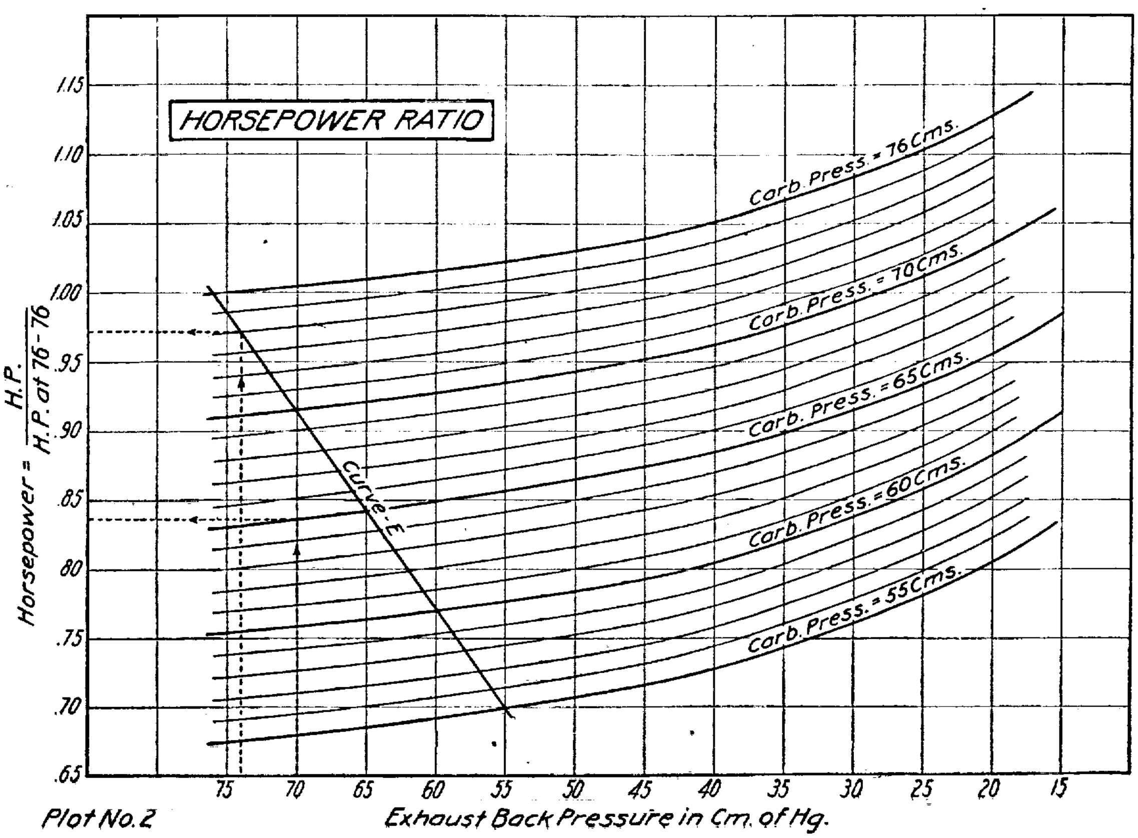
As the air enters the carburetor at the temperature t_2, after compression (corresponding to the absolute temperature T_2 of equation 2), is in most cases different from the observed temperature on the ground, t_1, the temperature correction factor $(F_2)_1$ must be included in equation 1 to give the correct output that would be developed at the existing air temperature at carburetor under the given conditions. (See Part III of this report.)

To facilitate computations, plots 3 and 4 were constructed for obtaining the temperature after compression t_2, according to equation 2, and the temperature correction factor $(F_2)_1$ respectively.

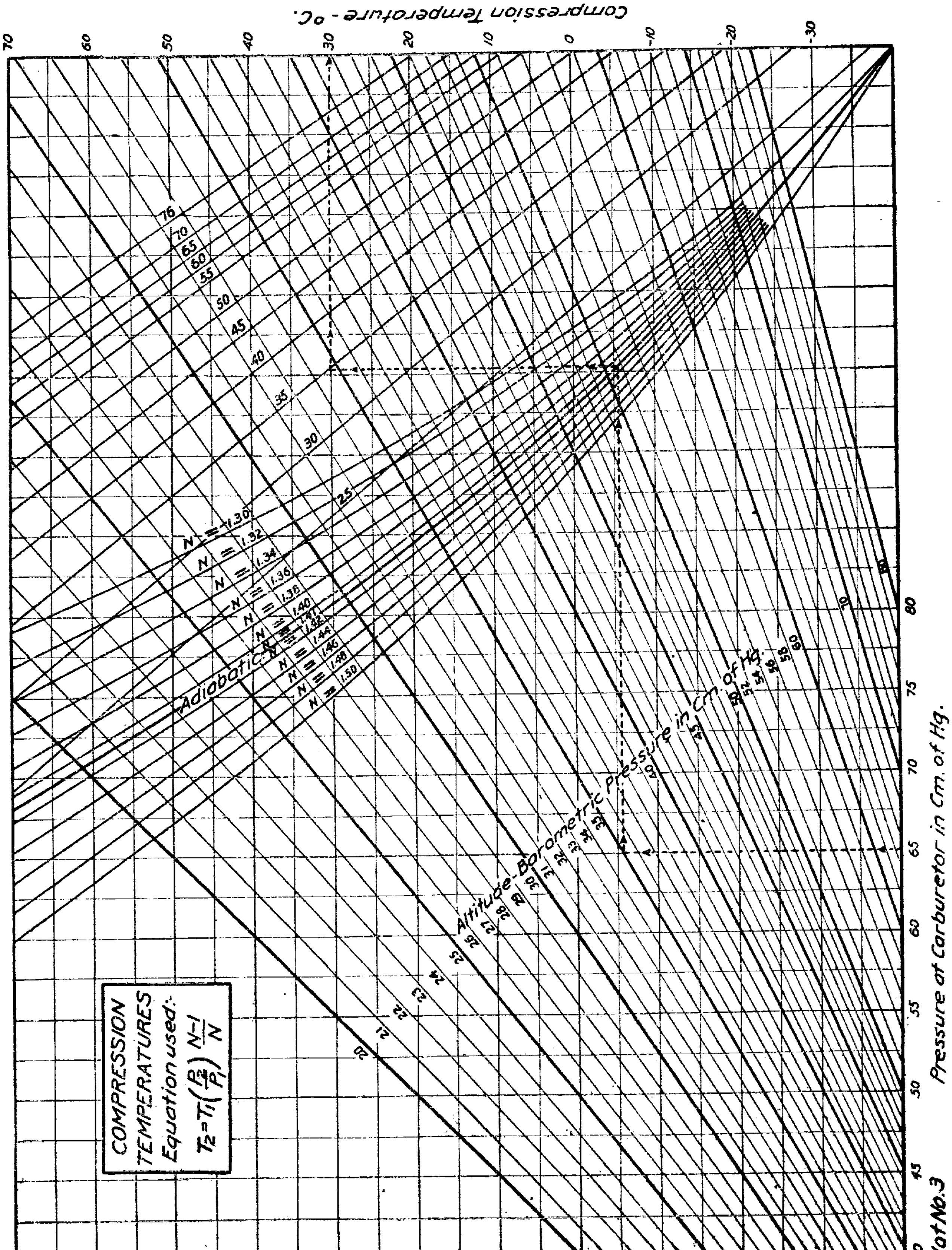
In using the chart for compression temperatures, it is unnecessary to determine the temperature of the altitude, as this is a function of the altitude barometric pressure, and is incorporated in the chart. To use this chart, locate carburetor pressure on the horizontal scale at the bottom, trace vertically upward to the line of barometric pressure corresponding to the given altitude,



Plot No. 1



Plot No. 2


Compression Temperature - °C.
70 60 50 40 30 20 10 0 -10 -20 -30
Pressure at Carburetor in Cm. of Hg.
40 45 50 55 60 65 70 75 80
Altitude-Barometric Pressure in Cm. of Hg.
20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 40 45 50 52 54 56 58 60 70 80
25 30 35 40 45 50 55 60 65 70 76
N = 1.30
N = 1.32
N = 1.34
N = 1.36
N = 1.38
N = 1.40
N = 1.42
N = 1.44
N = 1.46
N = 1.48
N = 1.50
Adiabatic N = 1.41
COMPRESSION TEMPERATURES
Equation used:-
$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{N-1}{N}}$

Plot No. 3

then horizontally to the curve of the desired compression exponent. From there trace vertically upward or downward to the line corresponding to the barometric pressure of the altitude, and horizontally to the right to the scale of temperatures. This gives the temperature after compression in degrees centigrade.

The temperature correction factor (F_2), may be obtained from plot 4. To use this chart, locate the observed temperature on the ground, t_1, on the horizontal scale on the bottom and trace vertically upward to the line corresponding to the compression temperature as obtained from chart on plot 3. From there trace horizontally to the scale of correction factors.

An example may serve to illustrate the use of the curves and charts. Assume that an engine capable of developing 400 horsepower on the ground at a temperature of 10° C. (50° F.) is to be equipped with an exhaust pressure turbine blower, which at a barometric pressure of 35 cm. Hg (corresponding to 21,100 feet altitude and at −21° C.) (see curves A and B on plot 5) exerts a back pressure on the engine of 35 cm. Hg and increases the carbureter pressure by 30 cm. Hg. Then we have for the exhaust pressure on the engine at the given altitude, $35+35=70$ cm. Hg, and for carbureter pressure, $35+30=65$ cm. Hg. From the curves on plot 2, we obtain a horsepower ratio of 0.836. To obtain the temperature after compression, we may assume an adiabatic compression with an exponent of 1.41, and from the chart on plot 3 obtain a temperature after compression of 30° C. From the chart on plot 4 we obtain the temperature correction factor to correct from 10° C. to 30° C. $=0.963$. Substituting these values in equation 1, we obtain for the horsepower at 21,100 feet with exhaust pressure turbine blower supercharging equipment:

$$400 \times 0.836 \times 0.963 = 322 \ HP.$$

If a geared blower were used, then in obtaining the horsepower ratio the barometric pressure at the given altitude would be used as the back pressure on the engine; and from the available output computed on this basis, the power necessary to drive the blower would be deducted.

If it is desired to include, as a further refinement in the above computations, a correction to the observed horsepower on the ground, HP, for barometric pressure, the output as computed by equation 1 may be multiplied by a pressure correction factor obtained from curve E on plot 2, as follows:

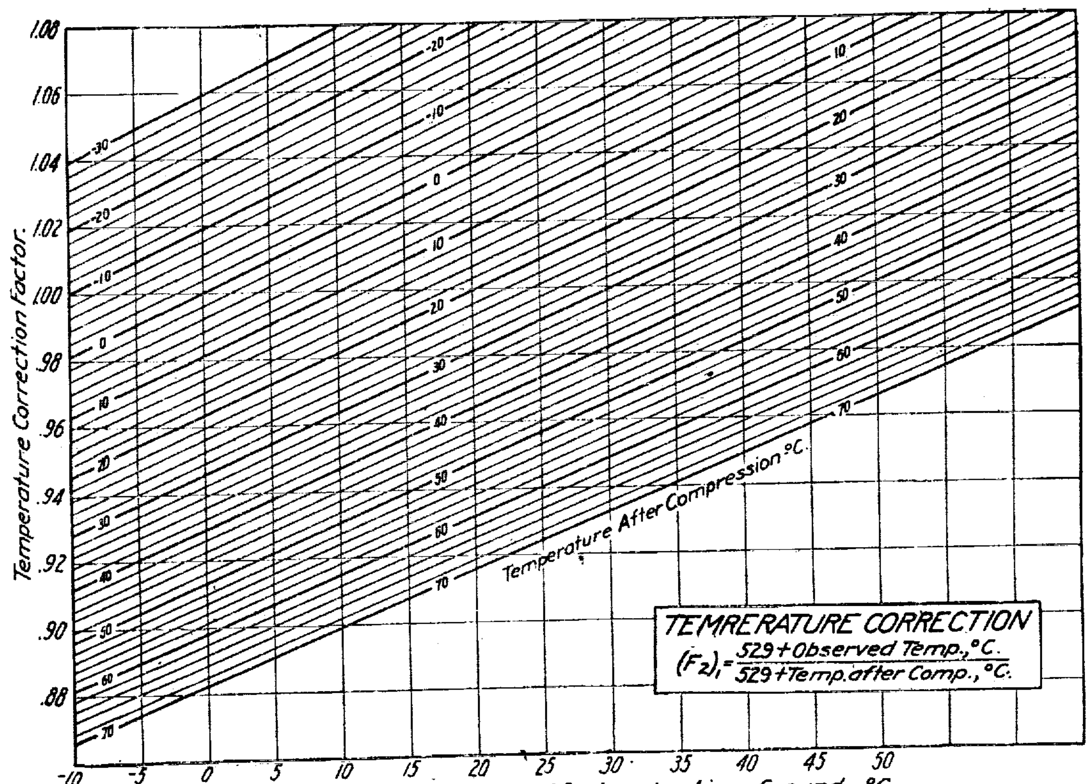
Locate the intersection of curve E with the curve of carbureter pressure corresponding to the observed barometric pressure on the ground, trace horizontally to the left and read horsepower ratio. The barometric pressure correction factor is 1 divided by this horsepower ratio.

An illustration will serve to make clear the use of this correction factor. Assume that in the above example, the observed horsepower (400) was obtained at an observed barometric pressure of 74 cm. Hg. From the curve E we obtain, by the method described above, a pressure correction factor of $\frac{1}{.972}$ (see plot 2) $=1.03$. Applying this to the horsepower obtained we get:

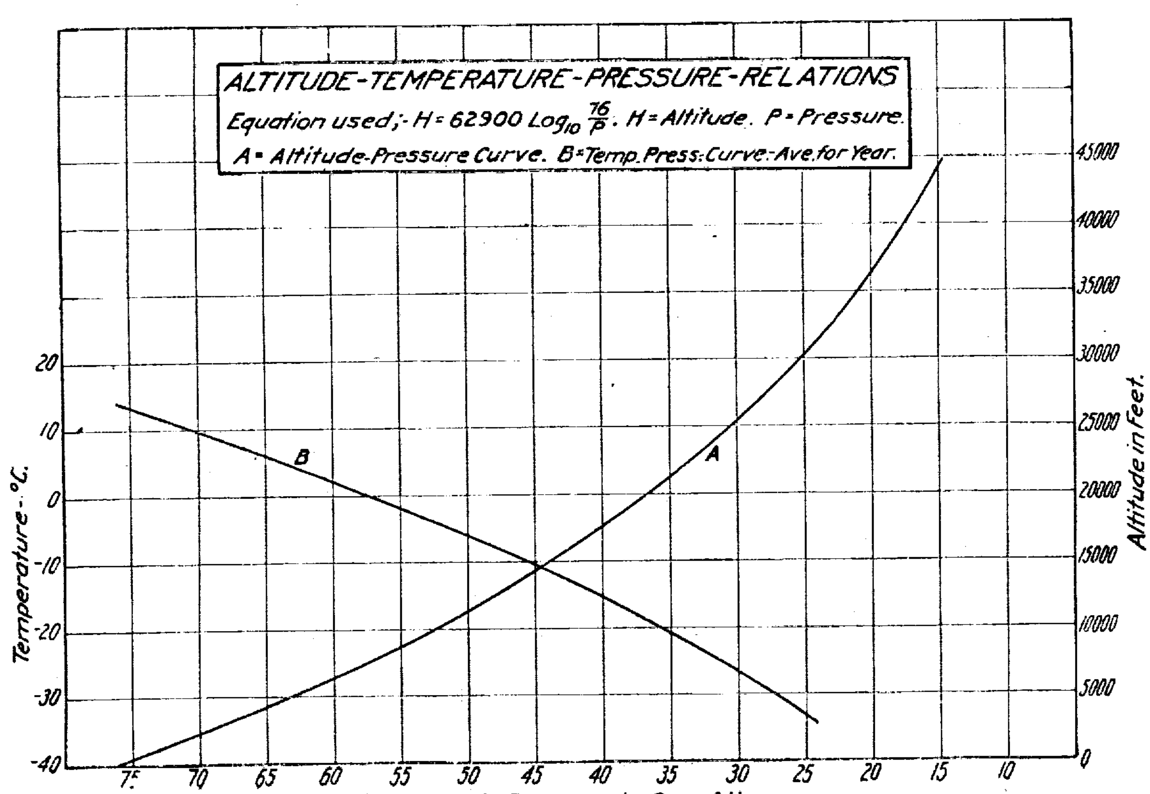
$$322 \times 1.03 = 332 \ HP.$$

TABLE I.—*Table of data on test 108 on the effect of supercharging.*

Pressure at exhaust port (cms. of Hg)	61.9	49.7	37.5	33.9	33.1	37.7	50.0	62.1
Pressure at carbureter intake (cms. of Hg)	72.67	71.42	71.12	70.22	55.22	55.22	55.22	55.22
Horsepower corrected to 0° C., and 1,500 revolutions per minute	170.2	171.3	173.4	171.8	132.9	129.6	125.4	122.0
Pounds of gasolene per horsepower per hour	.584	.593	.573	.580	.567	.545	.554	.559



Plot No. 4.



Plot No. 5

REPORT No. 45.

PART III.

VARIATION OF HORSEPOWER WITH TEMPERATURE.[1]

By H. C. Dickinson, W. S. James and G. V. Anderson.

RÉSUMÉ.

In connection with tests of airplane engines made in the altitude laboratory of the Bureau of Standards it has become necessary to reduce horsepower at a given temperature to arbitrary standard temperatures in order to permit comparison of different tests.

As the result of a number of experiments made with two Hispano-Suiza engines and three different makes of carburetors, a correction factor has been determined, which may be expressed by F in the following equation:

$$HP = F \times HP_o$$

$$F = \frac{920 + t_o \text{ °F.}}{920 + t \text{ °F.}} \text{ or } F = \frac{529 + t_o \text{ °C.}}{529 + t \text{ °C.}}$$

where HP_o is the observed horsepower at the temperature t_o °F. and HP is the horsepower corrected to t °F.

This correction factor has been found to be somewhat variable with engine and carburetor conditions, but the above expression is believed to be approximately correct for the type of engine under consideration and for temperatures between −20° and 50° C. (−4° and 122° F.).

Curves showing graphically the value of the correction factor are shown on plots 4 and 5, and charts for correcting for both temperature and barometric pressure are given on plots 10 and 11, the former being in metric and the latter in English units.

VARIATION OF HORSEPOWER WITH TEMPERATURE.

The horsepower of an internal-combustion engine varies with the temperature of the air admitted to the carburetor. In order to reduce the horsepower at any observed temperature to horsepower at a chosen standard temperature, it has ordinarily been assumed that the horsepower varies inversely as the absolute temperature of the carburetor air, other conditions being held constant.

In the testing of airplane engines at the altitude laboratory of the Bureau of Standards the horsepower at the observed carburetor air temperature has been reduced to arbitrary standard temperatures in order to furnish a common basis for comparing the results of different tests.

The tests used to determine the approximate variation of horsepower with temperature were all made on two Hispano-Suiza engines built by the Wright-Martin Aircraft Corporation, New Brunswick, N. J. The first engine, used in the majority of the runs, was of 150 horsepower, known as type A, while the remaining runs were made with the 180-horsepower, type E.

Three different carburetors were used, tests Nos. 79, 80, and 104 having been made on the 150-horsepower engine with the Claudel carburetor, test No. 103 on the same engine with the Tice carburetor, and tests Nos. 116, 117, and 119 on the 180-horsepower engine with the Stromberg carburetor.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 8.

The tests cover a wide range of altitudes from 2,000 to 30,000 feet, and for every change in barometric pressure the Claudel and Stromberg carburetors were adjusted by hand to give maximum power, but the Tice carburetor was an experimental one, designed for inherent altitude control, and was therefore not adjusted by hand. As the Tice carburetor differs radically from the others used in the tests, the agreement of the results in all cases indicates that the carburetor design may not greatly affect the magnitude of the temperature correction factor.

Tables I to VI contain the observed and computed data used in obtaining the correction factors.

To obtain an expression for the correction factor to reduce horsepower at a given observed temperature and pressure to horsepower at the arbitrarily chosen temperature of 0° C., and the same pressure, we have

$$HP_o = HP_t \times F_o \qquad (1)$$

in which HP_o = horsepower at arbitrarily chosen temperature of 0° C.

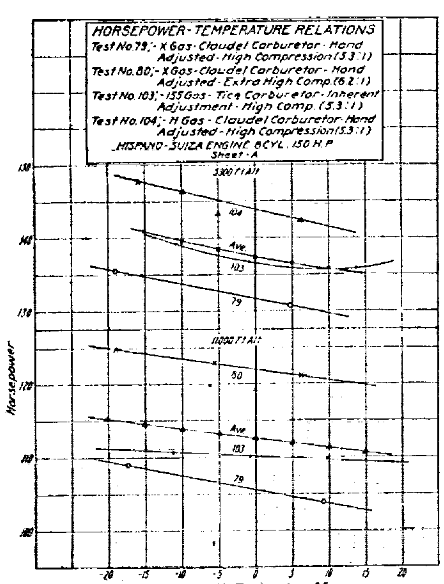
HP_t = horsepower at observed temperature t °C.

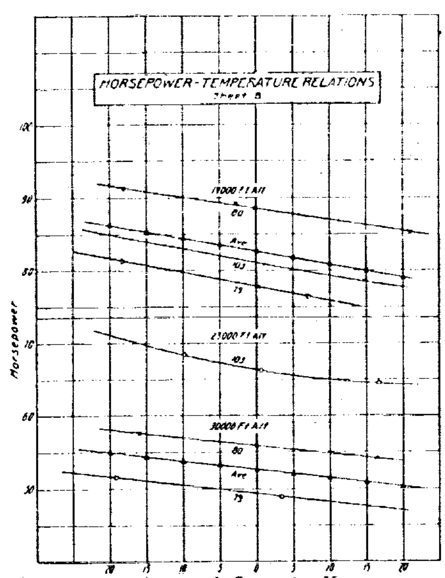
F_o = correction factor to reduce to arbitrary temperature of 0° C.

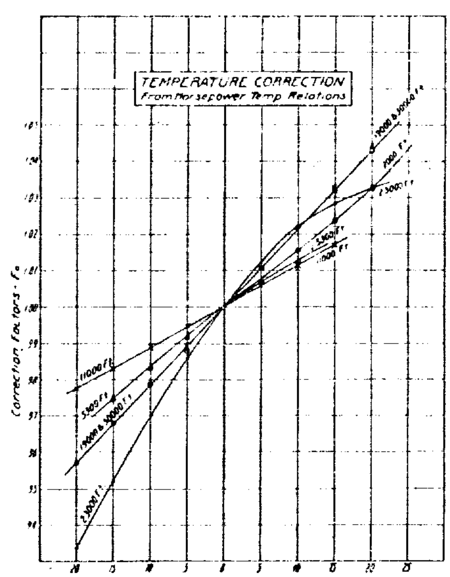
From (1)

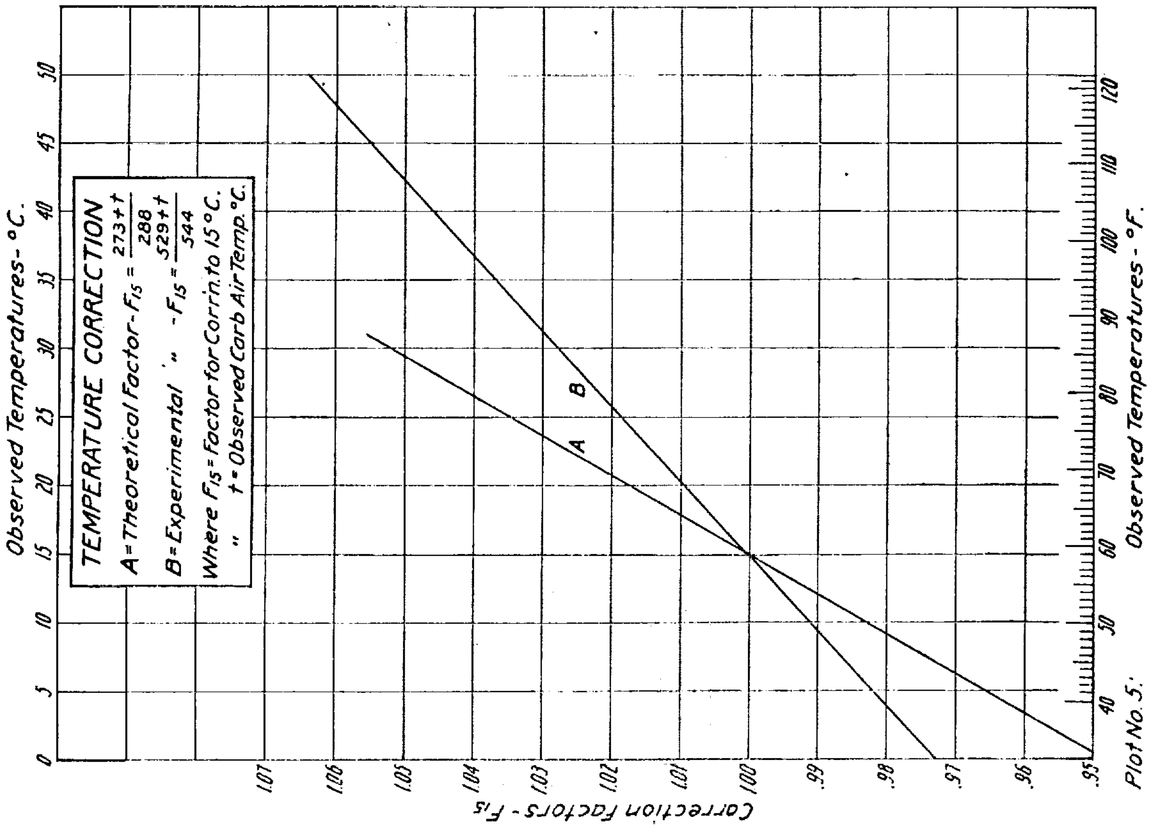
$$F_o = \frac{HP_o}{HP_t} \qquad (2)$$

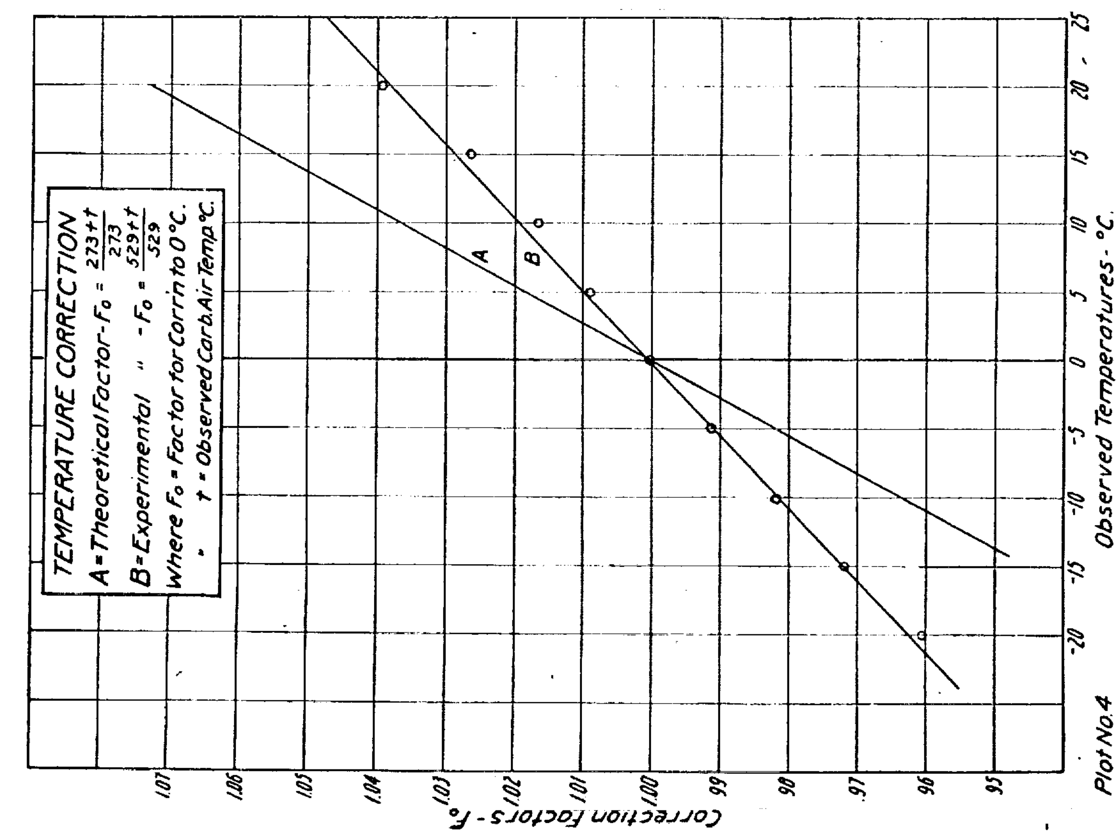
It is evident from equation 2 that the correction factors at the different temperatures for any given run depend upon an accurate determination of horsepower at the arbitrarily chosen temperature of 0° C. For this reason the horsepowers computed from the observed data were plotted against carburetor air temperatures and smooth curves drawn through as many of the points as possible, as shown on plots 1 and 2. Tests at the same altitude have been grouped together and an average curve drawn for each group. From these curves the average horsepowers were obtained at 0° C. and the other observed temperatures of the given run, and from the values of horsepower thus secured the correction factors F_o were determined by the use of equation 2. These factors, plotted against temperature, are given on plot 3.

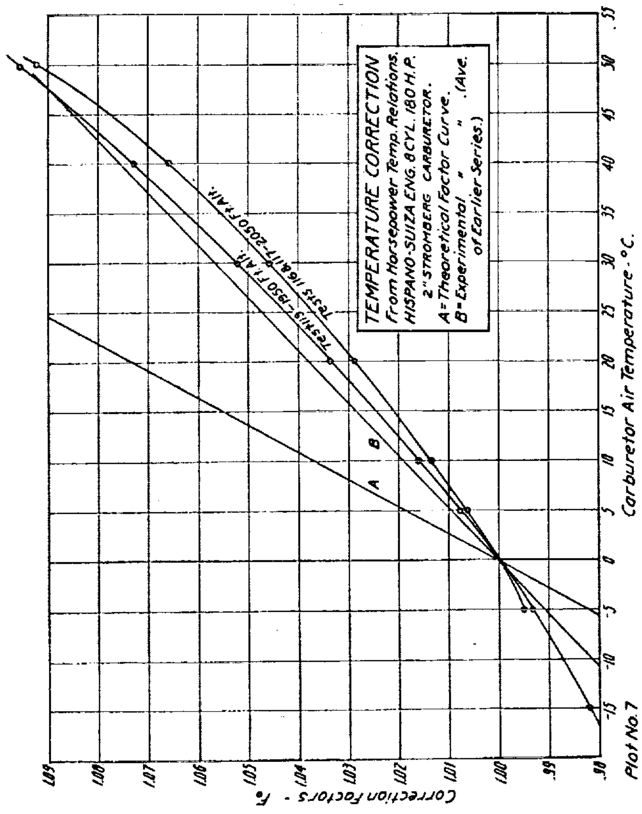


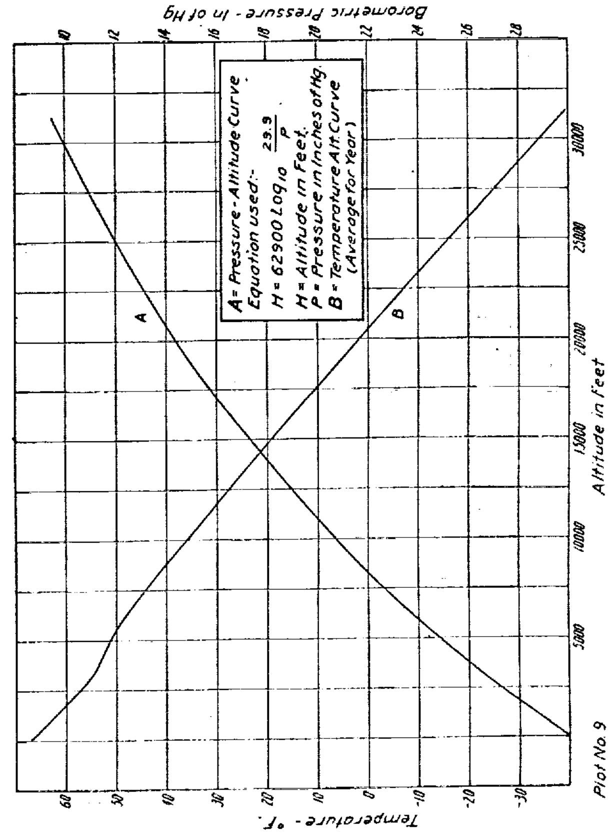


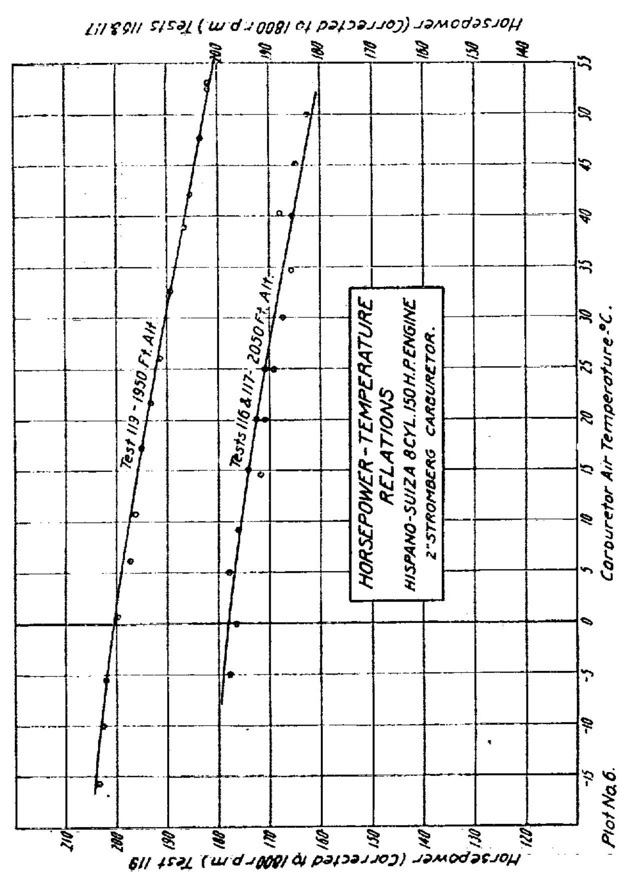


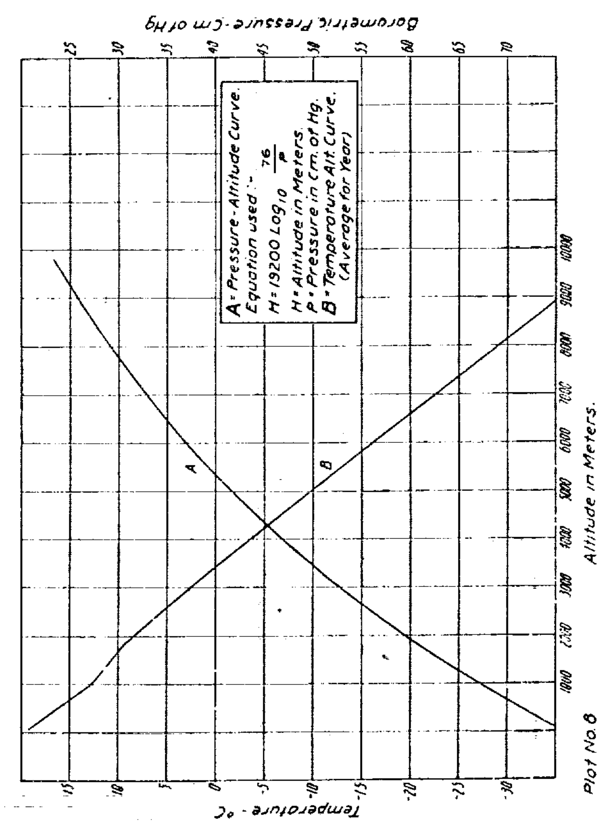

Observed Temperatures - °C.
TEMPERATURE CORRECTION
A = Theoretical Factor - F15 = (273+t)/288
B = Experimental " - F15 = (529+t)/544
Where F15 = Factor for Corr'n to 15°C.
" t = Observed Carb Air Temp. °C.
A
B
Correction Factors - F15
Observed Temperatures - °F.
Plot No. 5.


TEMPERATURE CORRECTION
A = Theoretical Factor - Fo = (273+t)/273
B = Experimental " - Fo = (529+t)/529
Where Fo = Factor for Corr'n to 0°C.
" t = Observed Carb. Air Temp. °C.
A
B
Correction Factors - Fo
Observed Temperatures - °C.
Plot No. 4


TEMPERATURE CORRECTION
From Horsepower Temp. Relations.
HISPANO-SUIZA ENG. 8 CYL. 180 H.P.
2" STROMBERG CARBURETOR.
A = Theoretical Factor Curve.
B = Experimental " " (Ave. of Earlier Series.)
Tests 116 & 117 - 2050 Ft. Alt.
Tests 113 - 1950 Ft. Alt.
Carburetor Air Temperature - °C.
Correction Factors - F.
Plot No. 7


A = Pressure - Altitude Curve
Equation used:-
H = 62900 Log10 29.9/P
H = Altitude in Feet.
P = Pressure in Inches of Hg.
B = Temperature Alt. Curve (Average for Year)
Barometric Pressure - In of Hg
Altitude in Feet
Temperature - °F.
Plot No. 9


HORSEPOWER - TEMPERATURE RELATIONS
HISPANO-SUIZA 8 CYL. 150 H.P. ENGINE
2" STROMBERG CARBURETOR.
Test 119 - 1950 Ft. Alt.
Tests 116 & 117 - 2050 Ft. Alt.
Horsepower (Corrected to 1800 r.p.m.) Tests 116 & 117
Horsepower (Corrected to 1800 r.p.m.) Test 119
Carburetor Air Temperature - °C.
Plot No. 6.


A = Pressure - Altitude Curve.
Equation used:-
H = 19200 Log10 76/P
H = Altitude in Meters.
P = Pressure in Cm. of Hg.
B = Temperature Alt. Curve. (Average for Year)
Barometric Pressure - Cm of Hg
Altitude in Meters.
Temperature - °C
Plot No. 8

Values of the correction factors obtained from these average curves (at the different altitudes) were averaged and plotted, giving the mean correction curve on plot 4. This curve may be represented by the equation:

$$F_o=\frac{529+t}{529} \tag{3}$$

in which t is the observed temperature of the carburetor air in degrees centigrade. Combining equations 2 and 3, we obtain,

$$\frac{HP_o}{HP_t}=\frac{529+t}{529+0} \tag{4}$$

which may then be written in a generalized form substituting t_1 °C for 0°C and t_2 for t, as follows:

$$\frac{HP_{t1}}{HP_{t2}}=\frac{529+t_2\ °C.}{529+t_1\ °C.} \tag{5}$$

or

$$HP_{t1}=\frac{529+t_2\ °C.}{529+t_1\ °C.}\times HP_{t2}=F\times HP_{t2} \tag{6}$$

where
HP_{t1} is the horsepower at temperature t_1 °C., to which HP_{t2} the horsepower at the temperature t_2 °C., is to be reduced and F is the reduction factor.

F may therefore be written,

$$F=\frac{529+\text{observed temperature in °C.}}{529+\text{correction temperature in °C.}} \tag{7}$$

In order to correct horsepower at a given observed barometric pressure and temperature to horsepower at the actual temperature corresponding to the altitude of the given barometric pressure, it is necessary to know the mean actual temperatures existing at the various altitudes.

To obtain this relation the information contained in Aeronautic Instruments Circular No. 3, issued by the Bureau of Standards, was used, resulting in the altitude-temperature curves on plots 8 and 9.

As it is necessary for the purpose of comparison to correct an observed horsepower for both temperature and barometric pressure it is desirable to obtain an expression for a correction factor which shall include both corrections.

The results of numerous tests in the altitude laboratory indicate that for the ordinary slight differences in barometric pressure met with from day to day, the assumption that the brake horsepower varies directly as the barometric pressure is sufficiently accurate. The true variation of horsepower with altitude is, however, fully covered in Part I of this report.

Upon the assumption that the horsepower developed varies directly as the barometric pressure we have:

$$\frac{HP_1}{HP_2}=\frac{P_1}{P_2} \tag{8}$$

or,

$$HP_1=\frac{P_1}{P_2}\times HP_2=F_1\ HP_2 \tag{9}$$

where,

HP_1 = Horsepower developed at correction pressure P_1.

HP_2 = Observed horsepower developed at observed pressure P_2.

$F_1=\frac{P_1}{P_2}$, the barometric pressure correction factor.

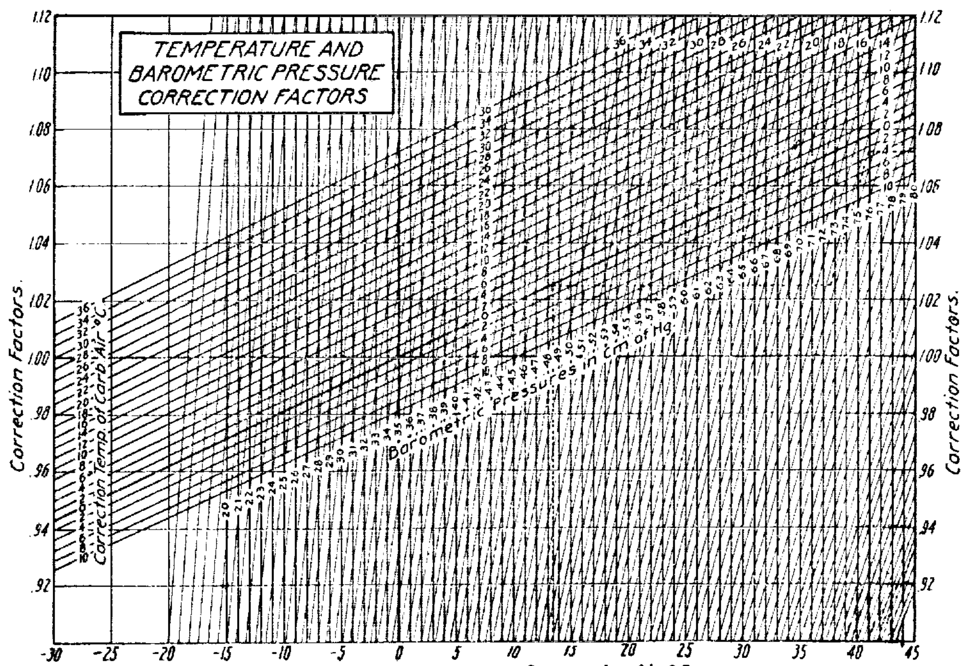
From equation (9) we get:

$$F_1=\frac{\text{Correction barometric pressure}}{\text{Observed barometric pressure}}. \tag{10}$$

Combining the temperature and pressure corrections from equations (7) and (10) we obtain an expression for a factor F_1, to correct horsepower from observed temperature, and pressure to standard or correction temperature and pressure, as follows:

$$F_1 = \frac{529 + \text{Obs. temp. °C}}{529 + \text{Correct temp. °C}} \times \frac{\text{Correct baro. pressure}}{\text{Obs. baro. pressure.}} \tag{11}$$

Plot 10 is constructed for obtaining this combined correction factor and is based on equation (11). To use this chart proceed as follows: Trace vertically upwards from observed carburetor air temperature to line of correction temperature, then horizontally to observed barometric pressure. From there trace in direction of radiating lines to correction pressure, then horizontally to the line of correction factors.



Plot No. 10.

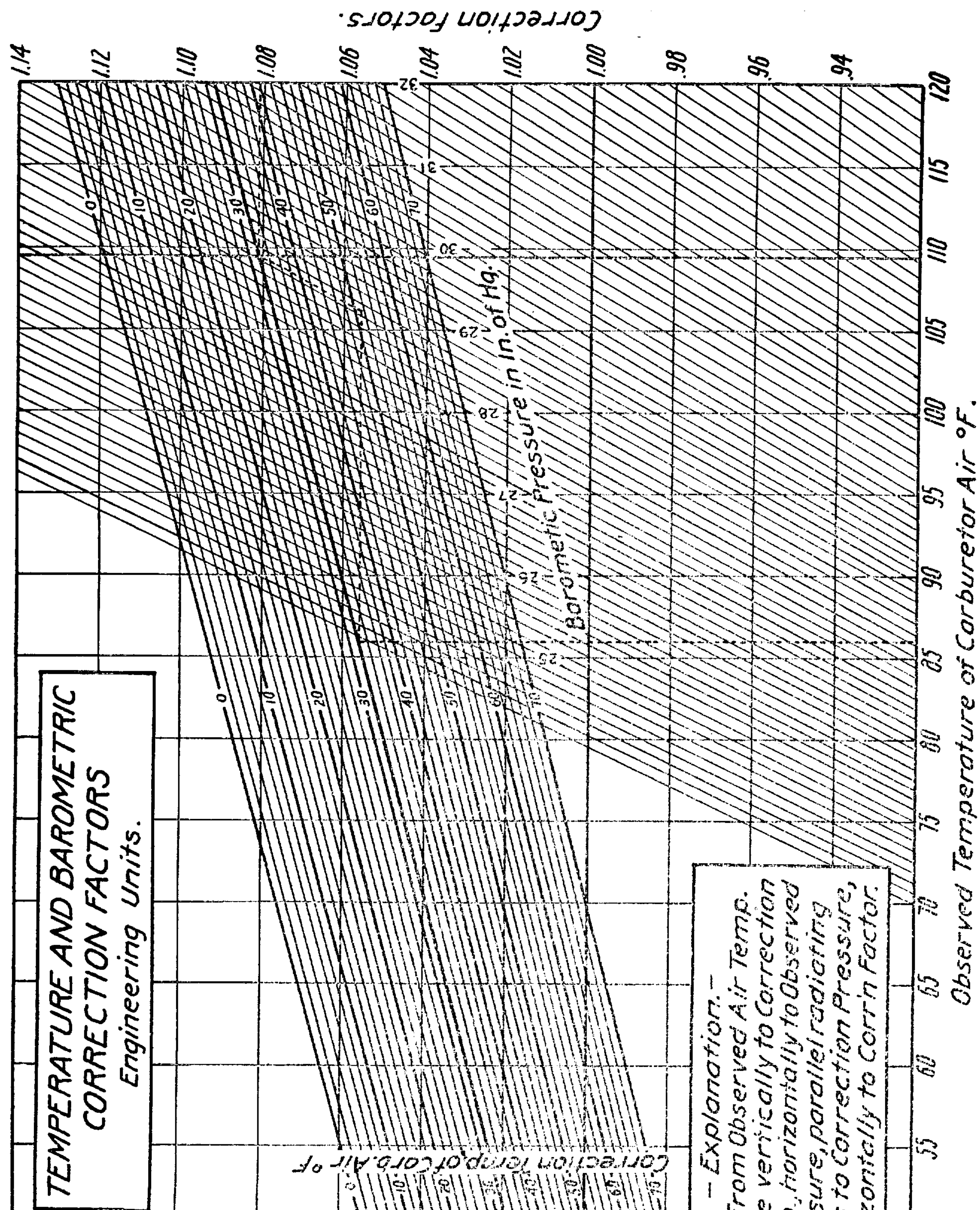
Plot 11 is constructed in a similar manner for obtaining the combined correction factor in terms of temperature in degrees Fahrenheit and pressure in inches of mercury.

In using these charts it should be borne in mind that the majority of the tests upon which this report is based were made on only one engine and between temperatures of approximately $-20°$ and $15°$ C. ($-4°$ and $59°$ F.), respectively. However, the three later tests with the 180 horsepower engine were made between temperatures of $-15°$ and $50°$ C. ($5°$ and $122°$ F.), and the results, as given in Tables V and VI and on plot 6, check very closely the average of the earlier runs. This is illustrated by the curves on plot 7, where the average curve as drawn on plot 5, is prolonged to include these higher temperatures.

It therefore appears safe to assume that this relation, expressed by the simple equation:

$$F = \frac{529 + t_2 \text{ °C.}}{529 + t_1 \text{ °C.}} \text{ or } \frac{920 + t_2 \text{ °F.}}{920 + t_1 \text{ °F.}},$$

which has been derived from tests at various altitudes on two engines equipped with three different carburetors, gives apparently accurate results for the type of engines considered within the experimental temperature range of $-20°$ to $50°$ C. ($-4°$ to 122 °F.).


TEMPERATURE AND BAROMETRIC CORRECTION FACTORS
Engineering Units.
– Explanation. –
From Observed Air Temp. trace vertically to Correction Temp., horizontally to Observed Pressure, parallel radiating lines to Correction Pressure, horizontally to Corr'n Factor.
Correction factors.
Correction Temp. of Carb. Air °F
Barometric Pressure in In. of Hg.
Observed Temperature of Carburetor Air °F.
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
.98
.96
.94
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120

Plot No. 11.

TABLE I, TEST No. 79.—*X gas, Claudel carburetor, hand adjusted, high compression (5.3:1).*

Altitude.	Temperature of carburetor air.	Dynamometer scale corrected for balance.	Back pressure correction. Height in Cms. of H_2O.	Back pressure correction. Scale correction.	Dynamometer scale corrected for balance and back pressure.	Revolutions per minute.	Horsepower at 1,500 revolutions per minute at observed temperatures.
Feet.	° *C.*	*Pounds.*		*Pounds.*	*Pounds.*		
30,000	−19.0	103.0			103.0	1,490	51.5
	+ 3.3	98.0			98.0	1,490	49.0
19,100	−18.2	162.5			162.5	1,500	81.3
	+ 7.0	152.5			152.5	1,490	76.3
11,500	−17.5	218.0			218.0	1,510	109.0
	+ 9.0	207.5			207.5	1,490	103.8
5,450	−19.0	271.0			271.0	1,550	135.5
	− 0.3	263.5			263.5	1,550	131.8

TABLE II, TEST No. 80.—*X gas, Claudel carburetor, hand adjusted, extra high compression (6.2:1).*

Altitude.	Temperature of carburetor air.	Dynamometer scale corrected for balance.	Back pressure correction. Height in Cms. of H_2O.	Back pressure correction. Scale correction.	Dynamometer scale corrected for balance and back pressure.	Revolutions per minute.	Horsepower at 1,500 revolutions per minute at observed temperatures.
Feet.	° *C.*	*Pounds.*		*Pounds.*	*Pounds.*		
11,600	−19.0	249.5	− 2.7	−0.1	249.4	1,491	124.7
	+ 6.2	242.0	− 2.15	−0.1	241.9	1,406	121.0
	− 5.5	245.5	− 4.2	−0.2	245.3	1,516	122.7
	0	238.3	− 4.3	−0.2	238.1	1,674	119.1
19,200	−18.0	182.4	+ 1.45	+0.1	182.5	1,488	91.3
	− 2.6	178.5	+ 3.3	+0.1	178.6	1,526	89.3
	+20.8	170.0	+ 3.0	+0.1	170.1	1,496	85.1
	0	177.0	+ 5.2	+0.2	177.2	1,524	88.6
29,750	−15.8	114.5	+15.5	+0.6	115.1	1,520	57.6
	0	111.0	+14.7	+0.6	111.6	1,558	55.8
	+16.2	107.6	+14.7	+0.6	108.2	1,500	54.1

TABLE III, TEST No. 103.—*Tice carburetor, inherent adjustment, 155 gas, high compression (5.3:1).*

Altitude.	Temperature of carburetor air.	Dynamometer scale corrected for balance.	Back pressure correction. Height in Cms. of H_2O.	Back pressure correction. Scale correction.	Dynamometer scale corrected for balance and back pressure.	Revolutions per minute.	Horsepower at 1,500 revolutions per minute at observed temperatures.
Feet.	° *C.*	*Pounds.*		*Pounds.*	*Pounds.*		
5,300	−10.9	278.5	− 2.5	−0.1	278.4	1,505	139.2
	− 0.8	273.5	− 2.0	−0.1	273.4	1,518	136.7
	+13.6	271.5	− 3.0	−0.1	271.4	1,530	135.7
11,400	−11.2	221.5	−11.0	−0.4	221.1	1,503	110.6
	+ 9.6	219.2	− 1.0	0	219.2	1,498	109.6
	− 0.7	220.5	0	0	220,5	1,508	110.3
19,250	−11.6	166.5	+ 3.0	+0.1	166.6	1,508	83.3
	+ 1.0	161.5	+ 2.5	+0.1	161.6	1,503	80.8
	+14.7	157.5	−15.5	−0.6	156.9	1,500	78.5
23,170	− 9.7	136.5	+ 4.0	+0.2	136.7	1,510	68.4
	+ 0.6	132.5	+ 3.0	+0.1	132.6	1,488	66.3
	+16.6	129.5	−19.0	−0.7	128.8	1,483	64.4

TABLE IV, TEST No. 104.—*H gas, Claudel carburetor, hand adjusted, high compression (5.3:1).*

Altitude.	Temperature of carburetor air.	Dynamometer scale corrected for balance.	Back pressure correction. Height in Cms. of H_2O.	Back pressure correction. Scale correction.	Dynamometer scale corrected for balance and back pressure.	Revolutions per minute.	Horsepower at 1,500 revolutions per minute at observed temperatures.
Feet.	° *C.*	*Pounds.*		*Pounds.*	*Pounds.*		
5,450	−15.8	296.5	−32.0	−1.2	295.3	1,520	147.6
	− 9.9	293.5	−33.0	−1.3	292.2	1,525	146.1
	− 5.0	287.5	−34.0	−1.3	286.2	1,515	143.1
	− 0.1	272.0	−20.0	−0.8	271.2	1,507	135.6
	+ 6.2	285.5	− 7.5	−0.3	285.2	1,530	142.6

TABLE V, TESTS NOS. 116 AND 117.—*Two-inch Stromberg carburetor, hand adjusted, high compression (5.3:1), X gas, altitude 2,050 feet.*

Temperature of carburetor air.	Dynamometer scale readings.	Revolutions per minute.	Horsepower at 1,800 revolutions per minute at observed temperatures.
° C.	Pounds.		
− 5.0	328.0	1,800	196.8
+ 0.2	326.3	1,800	195.8
+ 5.2	329.0	1,793	197.4
+ 9.4	326.0	1,790	195.6
+15.3	323.0	1,800	193.8
+20.1	321.0	1,795	192.6
+40.2	312.2	1,798	187.3
+50.0	303.5	1,806	182.1
+45.1	307.0	1,803	184.2
+40.0	309.0	1,800	185.4
+34.5	308.2	1,810	184.9
+30.0	310.8	1,803	186.5
+25.0	314.0	1,800	188.4
+20.1	317.0	1,813	190.2
+14.9	318.0	1,820	190.8

TABLE VI, TEST NO. 119.—*Two-inch Stromberg carburetor, hand adjusted, X gas, high compression (5.3:1), altitude 1,950 feet.*

Temperature of carburetor air.	Dynamometer scale readings.	Revolutions per minute.	Horsepower at 1,800 revolutions per minute at observed temperatures.
° C.	Pounds.		
−15.5	337.3	1,810	202.4
− 9.9	336.7	1,800	202.0
− 4.5	335.3	1,800	201.2
+ 0.7	332.0	1,795	199.2
+ 6.1	329.0	1,797	197.4
+10.9	326.0	1,815	195.6
+17.3	324.0	1,815	194.4
+21.7	321.0	1,820	192.6
+26.0	318.0	1,815	190.8
+32.5	315.0	1,795	189.0
+38.6	310.0	1,805	186.0
+42.0	308.5	1,800	185.2
+47.5	305.0	1,800	183.0
+52.8	302.5	1,795	181.5
+52.4	302.5	1,797	181.5

REPORT No. 45.

PART IV.

INFLUENCE OF WATER INJECTION ON ENGINE PERFORMANCE.[1]

By V. W. Brinkerhoff.

RÉSUMÉ.

A short investigation has been conducted at the Bureau of Standards to determine the effect of water injected into the intake manifold of an internal combustion engine. This investigation was carried out on two different engines, truck and automobile, but the results in general are such as to apply also to airplane engines.

The first series of tests was conducted to determine whether the use of water injected into the intake manifold has any effect on the horsepower output and fuel economy; the second series to determine the effect upon the carbon deposit on the cylinder walls and piston heads.

The data obtained indicate that in an engine of good design there is no appreciable gain in power or fuel economy due to the injection of water, but in a badly carbonized or a poorly designed engine, where hot spots due to improper cooling are present, a slight increase in power may result. If enough water be used, it will remove a small portion of the carbon but will cause at the same time a considerable reduction in the operating efficiency of the engine.

The maximum amount of water used in these tests was limited to that which did not materially interfere with the normal operation or power output of the engine and the results do not indicate the value of much larger quantities of water as injected under special conditions solely as a carbon removing agent.

INFLUENCE OF WATER INJECTION ON ENGINE PERFORMANCE.

The object of this investigation has been to determine from dynamometer tests the effect of the injection of water into the intake manifold of an engine on the power output, fuel economy, carbonization, and general engine performance. It has been claimed by advocates of water injection into the intake manifold that the use of water in this way results in—

(1) Increase of power.

(2) Decrease in fuel consumption.

(3) Decrease in carbon deposit on pistons, valves, and combustion chambers.

The tests made at the Bureau of Standards, covering a period of some seven weeks, have been run primarily to meet the needs of the Inventions' Board of the War College, and the scope of this investigation was determined by a conference between members of the Inventions' Board and the staff of the Bureau of Standards. While no attempt has been made at an exhaustive study of the problem it is thought that the data from these tests will answer in a general way the question of the effect of water injection upon engine performance. Although the engines used were of the type employed in motor trucks and automobiles, the results are of such character as to apply in general to airplane engines.

For use in these experiments the Inventions' Board provided one of the War Department's standardized truck engines, class B. This engine was connected to a Sprague Electric Co. 125-horsepower dynamometer, and provisions made for all auxiliary apparatus necessary to obtain the data recorded below. This engine is a 4-cylinder conventional design with a bore of 4.75 inches and stroke of 6 inches, giving a total piston displacement of 425 cubic inches. The intake manifold is of the "hot spot" type. The clearance volume was found to average 37 per cent of the swept volume, giving the very low compression ratio of 3.7.

The average compression pressure as determined by an O'Kill indicator was found to be 47.75 pounds per square inch at 100 revolutions per minute with jacket water at 55° C.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 34.

The test data given on the accompanying log sheets were obtained as follows:

The engine was first warmed up to operating temperature and the carburetor adjusted to give maximum power at maximum speed and then power runs made, using ordinary gasoline, with spark set for maximum power, all data being taken over a period of five minutes and averaged. Water was then admitted to the intake manifold at a point about 1.75 inches above carburetor throttle and the same data taken with the same spark settings, followed by another run with water, but with the spark advanced for maximum power. These runs were made over a speed range of from 400 to 1,200 revolutions per minute at intervals of 200 revolutions per minute. The amount of water used during any run was determined by reading the difference in height of the water, at the beginning and end of the run, in a graduate cylinder of 1,000 cc. capacity and observing time elapsed by means of a stop watch. The amount of water used was controlled by means of a glass stop cock in the line between the graduate cylinder and the intake manifold.

The preliminary and test runs No. 2 and No. 3 were made with a Zenith L6 carburetor fitted with 25 mm. choke, 1.15 mm. main jet, and 1.25 mm. compensator jet. Varying amounts of water were used throughout these runs. In test No. 4 a Stromberg M3 carburetor with $1\frac{5}{32}$-inch choke and No. 52 (0.0635 inch) bleeder was substituted to permit of varying the gas air mixture ratio for each speed. This adjustment was to give the lowest fuel consumption consistent with maximum power and to obtain a single setting with a rich mixture.

Tests No. 5 and No. 6 are part throttle runs of constant torque and power in each case, simulating the following road conditions: Road resistance, 50 pounds per ton; truck speed, 10 miles per hour; gross weight, 10 tons; diameter of wheels, 40 inches; gear ratio, 9.5:1.

In test run No. 3 a metal plate with an asbestos gasket was inserted between intake and exhaust manifold in order to ascertain any difference in operation due to a lower temperature of mixture.

Commercial gas, fulfilling United States General Supply Committee Specifications for 1918, and Aeroplane B oil, a product of the Atlantic Refining Co., were used in all runs. Particular care has been given throughout the tests to keep external conditions the same in so far as possible.

To determine the influence of water injection upon the removal of carbon in an engine, a Rutenber 6-cylinder, 3 by 5 inch engine was mounted upon a test stand and fitted with fan brake for providing a load. A thermo-syphon system of cooling was used and provision made for determination of oil and water temperatures, revolutions per minute, oil, water, and gasoline consumption. This engine was run for several days with a very rich mixture setting, spark retarded, cooling water temperature as low as possible, and oil occasionally introduced into cylinders until the valves, piston heads, and combustion chambers were well covered with carbon. The engine was then run for a period of six hours at wide-open throttle, with water injected into the intake manifold, with outlet water at a constant temperature and as high as possible. At the end of this run the cylinder head was removed for inspection. It was found on this inspection that the water had not made any appreciable effect upon the carbon deposit. This run was followed by others in which the amount of water injected into the manifold and the temperatures of the jacket inlet water were varied.

The only data taken on these tests have been the rate of water injection, number of hours, and maximum temperature of outlet water. The total amount of water used was 27.5 gallons for a total of 23.75 hours and a temperature of outlet water from a minimum of 55° to a maximum of 90° C. The water rate varied from 2.4 pints per hour to 7.05 pints per hour, this maximum rate causing some reduction in the engine power.

The following conclusions have been reached as a result of this investigation:

(1) The injection of water varying in amount from 0.03 pound per brake horsepower to 0.44 pound per brake horsepower per hour does not produce any appreciable effect upon power, fuel economy, or operation in general.

(2) Injection of water exceeding 0.44 pound per brake horsepower per hour is accompanied by an appreciable decrease in power, fuel economy, and smoothness of operation.

(3) It is quite probable that with an engine badly carbonized so that preignition occurs, or with an engine of poor design, manifesting this in form of hot spots due to lack of proper cooling of valves, piston, or head of combustion chamber, the use of water will result in increased power.

(4) With a Rutenber 6-cylinder 3 by 5 inch engine operating at a high-jacket water temperature the injection of water in amounts between 2 and 8 pounds per hour produced a softening and a slight reduction of carbon, the reduction in the amount of carbon deposit, not exceeding

25 per cent. This was most noticeable on piston heads and valves. At the same time, when using water at the maximum rate there was considerable reduction in the power of the engine. This deposit of carbon varies considerably in character, according as composed of (1) that due to a very rich mixture, (2) that due to an excess in use of lubricating oil, and (3) the above, with the addition of fine dust or dirt taken in through the carbureting system. Of these three types of carbon deposit the first is by far the most difficult to remove, and, in fact, it is found that water injection has little effect upon this kind of carbon.

Preliminary test, Class B engine, Zenith L6 carburetor.

Time.	Spark advance, degrees.	Tach. reading, r. p. m.	Scale beam, lb.	Brake horse-power.	B. M. E. P., lb. per sq. in.	Gas, lb. per hr.	Water, lb. per hr.	Gas, per lb. b. h. p. per hr.	Ratio water to gas.	Jacket water temp., °C.		Carb. air temp., °C.	Oil sump. temp., °C.	Oil pressure rear main bear., lb. per sq. in.	Pressure drop intake manifold, lb. per sq. in.
										Inlet.	Outlet.				
2:21..	0	410	112.5	15.38	69.9	12.40	0	0.81	0	43	63	26	42	7	0.16
2.35..	0	414	112.5	15.54	69.9	14.02	Neg.	.90	0	45	62	25	45	7	.16
2.48..	6.90	412	110.0	15.13	68.3	....	2.50	....	....	46	62	24	45	7	.16
2.59..	8.84	620	115.5	23.87	71.6	19.60	0	.82	0	47	62	25	46	9	.22
3.17..	8.84	620	112.0	23.15	69.6	19.40	2.50	.84	0.129	47	62	25	48	9	.22
3.25..	11.30	622	112.0	23.23	69.6	19.50	2.50	.84	.129	47	62	25	49	8	.22
3.36..	12.42	810	121.5	32.80	75.5	24.80	0	.73	0	48	62	25	50	10	.43
3.50..	12.42	825	118.0	32.45	73.3	21.50	3.75	.66	.174	48	62	26	54	9	.43
3.58..	17.10	826	123.0	33.90	76.4	24.50	2.82	.72	.115	48	62	27	55	9	.43
4.10..	13.80	1,032	117.5	40.40	73.0	30.70	0	.76	0	48	62	27	59	10	.68
4.21..	13.80	1,029	118.75	40.70	73.8	30.50	1.25	.75	.041	48	62	28	62	10	.68
4.28..	19.33	1,026	121.25	41.50	75.3	29.10	1.25	.70	.043	48	62	27	64	10	.68
4.36..	24.85	1,238	108.50	44.70	67.4	22.00	0	0	0	49	62	27	66	11	.98
4.47..	24.85	1,227	105.00	42.90	65.2	33.00	5.27	.77	.160	50	62	27	70	11	.98
4.55..	0	1,240	108.00	44.70	67.0	35.60	5.01	.80	.141	50	62	28	72	10	.98

Water injection test run number 2, Class B engine, Zenith L6 carburetor.

Time.	Spark advance, degrees.		Tach. reading, r. p. m.	Brake horse-power.	B. M. E. P., lb. per sq. in.	Gas, lb. per hr.	Water, lb. per hr.	Gas, lb. per b. h. p. per hr.	Ratio water to gas.	Water jacket temp., °C.		Carb. air temp., °C.	Oil sump. temp., °C.	Oil pressure, rear main bear., lb. per sq. in.	Pressure drop intake manifold, lbs. per sq. in.	Scale beam, pounds.
	Batt.	Mag.								Inlet.	Outlet.					
1.05..........	4.1	9.5	416	16.7	75.0	14.63	0	0.88	0	45.5	62.0	34.0	48.0	5.0	0.13	120.50
1.14..........	4.1	9.5	411	16.1	73.0	12.58	6.03	.78	0.48	45.0	61.0	34.0	49.0	5.0	.13	117.70
1.24..........	9.7	11.5	416	16.5	74.0	13.88	5.96	.84	.429	43.0	62.0	34.0	49.0	5.0	.13	119.35
1.34..........	12.4	18.0	621	25.4	76.3	19.28	0	.76	0	47.0	62.0	35.0	50.5	7.5	.25	122.85
1.44..........	12.4	18.0	616	24.4	74.0	19.52	11.02	.80	.365	47.8	61.5	36.5	50.5	7.5	.25	119.00
1.52..........	18.0	22.5	620	25.0	75.2	19.10	10.03	.76	.572	48.0	62.0	36.0	52.5	7.5	.25	121.00
2.01..........	18.4	22.0	825	34.3	77.5	24.85	0	.72	0	49.0	64.0	36.0	53.0	9.2	.38	124.60
2.10..........	18.4	22.0	826	33.5	75.7	25.50	11.38	.76	.147	49.0	62.5	38.0	57.5	8.0	.38	121.75
2.18..........	19.3	24.0	820	34.4	78.2	24.45	11.38	.71	.467	49.0	62.0	36.5	60.0	7.5	.38	125.75
2.29..........	18.0	21.5	1,032	40.8	74.0	30.45	0	.75	0	46.5	63.0	36.5	63.0	9.75	.74	118.85
2.37..........	18.0	21.5	1,030	41.2	74.5	29.30	11.38	.72	.396	49.5	63.0	37.0	66.0	9.0	.74	119.75
2.46..........	23.5	30.0	1,034	41.7	75.0	30.30	11.47	.73	.379	49.0	62.0	39.0	69.0	8.5	.74	120.80
2.55..........	33.2	36.0	1,256	44.25	65.8	36.90	0	.83	0	50.0	62.0	38.5	70.5	11.5	.98	106.75
3.04..........	33.2	36.0	1,244	44.3	66.5	33.15	19.05	.75	.575	50.5	61.0	38.5	72.5	11.0	.98	107.00
3.12..........	36.6	36.0	1,250	44.3	66.2	34.10	19.20	.77	.563	50.5	61.0	38.0	75.5	10.0	.98	106.50

Test number 3, Class B engine, Zenith L6 carburetor, metal plate (asbestos-lined) inserted between intake and exhaust manifold.

Time.	Spark advance, degrees.		Tach. reading, r. p. m	Brake horse-power.	B. M. E. P., lb. per sq. in.	Gas, lb. per hr.	Water, lb. per hr.	Gas, lb. per b. h. p. per hr.	Ratio water to gas.	Water jacket, temp., °C.		Carb. air, temp., °C.	Oil, sump. temp., °C.	Oil pressure, rear main bear., lb. per sq. in.	Pressure, drop intake manifold, lb. per sq. in.	Scale beam, pounds.
	Batt.	Mag.								Inlet.	Outlet.					
1.32	8.2	13.0	416	16.8	75.5	15.00	0	0.89	0	45	62	36.5	59	5	.13	121.50
1.41	8.2	13.0	412	16.3	73.6	13.05	6.15	.80	0.470	45	61	38.0	59	5	.13	118.50
1.50	12.4	15.0	421	16.7	73.9	14.10	6.13	.85	.435	46	61	38.0	57	5	.13	119.00
2.00	19.2	22.0	618	25.2	75.8	19.40	0	.77	0	48	62	38.0	57	8	.22	122.00
2.08	19.2	22.0	622	24.9	74.5	19.20	3.93	.77	.205	48	62	39.0	57	8	.22	120.00
2.16	24.8	28.5	622	25.2	75.6	19.80	3.93	.79	.1985	48	62	39.0	58	8	.22	121.75
2.26	24.8	27.5	832	34.7	77.7	24.30	0	.70	0	48	62	38.0	59	10	.43	125.00
2.34	24.8	27.5	834	34.9	78.0	25.80	4.40	.74	.170	49	62	38.0	60	9	.43	125.50
2.41	30.4	30.0	832	34.7	77.7	25.60	4.24	.74	.166	48	62	38.0	61	9	.43	125.00
2.50	29.0	31.0	1,040	41.7	74.8	24.70	0	.59	0	48	62	38.0	63	10	.68	125.50
3.01	29.0	31.0	1,046	42.3	75.2	25.00	3.22	.59	.129	49	62	38.0	66	10	.68	121.00
3.08	34.6	36.0	1,034	41.8	75.2	25.30	4.48	.61	.177	49	62	38.0	68	10	.68	121.00
3.17	38.6	36.0	1,254	43.5	64.6	32.00	0	.74	0	50	62	40.0	70	12	1.02	104.00
3.25	38.6	36.0	1,246	43.6	65.3	31.80	4.92	.73	.154	50	62	40.0	74	11	1.02	105.00
3.30	40.8	36.0	1,250	43.7	65.1	31.10	4.82	.71	.155	50	62	40.0	76	11	1.02	104.75

NOTE.– In the above table the first run in each group of three runs was made with gasoline only and spark set for maximum power. The second run was made with water injected into the mixture, using the same spark setting as on the first run. The third was made with water and the spark adjusted for maximum power.

Test number 4, Class B engine, Stromberg M3 carburetor.

Time.	Tach. reading, r. p. m.	Brake horsepower.	B. M. E. P., lb. per sq. in.	Gas, lb. per hr.	Water, lb. per hr.	Gas, lb. per b. h. p. per hr.	Water, lb. per b. h. p. per hr.	Ratio water to gas.	Scale beam pounds.	Jacket water temp., °C. Inlet.	Jacket water temp., °C. Outlet.	Carb. air temp., °C.	Oil sump. temp., °C.	Oil pressure rear main bear., lb. per sq. in.	Pressure drop intake manifold., lb. per sq. in.	Spark advance, degrees. Batt.	Spark advance, degrees. Mag.
11.11	421	16.90	74.6	18.83	0	1.11	0	0	120.1	46.5	62.5	32.5	41.0	8.0	.31	11.00	17.00
11.20	417	16.70	74.7	17.75	1.79	1.06	.107	.101	120.3	47.0	62.5	33.5	41.5	8.0	.31	11.00	17.00
11.20	419	17.00	75.5	19.10	1.80	1.12	.106	.094	121.6	46.0	62.0	34.0	43.5	7.5	.31	13.75	20.00
11.40	620	25.90	77.7	25.95	0	1.00	0	0	125.1	48.5	62.0	34.5	45.5	10.0	.58	22.00	26.00
11.49	622	25.80	77.3	26.50	3.43	1.03	.133	.130	124.6	48.5	62.0	34.5	47.5	9.0	.56	22.00	26.00
11.57	616	25.60	77.3	26.10	3.42	1.02	.134	.131	124.4	49.0	63.0	35.0	49.5	8.5	.56	24.75	27.00
12.06	828	35.40	79.5	29.70	0	.84	0	0	128.3	49.0	63.0	34.0	51.5	10.0	1.00	27.50	31.00
12.15	830	35.40	79.5	0	3.33	0	.131	0	128.0	49.5	63.0	35.0	55.0	10.0	1.00	27.50	31.00
12.23	826	35.20	79.3	33.10	3.83	.94	.109	.116	127.8	50.0	63.0	36.0	57.5	9.5	1.00	30.25	32.00
12.35	1,034	41.20	74.2	36.00	0	.87	0	0	119.4	50.0	63.0	35.5	61.0	10.0	1.56	30.25	35.00
12.44	1,042	41.60	74.5	41.30	3.42	1.00	.082	.083	119.8	50.0	62.5	36.0	64.5	10.0	1.56	30.25	35.00
12.52	1,038	41.50	74.5	36.70	3.40	.89	.082	.092	119.8	50.0	62.0	36.0	66.5	10.0	1.56	33.00	37.00
1.03	1,246	44.40	66.5	42.80	0	.96	0	0	106.9	51.0	62.0	37.0	70.5	10.5	2.06	37.00	37.00
1.12	1,238	44.20	66.5	44.50	3.57	1.01	.081	.080	107.0	51.0	62.0	36.5	73.5	10.5	2.06	37.00	37.00
1.18	1,232	43.40	65.8	41.30	3.52	.96	.0808	.085	106.0	51.0	62.0	37.0	75.5	10.0	2.06	41.25	37.00
WITH CARBURETOR SETTING FOR MAXIMUM POWER AT EACH SPEED.																	
2.58	420	16.95	75.5	16.35	2.36	.96	.139	.114	121.1	46.0	62.0	36.0	52.0	5.0	.31	13.75	15.00
3.11	622	25.70	77.2	21.50	2.64	.84	.1025	.123	124.1	47.0	62.5	37.0	52.0	8.0	.56	22.00	24.00
3.27	832	35.40	79.5	29.70	3.02	.84	.085	.102	127.6	50.0	63.5	38.0	56.0	10.0	1.00	20.50	26.00
3.39	1,036	41.50	74.9	30.30	3.33	.73	.080	.110	120.2	50.0	63.0	39.0	61.0	10.0	1.50	27.50	31.00
3.55	1,244	44.80	67.4	35.60	3.70	.80	.0795	.104	108.1	50.0	62.5	39.0	67.5	12.0	2.06	33.00	33.00

NOTE.—In the first part of the above table the first run in each group of three runs was made with gasoline only and spark set for maximum power. The second run was made with water injected into the mixture, using the same spark setting as on the first run. The third was made with water and the spark adjusted for maximum power.

Test number 5, Class B engine, Stromberg M3 carburetor.

Time.	Tach. reading, r. p. m.	Brake horsepower.	B. M. E. P., lb. per sq. in.	Gas, lb. per hr.	Water, lb. per hr.	Gas, lb. per b. h. p. per hr.	Water, lb. per b. h. p. per hr.	Ratio water to gas.	Scale beam pounds.	Jacket water temp., °C. Inlet.	Jacket water temp., °C. Outlet.	Car. air temp., °C.	Oil sump. temp., °C.	Oil pressure rear main bear., lb. per sq. in.	Pressure drop intake manifold., lb. per sq. in.	Spark advance, degrees. Batt.	Spark advance, degrees. Mag.
10.26	409	6.81	31.10	10.0	0	1.47	0	0	50.0	42.0	55.0	20.0	35.0	8.0	5.8		15.00
10.34	405	6.75		9.0	5.16	1.33	.764	.575		41.0	54.0	20.0	36.5	8.0	5.6		15.00
10.45	411	6.85		9.0	4.94	1.31	.720	.550		39.5	51.0	20.0	37.5	8.0	5.86		31.00
10.56	642	10.70		12.0	0	1.12	0	0		46.0	57.0	20.0	38.5	10.0	5.5		26.00
11.04	650	10.82		10.9	3.21	1.01	.296	.293		47.0	59.0	20.0	40.0	10.0	5.6		26.00
11.12	662	11.05		12.0	3.19	1.08	.289	.268		47.0	59.0	20.5	41.5	10.0	5.6		36.00
11.20	834	13.90	Constant.	0	0	0	0	0	Constant.	51.0	62.5	21.0	44.0	11.0	5.3	Dead.	21.00
11.27	832	13.88		15.0	7.54	1.08	.543	.502		51.0	64.0	21.0	46.0	10.5	5.1		21.00
11.36	784	13.08		15.0	7.72	1.15	.591	.514		50.5	61.5	22.0	48.5	10.0	5.1		29.00
11.45	1,062	17.70		21.0	0	1.19	0	0		51.5	63.0	22.0	51.0	11.0	4.5		16.00
11.55	1,038	17.30		18.0	3.21	1.04	.185	.178		51.0	63.0	22.5	54.5	10.0	4.5		16.00
12.03	1,034	17.25		18.0	3.17	1.04	.184	.177		52.0	63.0	23.0	57.5	10.0	5.2		36.00
12.13	1,230	20.50		18.0	0	.876	0	0		52.0	62.5	23.0	61.0	11.0	4.8		27.00
12.21	1,176	19.60		15.0	8.55	.765	.436	.222		52.0	62.5	23.5	65.5	10.6	4.8		27.00
12.28	1,224	20.40		18.0	8.65	.880	.424	.208		52.0	63.0	23.5	65.5	10.5	4.9		36.00

NOTE.—In the above table the first run in each group of three runs was made with gasoline only and spark set for maximum power. The second run was made with water injected into the mixture using the same spark setting as on the first run. The third was made with water and the spark adjusted for maximum power.

Test number 6, Class B engine, Stromberg M3 carburetor.

Time.	Tach. reading, r. p. m.	Brake horsepower.	B. M. E. P., lb. per sq. in.	Gas, lb. per hr.	Water, lb. per hr.	Gas, lb. per b. h. p. per hr.	Water, lb. per b. h. p. per hr.	Ratio water to gas.	Scale beam pounds.	Jacket water temp., °C. Inlet.	Jacket water temp., °C. Outlet.	Car. air temp., °C.	Oil sump. temp., °C.	Oil pressure rear main bear., lb. per sq. in.	Pressure drop intake manifold., lb. per sq. in.	Spark advance, degrees. Batt.	Spark advance, degrees. Mag.
2.28	403	13.40	62.3	17.25	0	1.29	0	0	100.00	41.0	56.5	20.5	36.5	5.0	2.7	19.2	15.0
2.37	404	13.40	62.3	17.05	7.72	1.27	.576	.453	100.00	38.5	51.5	20.0	38.5	5.0	2.7	19.2	15.0
2.45	412	13.70	63.3	14.60	7.80	1.07	.569	.535	100.00	38.5	50.5	20.0	40.0	5.0	2.7	33.0	26.0
2.56	643	14.25	41.5	21.10	0	1.48	0	0	66.66	40.0	51.0	20.0	40.0	5.0	3.6	41.3	36.0
3.03	651	14.45	41.5	21.40	5.47	1.48	.379	.258	66.66	40.0	50.5	20.0	40.0	5.0	3.6	41.3	36.0
3.11	892	14.85	31.1	24.10	0	1.62	0	0	50.00	40.5	49.5	20.0	40.0	5.0	3.6	41.3	36.0
3.18	884	14.70	31.1	23.80	8.30	1.62	.565	.348	50.00	40.5	49.5	20.0	40.5	5.0	3.5	41.3	36.0
3.28	1,034	13.80	24.9	24.50	0	1.78	0	0	40.00	52.0	61.5	20.0	42.0	6.0	3.4	41.3	36.0
3.35	1,008	13.45	24.9	24.40	6.70	1.81	.498	.274	40.00	52.0	61.0	20.0	43.5	6.0	3.4	41.3	36.0
3.45	1,242	13.80	20.8	27.20	0	1.97	0	0	33.33	53.0	61.0	21.0	45.5	7.0	3.4	41.3	36.0
3.52	1,198	13.30	20.8	25.10	8.47	1.89	.638	.338	33.33	54.0	61.0	21.0	48.5	7.0	3.5	41.3	36.0

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