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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 210

THE TESTING OF AVIATION ENGINES UNDER APPROXIMATE ALTITUDE CONDITIONS.

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The desirability of a test to determine the performance of aviation engines at altitudes was early recognized. With information obtained from such a test, the performance in flight could be predicted, possible engine failures at high altitudes foreseen, and the danger to pilots therefrom greatly minimized. This led to the construction, at the Bureau of Standards, of a laboratory in which the conditions encountered at altitudes up to 30,000 feet can be simulated. A description of this laboratory, which has been in successful operation for over six years, is contained in Report No. 44 of the National Advisory Committee for Aeronautics.

The cost of a laboratory of this type has led to many suggestions for a modified method of testing which would not require the equipment necessary for a "true" altitude test, but which might give approximately correct results at less expense. In making an altitude test in the laboratory at the Bureau of Standards, the pressures at the carbureter entrance, at the exhaust ports and in the chamber surrounding the engine are reduced to a value corresponding to the desired altitude. Among the suggested approximate methods of test is one in which the pressures at the carbureter entrance and exhaust ports are reduced as above described, but the air surrounding the engine allowed to remain at sea-level pressure. Tests can be made in this way without the use of the strongly reinforced airtight chamber essential to the "true" altitude test.

This paper is based upon tests made in the altitude laboratory of the Bureau of Standards to determine the value of this approximate method of test.

The engine used in the tests was a Curtiss, Model D-12 (1145), having 12 cylinders of 4.5 in. bore by 6 in. stroke, comp. ratio 5.3.

A comparison was made between runs under the approximate altitude conditions, i.e., with air surrounding the engine at sea-level pressure, and similar runs made under "true" altitude conditions in which the surrounding air is reduced to a pressure corresponding to the altitude. Runs under both conditions were made at air pressures corresponding to sea level and altitudes of 5,000, 10,000, and 15,000 feet. At each altitude, the group of runs under approximate conditions was immediately followed by a similar group under the "true" conditions.

Any important change in engine performance brought about by the change in pressure of the air surrounding the engine should manifest itself by a change either in specific fuel consumption or in brake horsepower developed. Figs. 1 and 3 are therefore of primary interest.

From Fig. 3, it is seen that the relation between specific fuel consumption (lb. fuel per indicated horsepower-hour) and fuel-air ratio was the same for both types of test.

Fig. 1 shows that the maximum brake horsepower developed at each altitude was the same under both conditions. The values given in this curve are taken from the curves of fuel-air ratio versus brake horsepower shown in Fig. 2.

Since the power developed in the two types of tests was the same, no difference in actual volumetric efficiency was to be expected. Past experience, however, has shown that the observed volumetric efficiency is often less than the true value, due to unnoticed leaks in intake manifolds and the air line to the carbureters. In both methods of altitude test, the reduced pressure at the carbureter entrance is obtained by throttling the air entering the carbureter. If leaks had existed in the carbureter air line, their presence would, of course, have caused a much greater error in the air measurements when the surrounding air was at sea level pressure than when it was reduced to approximately the same pressure as at the carbureter entrance. Since no consistent difference was found between the volumetric efficiencies in the two types of test (Fig. 4), it is safe to assume that in these tests appreciable leaks were not encountered.

Since the pressures at carbureter entrance and exhaust ports are the same under either approximate or "true" altitude conditions, there should be no difference in the conditions in the combustion chamber. However, the increased pressure in the crankcase during an approximate test may have some slight influence on the amount of oil passing by the piston. Another effect of increased crankcase pressure is to increase the work of moving the piston on the downward stroke. This, however, is compensated for by the decreased work of the upward stroke and therefore does not affect the power output.

The maintenance of reduced pressure at the exhaust ports during an altitude test necessitates the use of exhauster pumps of large capacity. The possibility of emergency tests without the use of such equipment, or with equipment of less capacity, made it advisable to investigate the effect of changes in exhaust pressure on the performance of the engine during an approximate altitude test. Runs were accordingly made under approximate conditions, at carbureter entrance and exhaust pressures corresponding to sea level and altitudes of 5,000, 10,000 and 15,000 feet. At carbureter entrance pressures corresponding to each altitude, runs were also made with exhaust pressures both greater and less than the carbureter entrance pressures, one group at each altitude being made with sea-level exhaust pressure. The results of these runs are shown in Fig. 5.

Exhaust back-pressure causes a reduction in the power developed which may be considered as divided into two parts. The first is the loss occasioned by the decrease in volumetric efficiency due to the greater pressure of the gases in the clearance space at the beginning of the intake stroke. A second loss is caused by the increased work done by the piston on the exhaust stroke in expelling the spent gases against a higher exhaust pressure.

The following computation may serve to illustrate this change in power with change in exhaust pressure:

Let P_1 = absolute pressure at exhaust port.

P_2 = absolute pressure at carbureter entrance.

P_3 = absolute pressure at end of suction stroke.

V_1 = clearance volume.

V_2 = volume occupied by clearance gases at end of suction stroke.

D = piston displacement.

n = exponent of adiabatic expansion, taken as 1.3.

To simplify the calculations, a number of assumptions are made: First, that with or without exhaust back-pressure, the pressure in the cylinder reaches the same value P_3 at the end of the suction stroke. (The values of P_3 will be slightly different due to change in conditions of flow into the cylinder with change in pressure of the gases in the clearance volume.) Second, that when there is no back pressure, P_3 equals the carbureter entrance pressure P_2 and therefore for that condition V_2 equals V_1. Third, that the pressure in the cylinder at the end of the exhaust stroke is equal to P_1, the pressure at the exhaust port. Fourth, that the indicated mean effective pressure is directly proportional to the weight of charge drawn into the cylinder and hence to the volumetric efficiency. This is borne out by the results of many tests, both in the altitude laboratory and elsewhere.

For an example, take $P_1 = 14.7$ lb. per sq.in., $V_1 = 10$ cu.in., $D = 40$ cu.in., I.M.E.P. developed with no back-pressure = 100 lb. per sq.in. It is desired to find the decrease in I.M.E.P. to be expected with an increase in exhaust pressure of 4 lb. per sq.in. In this case the gases in the clearance volume will have at the end of the exhaust stroke a pressure P_1 (14.7 + 4 = 18.7 lb. per sq.in.), and when expanded during the suction stroke to the pressure $P_3 = P_2 = 14.7$ lb. per sq.in., will occupy a volume V_2 which may be determined by the use of the expression

$$P_1 V_1^n = P_2 V_2^n$$

then $$V_2 = V_1 \sqrt[n]{\frac{P_1}{P_2}} = 10 \sqrt[1.3]{\frac{18.7}{14.7}} = 12.03 \text{ cu.in.}$$

With no back-pressure, the clearance gases occupied the same volume at the end of the suction stroke as at its beginning, ($V_2 = V_1 = 10$ cu.in.), whereas with 4 lb. per sq.in. back-pressure $V_2 = 12.03$ cu.in. $= V_1 + 2.03$ cu.in.

The space available for the fresh charge at the end of the suction stroke is therefore 2.03 cu.in. less than under the first condition. This causes a reduction in volumetric efficiency of $\frac{2.03}{40}$ or 5.1%. The reduction in I.M.E.P. due to the decreased volumetric efficiency is then 100 × .051 = 5.1 lb. per sq.in. To this must be added the loss due to the work of expelling the gases against a higher exhaust pressure. This is equal to the difference $P_1 - P_2 = 4$ lb. per sq.in. The total decrease in I.M.E.P. due to an increase in exhaust pressure of 4 lb. per sq.in. is then $5.1 + 4 = 9.1$ lb. per sq.in.

The dotted lines of Fig. 5 are values calculated by this method, based upon the indicated mean effective pressure developed at each altitude with exhaust pressure equal to carbureter entrance pressure.

There are many assumptions made in these calculations, but the values obtained are near enough to the actual test values to make the method of calculation useful where it is desired to predict, approximately, altitude performance without using the equipment necessary to reduce the exhaust port pressure to the true value, or where unintended fluctuations of this pressure have occurred.

The difficulties of the approximate type of altitude test are chiefly those due to the difference between the pressure of the air surrounding the engine and that existing in the air horn, carbureter, and exhaust pipes. Great care must be taken to prevent leaks into the air horn and carbureter, as these will render the air measurements inaccurate. Air bleeds to the carbureter must be enclosed and connected to the air horn. Leaks in the exhaust pipes will, of course, greatly increase the difficulty of keeping the exhaust port pressure at the proper value. It is believed that with the abovementioned precautions, this type of test may be found useful in obtaining approximate altitude performance data where facilities are insufficient to reproduce the true altitude conditions.

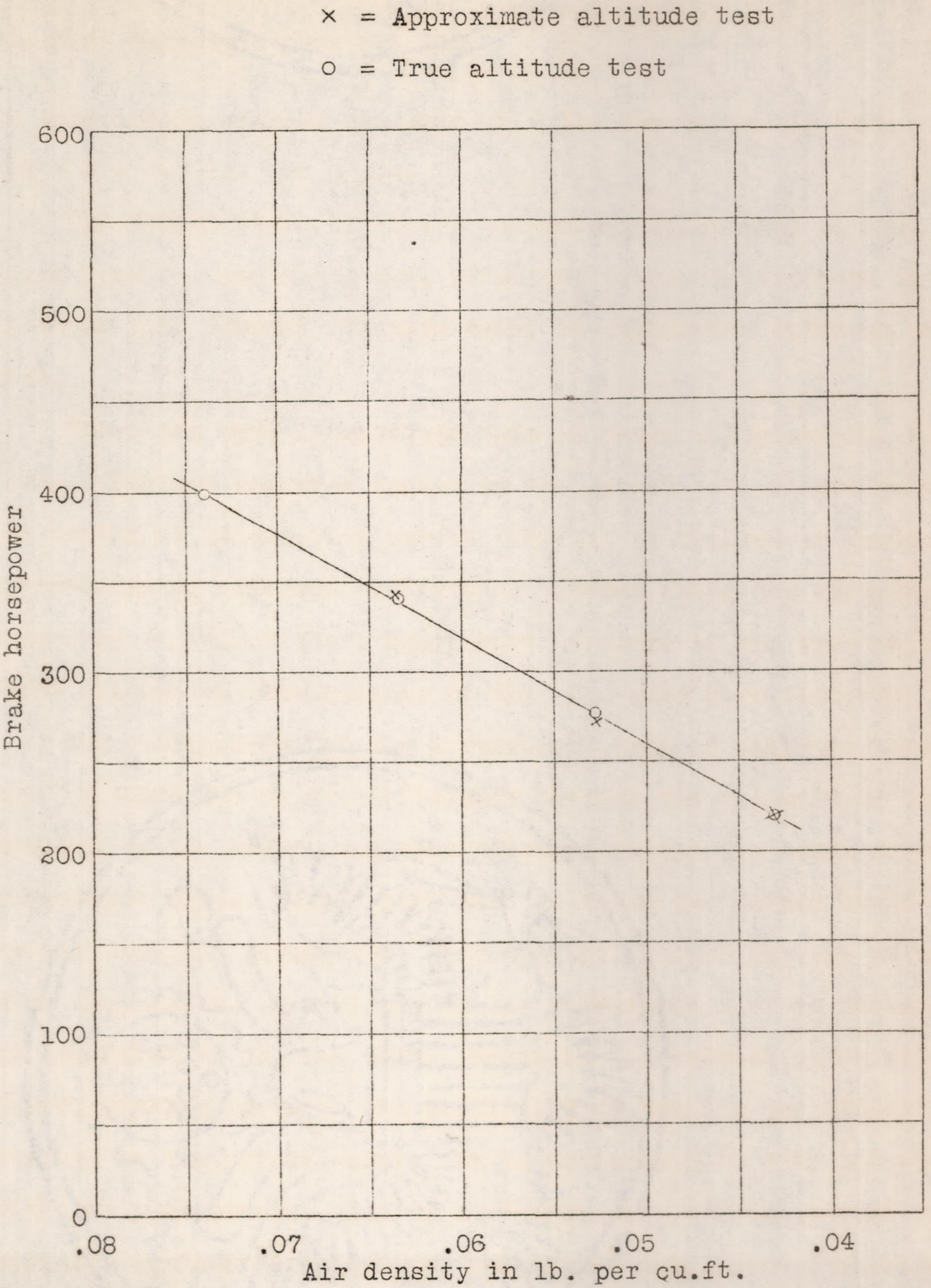
× = Approximate altitude test
○ = True altitude test
600
500
400
300
200
100
0
Brake horsepower
.08
.07
.06
.05
.04
Air density in lb. per cu.ft.

Fig.1.

× = Approximate altitude test

○ = True altitude test

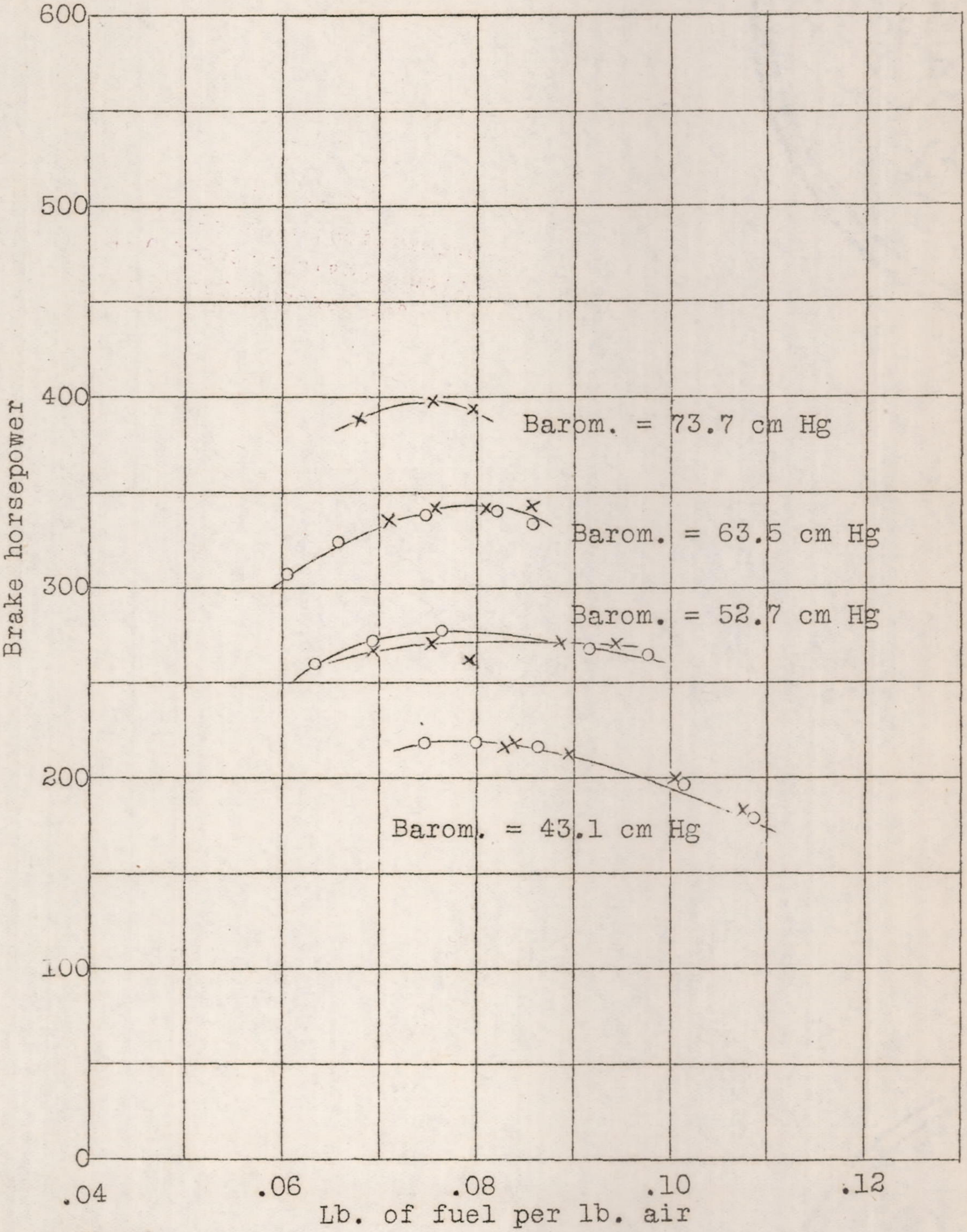

Fig.2.

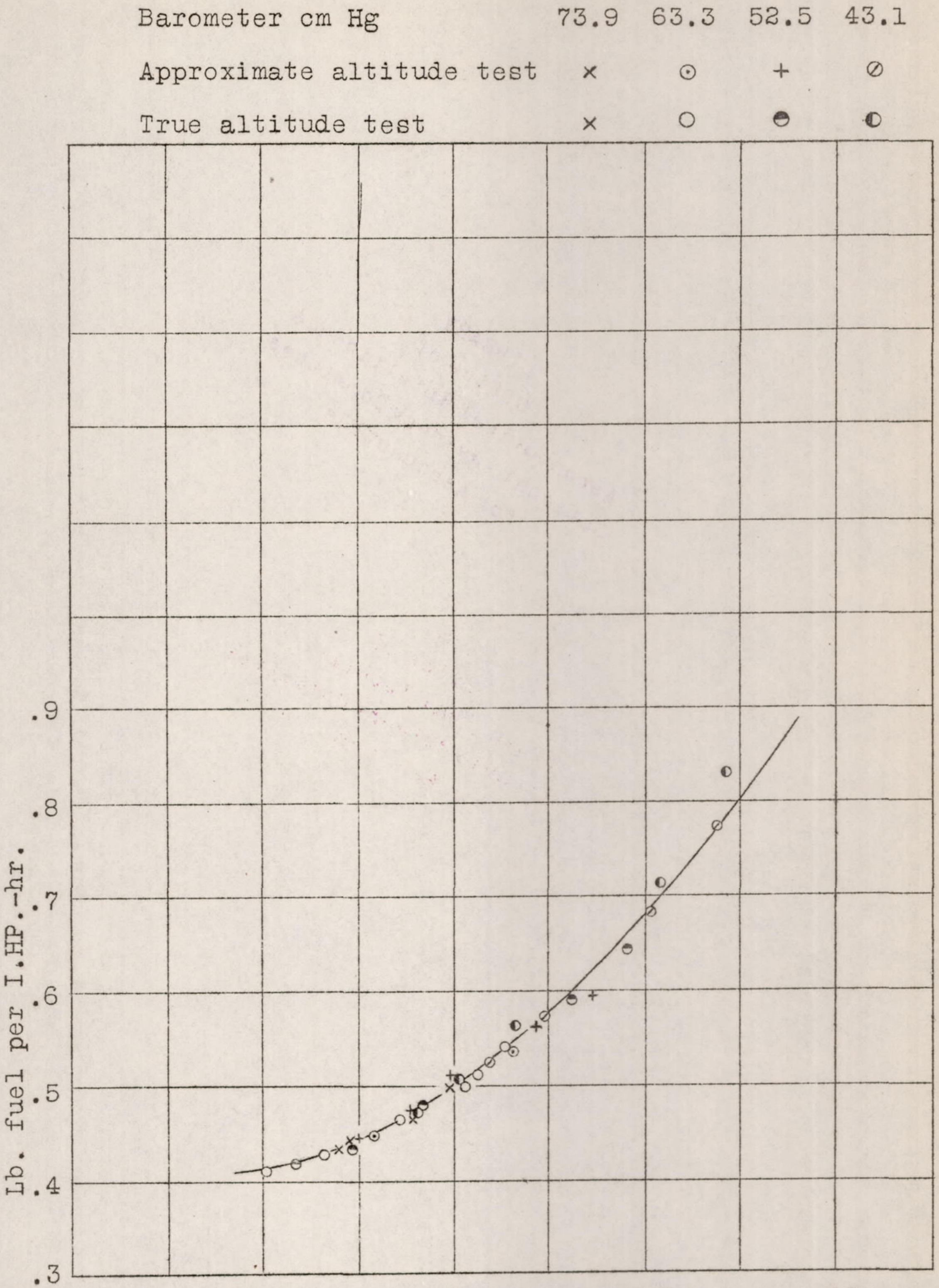
Barometer cm Hg 73.9 63.3 52.5 43.1
Approximate altitude test × ⊙ + ∅
True altitude test × ○ ◓ ◐
.3
.4
.5
.6
.7
.8
.9
Lb. fuel per I.HP.-hr.
.04
.06
.08
.10
.12
Lb. of fuel per lb. air

Fig.3.

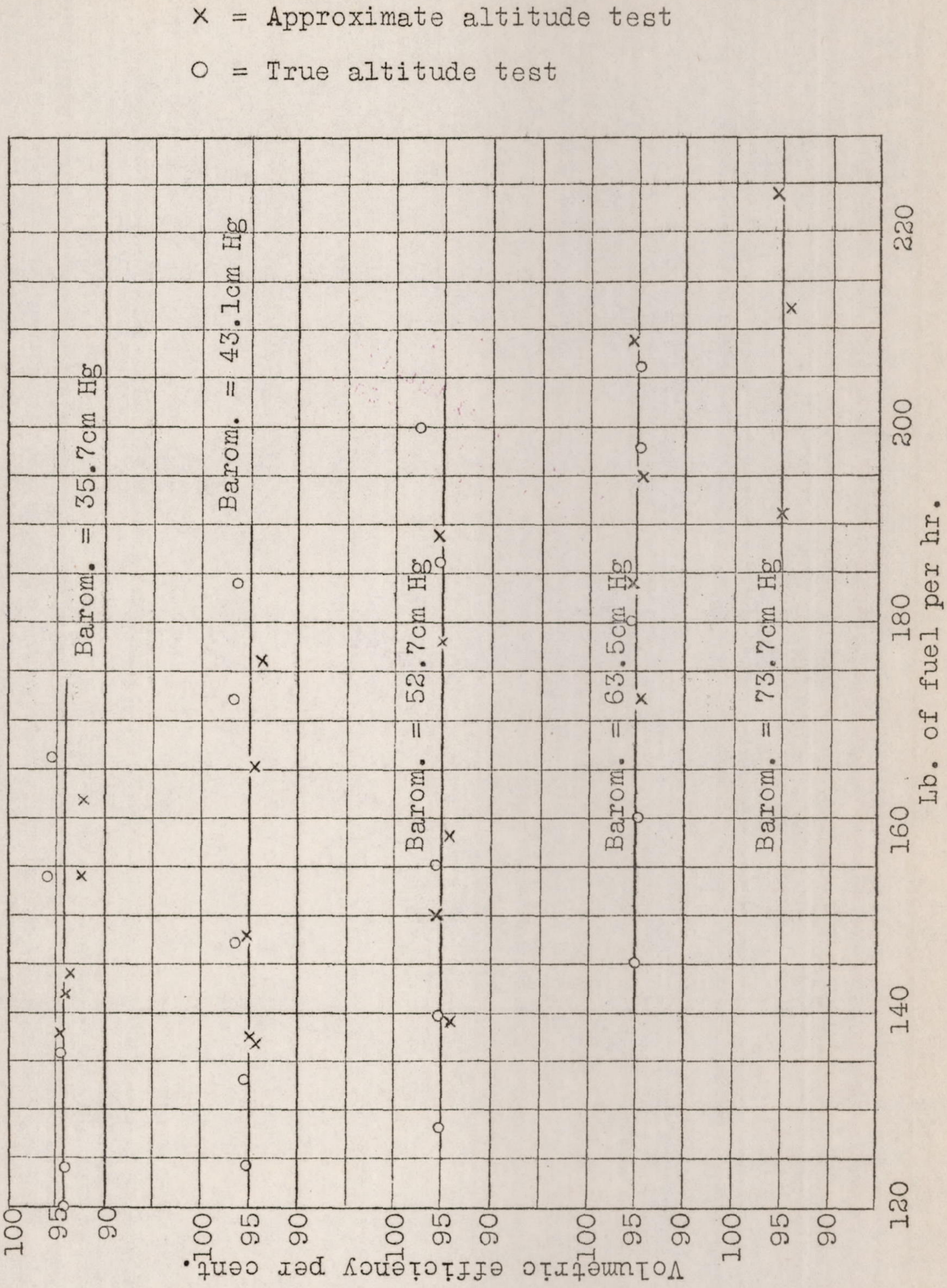
× = Approximate altitude test
○ = True altitude test
Barom. = 35.7cm Hg
Barom. = 43.1cm Hg
Barom. = 52.7cm Hg
Barom. = 63.5cm Hg
Barom. = 73.7cm Hg
100
95
90
100
95
90
100
95
90
100
95
90
100
95
90
Volumetric efficiency per cent.
120
140
160
180
200
220
Lb. of fuel per hr.

Fig.4.

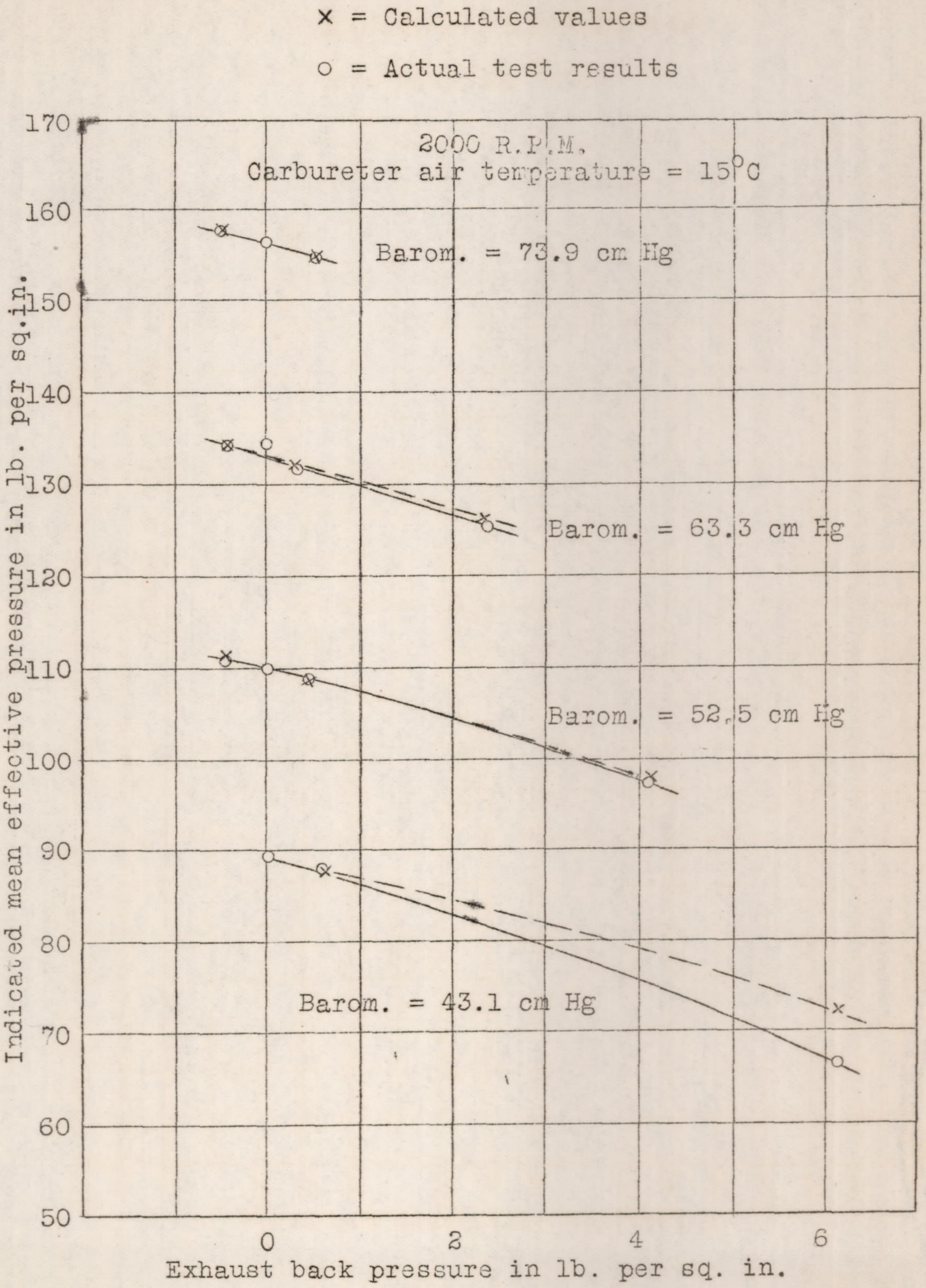
× = Calculated values
○ = Actual test results
2000 R.P.M.
Carbureter air temperature = 15°C
Barom. = 73.9 cm Hg
Barom. = 63.3 cm Hg
Barom. = 52.5 cm Hg
Barom. = 43.1 cm Hg
Indicated mean effective pressure in lb. per sq.in.
170
160
150
140
130
120
110
100
90
80
70
60
50
0
2
4
6
Exhaust back pressure in lb. per sq. in.

Fig.5.