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THE POWER OF AIRCRAFT ENGINES AT ALTITUDE

By Paolo Ragazzi

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The consistent increase in flying speed is perhaps the most outstanding feature of modern aircraft design. This rise is due in part to the progressive improvement of the aerodynamic characteristics of the airplane, and in part due to greater horsepower of the installed engines and the normal flying heights. As a result the airplane designer is faced with the quest for engines capable of developing greater performance and at higher altitude.

Among the many problems involved in the development of high-powered altitude engines the prediction of engine characteristics presents many obstacles which increase in the same measure as the power and the rated horsepower ceiling. As a result of this the last few years have seen numerous investigations in the attempt to find formulas and methods by means of which the performance characteristics established on the ground could be correlated to the performance expected at altitude.

The conventional formulas and systems are accurate enough for engines of average performance and low rated horsepower ceiling, but not for engines with rated horsepoer ceiling of over 4,000 meters, as built today. The formulas are then quite inaccurate and fail altogether if applied to engines intended for substratosphere flying.

The difficulties are particularly great in an attempted comparison of the cooling conditions of air-cooled engines at sea level with those at altitude. By the present state of knowledge this problem has not been solved satisfactorily; it may even be contended that our present technique does not rest on reliable data on the basis of which the results of engine-cooling flight tests carried out at a certain flying speed and air density can be aceurately compared with the diverging conditions.

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*"Contributo allo studio del comportamento in quota dei motori d'aviazione." Reprint of paper presented at meeting of Lilienthal-Gesellschaft für Luftfahrtforschung, October 12-15, 1938, Berlin.

The efforts of numerous able engineers in the attack of this problem have, to be sure, increased our knowledge enormously, but still fall short of generally applicable practical results. The reason for this lies in the fact that the formulas and coefficients are largely dependent upon the cylinder form and cooling fins as well as on the type of cowling used, i.e., on quantities which change from one engine to the next and are subject to continuous modifications and improvements.

The subject of the present report is confined to the investigations and methods employed by the Fiat company in their studies on the altitude performance of an air-cooled engine of the production type. These studies, it should be borne in mind, were not undertaken for the purpose of obtaining scientific data or general formulas, but primarily to assure all the data necessary for uninterrupted and constant progress in the manufacture of the engine and to predetermine the operating characteristics in flight of new types.

The experiments therefore have a more industrial than scientific character; but even so, it is hoped that the description of a complete test program on a modern engine will contribute to the study of altitude performance of aircraft engines.

DESCRIPTION OF TESTS

Experimental Set-Up

The altitude test stand, begun in 1932, (figs. 1 and 2) has already been described elsewhere (Rivista Aeronautica, no. 5, May 1934). Originally designed for water-cooled engines of 1,000 hp. at 5,000 m and for 500 hp. at 10,000 m, and for air-cooled engines of 500 hp. at 5,000 m, subsequent improvements have made it possible to accomodate air-cooled engines up to 1,000 hp. at 5,000 m at air speeds up to 350 km/h.

Test-Engine Data

The engine used for the tests is an air-cooled, 18-cylinder 2-row radial, type A 80 RC 41 (fig. 3) with the following principal characterisitcs:

Bore and stroke	140 x 165 mm
Displacement	45,720 cm^3 2890 in^3
Rated r.p.m.	2,100
Rated altitude	4,100 m
Compression ratio	6.7
Rated supercharge ratio	1.61
Rate boost pressure	735 mm Hg
Rated full power at 4,100 m	1,000 hp.
Peak horsepower	1.100 hp.

The total cooling surface of a cylinder is 0.8930 m^2 divided as follows:

Cooling surface of barrel	0.3650 m^2
Cooling surface of head	0.5280 m^2

The design of the cooling fins and the disposition of the baffles can be seen (fig. 4).

Mounting of Engine on Torque Stand

The engine was mounted on the stand with the same baffles ordinarily used, and so was the cowling. The exhaust collector had the same section as employed on the airplane, in addition to an outside water jacket with which the cooling air was heated from the engine direct.

The cowling was fitted to the outlet opening of the cowling air nozzle by means of a conoid so that the circulating air passed across the cylinders. The engine shaft was connected with the brake by means of an elastic coupling of the same polar moment of inertia as the regular propeller. The original intention was to connect a fan with the coupling so as to give the cooling air the same turbulent motion as afforded by the regular propeller, but was dropped again because of the almost insuperable complications in the measurement of the engine performance.

Particular attention was paid to the instrumental recording of

a) The total pressure in the air inlet duct before the conoid connecting the cowling,

b) The static pressure in the test chamber behind the motor,

c) The total head and the static pressure under the cowling ahead of the cylinders. It was found that this pressure was practically equal to the static pressure and that the velocity effect can be almost completely neutralized or reduced to a simple turbulent motion. The pressure was computed from the records of eight suitably arranged (reference 2) pressure recorders,

d) Total head and static pressure behind the cowling, measured as for (c).

The cited pressure recorders were purported to give the pressures and velocities to which the temperature values during the cooling tests were referred. For comparison with the velocity conditions encountered in free flight, it was decided to assume the velocity between the cylinders, which corresponds to the difference between the total pressure before the conoid and the static pressure downstream from the engine as flow velocity. This is not quite exact, since the pressure difference between entry and exit from the cowling is not merely dependent upon the airplane speed, but also on other factors, such as the cowling form, type of baffles, etc. But for the purpose of our investigations the approximate values obtained on this premise were sufficient. For more accurate appraisals, we refer to figure 5, which gives the pressure difference between air entry and exit from the cowling in relation to the recorded velocity as indicated above.

Other than these instruments, we used

e) Thermocouples and special thermometers for cylinder temperature, cooling air, air intake, mixture temperature at cylinder entry and exhaust gases,

f) An air flowmeter mounted outside,

g) The customary other instruments used on altitude test stands, such as revolution counters, flowmeters, exhaust-gas analyzers, altimeters, pressure gages, etc.

EXPERIMENTS CONCERNING THE HORSEPOWER CHARACTERISTICS

The change in power of supercharged engines in relation to altitude is a problem of capital importance with which numerous investigations within the last few years have been concerned.

The prediction of the power at altitude on the basis of sea-level data is generally achieved by either one of two methods, one derived from English, the other from N.A.C.A. researches and experiments.

The N.A.C.A. method is based on the determination of the sea-level power with open throttle, either measured direct (but under abnormal operating conditions) or, if this is impossible, determined by extrapolation.

The altitude performance is computed from the sea-level data by means of suitable formulas. This method has found widespread use in the United States for the lightly supercharged engines built there during the years, because the low supercharge of the U.S. engines enables, by quick execution of the measurements, the determination of the sea-level power of the engine without mechanical injuries.

In Europe, where for military reasons higher supercharging is customary, the English method has proved more suitable. In this method an altitude depression box is hooked up to the air intake and the power computed with well-known correction formulas.

At times a compound system is employed. The power at rated altitude is determined by the English method, after which formulas starting from the rated altitude give the decrease in power with increasing height.

DISCUSSION OF FORMULAS OF REDUCTION OF POWER WITH ALTITUDE

The best-known formulas are:

$$K = \frac{p_z}{p_o}\sqrt{\frac{T_o}{T_z}} \qquad (A)$$

which rests on the relative air density.

$$K = \frac{P_z}{P_o}\sqrt{\frac{T_o}{T_z}}\left(1 + \frac{\lambda - \lambda\eta}{\eta}\right) - \left(\frac{\lambda - \lambda\eta}{\eta}\right) \qquad (B)$$

(N.A.C.A. Report No. 295)

$$K = \frac{\rho}{\rho_o}\,\frac{1 + \eta K_1 - K_1}{\eta} + \frac{(\eta - 1)(1 - K_1)}{\eta} \qquad (C)$$

(From Devillers: Le Moteur à Explosion 1935)

$$K = \left(\delta - \frac{1 - \delta}{7.55}\right) \qquad (D)$$

(Formula by Gagg and Farrar, SAE Journal, June 1934)

$$K = \frac{p_z}{p_o}\,\frac{529 + 15}{529 + t_z} \qquad (E)$$

(Formulas of the Italian Committee for Aircraft Specifications) Formula E is derived from formula A.

In experiments with a liquid-cooled nonsupercharged engine in the Italian altitude test chamber, the following formula was arrived at:

$$K = \frac{p_z - 60}{700}\,\frac{617 - t_z}{617 - t_o} \qquad (F)$$

(Aerôtecnica, May 1935)

Experiments with liquid-cooled supercharged Fiat engines (A 30 RA and similar) in the altitude test chamber gave the formula

$$K = \frac{p_z - 85}{675} \, \frac{350 - t_z}{350 - t_o} \qquad (G)$$

which resembles F.

From tests on air-cooled supercharged engines tested in the Fiat altitude test chamber the following formula was developed:

$$K = \frac{\rho_z}{\rho_o}\left(1 + \frac{Pmpo}{Pmeo}\right) - \frac{Pmpo}{Pmeo} + \frac{\epsilon z}{Pmeo} \qquad \text{(Fiat)} \qquad (H)$$

Herein:

ρ_z is air density at altitude z

ρ_o, air density at altitude o

Pmpo, mean piston pressure corresponding to the power loss due to parasite resistance in operation with full throttle at altitude o

Pmeo, mean effective piston pressure of engine operating with full throttle at altitude o

z, operating height (km)

ϵ, proportionality factor of equation

$$Pmpz = Pmpo - \epsilon z \qquad (1)$$

The above formula presents the change with altitude of the mean piston pressure corresponding to the power loss at sea level. For the A 80 engine, the value

$$\epsilon = 0.0455$$

was experimentally arrived at.

Formula H rests on the assumption that the mean indicated piston pressures at the various heights are proportional to the respective density, i.e.,

$$Pmez + Pmpz = \frac{\rho_z}{\rho_o} (Pmeo + Pmpo)$$

Substitution herein of the value of equation (1) for Pmpz gives formula (H).

It should be noted that when applying the above formulas the engine power as well as the total power losses at o altitude must be determined.

For the A 80 engine with full throttle at altitude o, a power of 1,625 hp. by a brake mean effective piston pressure (Pmeo) of 15.24 kg/cm^2 and a pressure loss (Pmpo) of 2.44 kg/cm^2 was established.

The potential errors involved in measurements of this kind are deleterious factors in the application of these formulas as regards accuracy.

Figure 6 illustrates the actual power drop starting at the rated altitude of 4,100 m in comparison with the percent of power drop at altitude o computed on the basis of formulas (A), (C), (D), and (H).

The degree of accuracy of the various formulas is readily apparent.

If the power at rated altitude can be obtained direct (either in altitude test chamber or by dynamometer hub in free flight), this power may be used as the starting point of the calculations, beginning with the horsepower at rated altitude instead of with the power at sea level. In this case, the accuracy of the formulas is noticeably greater, as seen in figure 6.

DISCUSSION OF CONVENTIONAL CORRECTION FORMULAS EMPLOYED IN TESTS WITH ALTITUDE DEPRESSION BOX

The formulas in the engine test specifications of the Italian Air Ministry, which are largely patterned after the British (reference 3), stipulate that, to determine the power at altitude z, the power obtained at sea level from an altitude depression box at negative pressure z must be multiplied by the following coefficients:

$$W_z = W_o \times 1 + 0.00063\,\rho^2 (t - t_z) \frac{529 + t}{529 + t_z} \left(1 + \frac{1}{100}\,\frac{760 - p_z}{35}\right) \qquad (2)$$

These three coefficients serve, as is known, at altitude z to account for

a) The increase in the boost ratio of the supercharger

b) The change in temperature of the inducted air

c) The drop in exhaust back pressure.

The method of checking the total error deriving from the application of altitude depression boxes and the relative conversion formulas was as follows:

The engine was tested in the altitude test chamber under the same conditions as in the test with altitude depression box, i.e., at a 760 mm Hg exhaust back pressure and 15° C. intake-air and cooling-air temperature. The charge pressure and the power with full throttle up to 8,000 m were computed by the official formulas. The above cited formulas are valid only up to 7,000 m, while, for the sake of clarity, the tests were made up to 8,000 m.

Subsequently the actual power and the charge pressure under otherwise identical conditions were measured on the altitude test stand under actual conditions of altitude operation.

The findings of the two tests made at normal r.p.m. are compared in figure 7. For other r.p.m. the curves are very similar.

An examination of the curves reveals two very significant facts:

a) The actual power decrease (curve B), beyond the rated altitude differs from that computed on the basis of the test with altitude depression box (curve A).

b) The actual rated boost pressure (735 mm Hg) is considerably below that established on the basis of the formula (765 mm Hg)

c) In spite of this pressure difference the effective power at rated altitude is little different from that arrived at by formula. This indicates that the formulas lead to a substantial minus error and that the relation between boost pressure and amount of mixture inducted into the engine (and hence the engine power) varies considerably on changing from the test conditions in the altitude depression box to the actual operating conditions at altitude.

The verification of the change of this relation and of the accuracy of the individual factors of the correction formula are treated next.

EFFECT OF DECREASE OF EXHAUST BACK PRESSURE

In nonsupercharged engines a reduction in exhaust back pressure is synonymous with an increase in effective displacement and hence in the horsepower, which is a function of the difference between intake pressure and exhaust back pressure.

In supercharged engines the variation in power is more complicatedly connected with this pressure difference. A change in pressure, owing to decrease in back pressure, of the burned rest gases in the cylinder changes at the instant of inlet-valve opening the conditions on the outlet side of the supercharger and hence it operating conditions. A change in air volume and boost ratio result, i.e., the supercharger operates at a different point of its characteristic power curve.

The increased engine power represents the algebraic sum of the following factors:

a) Power gain resulting from greater cylinder charge,

b) Change of power absorbed by supercharger through increased volumetric output,

c) Gain due to changed pumping cycle.

Two important observations follow herefrom, namely:

a) It is not correct to employ the same formulas for engines with and without superchargers,

b) The test specifications make no allowance for the change in intake pressure resulting from the changed delivery volume at the different exhaust back pressures.

Since this change in boost pressure is a function of the delivery volume, it naturally is dependent upon the type of supercharger. From this it becomes clear that it is very difficult to establish a formula of general validity accurately enough for all engines.

The above cited pressure change, which has also been treated by Gagg and Farrar (reference 4), afforded an explanation for many abnormal phenomena during the testing of carburetors with diffusers of different diameters on the Fiat altitude test stand; it also explains the deficiency in effective charging pressure observed on many engines in relation to that obtained by formula, which is particularly noticeable in climbing where the auxiliary action of the dynamic pressure is lower.

VARIATION OF CHARGE PRESSURE IN RELATION TO EXHAUST BACK PRESSURE

For the determination of the effect of exhaust back pressure on the charging pressure, the procedure was as follows: At 760 mm Hg. exhaust back pressure the engine was so regulated that the charging pressure at altitude with full throttle and a constant intake temperature of 15° C. amounted to 800 mm Hg. The throttle was locked in that position and the back pressure lowered by stages while the charge pressure was measured.

The charging pressure range from 800 to 500 mm Hg. was plotted which gives the decrease in charging pressure in relation to the back pressure (fig. 8).

These curves disclose that the decrease in back pressure is followed by an increase in delivery volume and simultaneously by increased engine power, while the charging pressure drops almost proportionally to the increase in delivery volume.

The drop in charging pressure follows along a very flat curve, approaching at great heights the abscissa asymptotically. This is indicative of a consistent decrease in the effect of the back-pressure reduction with decreasing back pressure; it approaches zero when the exhaust back pressure becomes zero (absolute vacuum). Up to 6,000 or 7,000 m the curve remains practically linear, which greatly facilitates the development of a correction formula and this allows for the effect of the too high exhaust back pressure in test with altitude depression box.

The correction factor is a function of charge pressure and altitude, from the equation for the rectilinear part of the curves in figure 8 the correction factor

$$= 1 - \frac{z}{1000}\,\frac{250 + P_o}{250\,P_o} \qquad (3)$$

where z is operating height

P_o, boost pressure at altitude o.

This formula holds only for engines with supercharger characteristics similar to those of the A 80 type, since the boost pressure decrease is intimately related with the type and the operation conditions of the supercharger.

Discrepancies of about the same order of magnitude were observed in the altitude chamber tests of 7 and 9 cylinder radials of different design from the A 80.

CHANGE OF ENGINE POWER IN RELATION TO EXHAUST BACK PRESSURE

To establish the formula for computing the change in horsepower in relation to exhaust back pressure, the engine was operated at various back pressures, while all other factors controlling the power change, such as r.p.m., boost pressure, mixture ratio, etc., were kept constant. These tests were made for the whole practical range of boost pressures, and the results plotted for altitudes up to 8,000 m (26,250 ft.) at constant r.p.m. (2,100) and constant induction temperature (15° C.) (fig. 9). The tests were so carried out that in the recording of the curves only one variable was changed at a time.

Admittedly this method afforded only individual points, but the chosen r.p.m. ranges were characteristic and the uniformity of the test values constituted an important check on the accuracy of the measurements.

The plotting of the test curves for different heights is, besides, of great importance because it enables one to determine the engine power at throttle r.p.m. (cruising speed), where the formulas for the power decrease and the formulas for power computations based on altitude depression-tank tests are inapplicable.

Figure 9 indicates a different rise for the curves plotted at different heights under altitude conditions and also that the engine requires by increasing altitude a lower boost pressure for the same power output. For that reason it is not possible to compute the actual course of the calibration curves at altitude on the basis of sea-level test data nor from formulas. These calibration curves were developed by the Fiat Company and applied to all altitude engine testing (reference 5).

It affords the double advantage of obtaining valuable data for flight testing as well as a simple method of studying the effect of the different factors governing horsepower at altitude. Figure 10 shows the engine power plotted against the exhaust back pressure for different boost pressures. As far as 7,000 m the curves are approximately linear. Applying to each of these straight lines a formula similar to that given in the official test specifications the correction factors for the different boost pressures are as follows:

For 800 mm boost pressure: $K = 1 + \dfrac{1}{100}\,\dfrac{\Delta p}{36.3}$

For 750 mm boost pressure: $K = 1 + \dfrac{1}{100}\,\dfrac{\Delta p}{31.55}$

For 700 mm boost pressure: $K = 1 + \dfrac{1}{100}\,\dfrac{\Delta p}{27.02}$

For 650 mm boost pressure: $K = 1 + \dfrac{1}{100}\,\dfrac{\Delta p}{22.93}$ 28,3

For 600 mm boost pressure: $K = 1 + \dfrac{1}{100}\,\dfrac{\Delta p}{19.46}$ .305

For 550 mm boost pressure: $K = 1 + \dfrac{1}{100}\,\dfrac{\Delta p}{16.00}$ .340

For 500 mm boost pressure: $K = 1 + \dfrac{1}{100}\,\dfrac{\Delta p}{13.16}$ .350

The formulas differ merely by a numerical value in the denominator. The formula given in the test specifications and containing only the numerical value 35, is therefore not applicable for all operating conditions of the engine, but merely for boost pressures around 760 mm for which it was established. At lower boost pressures the formula gives too low , at higher boost pressures, too high values.

To make the formula applicable for all boost pressures, the denominator must be made a function of the boost pressure instead of a constant.

Figure 11 gives the change in the denominator term in relation to the boost pressure. Writing the equation for this curve in the formula of the test specifications gives a formula applicable to any other boost pressure P_a.

Correction factor =

$$1 + \frac{760 - h_z}{2295 + 7.55\ (P_a - 650) + 1.52\ (P_a - 650)^{0.92}} \qquad (4)$$

This correction factor allowing for the exhaust back pressure has proved satisfactory for engine types similar to the A 80.

EFFECT OF INDUCTION PRESSURE ON ENGINE HORSEPOWER

Tests of Fiat engines with natural aspiration in the altitude test chamber indicated that the power correction formula can be suitably expressed by

$$K = \frac{350 - t_z}{350 - t_o}$$

The approximate results with this formula are much better than are obtainable with

$$K = \sqrt{\frac{273 + t_o}{273 + t_z}}$$

or with the official Italian acceptance test formula

$$K = \frac{529 + t_o}{529 + t_z}$$

Subsequent tests with supercharged engines disclosed that for this type no general formula, which reproduces the change in engine power in relation to the temperature of the aspirated air alone with sufficient accuracy, can be established for the reason that the power of the supercharged engine is not dependent upon the temperature of the inducted air but on that of the mixture entering the cylinders, i.e., on the density of the charge. The mixture temperature depends upon the following factors:

a) temperature of inducted air

b) temperature rise due to the work of the supercharger

c) cooling due to evaporation of fuel

d) heat input of the oil circulation through the walls of the supercharger

e) cooling due to the outside air through the outside walls of the supercharger and the gas leads to the cylinders

f) heating of mixture in the induction pipes in proximity of the cylinders because of conduction, convection, and friction.

Since the mixture temperature is the resultant of all these factors no constant proportionality with the temperature of the inducted air is possible, and as a result the correction factor for engine power cannot be made exclusively a function of the air temperature. In consequence, to establish this relation the correction factor must be changed according to height and induction pressure.

The height effect can be eliminated by referring the correction factor to the mixture temperature instead of to the temperature of the inducted air.

This factor is suitable, however, for comparative tests but not for correction formulas intended for the calculation of the altitude performance of an engine at altitude temperature on the basis of depression-tank tests and of intake-air-temperature measurements. So long as the formula is applied to the temperature of the inducted air, both values appearing in the formula are known, i.e., the temperature of the outside air which can be measured, and the air temperature at altitude which is assumed to be equal to the standard air temperature for this altitude. But the use of a formula based upon the mixture temperature lacks the altitude reference values. Depression-tank tests afford the mixture temperature at sea level but not at altitude, which is dependent upon the factors cited under a) to f).

In our tests on the A 80 engine the effect of changes in intake-air temperature on the power in operation under normal air conditions at rated altitude was investigated.

Calibration curves for varying inlet-air temperature at full throttle (fig. 12) were plotted, and the curves (fig. 13) giving the power in relation to the mixture temperature at constant boost pressure, derivated. Figure 14 follows from figure 13. It gives the change in correction factor K when value 1 (base point for the corrections) corresponds to 15° C. inlet-air temperature.

Figure 15, giving the correction factor plotted against the temperature of the inlet air, was obtained in the samo manner.

The correction curve is seen to be much more uniform when referred to mixture temperature than if referred to the inlet-air temperature.

The correction percentage decreases with the charge pressure. Figure 15 indicates at the same time a comparison with the values obtained on the basis of the official specification formula

$$K = \frac{529 + t_o}{529 + t_z}$$

From figure 14 a linear relation giving the change in correction factor K in function of the mixture temperature can be deduced, while from figure 15 a much more complicated formula results for K.

CORRECTION FORMULA FOR THE BOOST RATIO

In the study of the effect of inlet-air temperature on the supercharge ratio, the engine was operated at rated altitude and the change in supercharge ratio measured between -40° and $+40^\circ$ by changing inlet-air temperature.

Mixture ratio, cylinder temperature and all other factors of potential influence on the supercharge ratio were kept constant.

In the attempt to define the change in supercharge ratio by means of a formula similar to the well-known

$$1 + 0.00063\ \rho^2 (t - t_z)$$

it was found that the numerical value for the rated height is 0.00045 rather than 0.00063 (fig. 16).

To check the effect of the suction head on the supercharge ratio, the suction pressure at full throttle was gradually reduced - starting at 4,100 m - to a value corresponding to that of 8,000 m altitude, whereby the supercharge ratio was found to increase with altitude, as shown in figure 17.

Figures 8, 16, and 17 illustrate the change in supercharge ratio under changing air conditions of the engine.

CONCLUSIONS FOR THE PERFORMANCE DETERMINATION

From the foregoing test data it is clear that the formulas in the present test specifications are no longer applicable to modern engines.

In the Fiat factories every engine type was subjected to tests similar to those described, and correction formulas or curves established which were satisfactorily applicable to engines of similar design.

The Fiat method is as follows:

a) The engine, receiving the inlet air from a depression tank, operates at an induction pressure corresponding to altitude z: the charge pressure is recorded.

b) The charge pressure is corrected according to formula 3, giving the pressure corrected for reduced exhaust back pressure effect.

c) The supercharge ratio is computed and corrected for temperature effect according to the known formula by applying a suitable correction factor; it affords the true charge pressure at altitude z.

d) Read from the sea-level calibration curve the sea-level power at the real charge pressure corresponding to altitude z as established in (c).

e) Correct this power with the factor given in formula (4), which gives the power corrected for exhaust back pressure.

f) Reduce this performance in accord with the air-fuel temperature (fig. 14) or the inlet-air temperature (fig. 15), which gives the true power at altitude z.

This method is very advantageous for normal torque-stand use because it enables computation of the power at altitude from torque-stand tests by means of the calibration curves without having to resort to measurements on a dynamometer brake.

If the test is made on a dynamometer brake the procedure is reversed, i.e., the sea-level power at charge pressure corresponding to altitude z is measured on the basis of the calibration curves, followed by (e) and (f).

ENGINE COOLING

The factors governing the cylinder temperature of an engine may be classified into:

a) Factors governed by engine design:

1. Engine diameter and cylinder arrangement

2. Design and dimensions of cooling fins

3. Design of cowl (baffles and N.A.C.A. cowling)

b) Factors governed by loading of engine:

1. Indicated horsepower developed in cylinder
2. Air-fuel ratio and type of fuel used

c) Factors governed by atmosphere:

1. Speed of cooling air
2. Temperature of cooling air
3. Density of cooling air
4. Temperature of inlet air

d) Factors governed by (a), (b), and (c):

1. Mixture temperature

In our altitude chamber tests, the factors cited under (a) were disregarded since they already had been established in the design, neither did we explore the absolute effect of every single effect for itself, but rather attempted to study the actual behavior of the engine at altitude.

First we studied the relationship existing between spark plug and cylinder-flange temperature and the mean cylinder temperature.

The cylinder temperature of an engine is, in general, gaged by the temperature of the spark plugsand that of the cylinder flange.

In some engines where the spark plugs are especially cooled (for instance, by lateral arrangement on the cylinder), it is standard practice to mount thermocouples at the rear portion of the cylinder head, that is, at the points considered characteristic of the mean cylinder temperature by the designer.

On the A 80 the rear spark plugs are in fact the hottest part of the cylinder and the rear of the cylinder flange the hottest part of the cylinder barrel, which are therefore fitted with thermocouples intended as a check on the engine cooling in flight as well as on the torque stand.

The method of exploring the relation between the rear spark-plug temperature and the mean barrel temperature was as follows:

While the engine was operated at constant air-fuel ratio and constant rate and temperature of cooling, the temperature was recorded with thermocouples at different loads. To avoid interference with the flow of cooling air at the fins the thermocouples were not all mounted at once, but in several stages. Figure 18 shows a cylinder ready for such a test. By averaging the temperature readings and proportional distribution of the cooling surface covered by each thermocouple the mean temperatures were established.

In this manner the curves of figure 19 were obtained, which show the temperature of the rear spark plug and of the flange plotted against the mean cylinder-head temperature and the mean barrel temperature.

The same measurements were repeated on the altitude test stand with a smaller number of suitably distributed thermocouples. It was found that the relation shown in figure 19 remains applicable without excessive error up to heights of 8,000 m for standard air and speeds between 200 and 350 km/h (125 - 217 m.p.h.)

It was found that pressure and temperature changes of the outside air have an identical effect at any point of the cylinder.

Changes in air speed increase the temperature difference between front and rear cylinder portions. The mean cylinder temperature rises a little faster with altitude than the spark plug temperature, although it causes no perceptible change in the curve of figure 19 at the speeds and heights in question.

To determine the mean temperature increment the air-outlet temperature at the cylinder-head baffles and barrel as well as the mean air-outlet temperature at the cowling aft of the engine were recorded separately. Of course, this temperature included the temperature rise due to heat dissipation from the crankcase.

The temperature measurements at the cylinder head and barrel are quite inaccurate, since the radiation of the cylinder itself affects the thermocouples. For this reason the mean temperature difference of the cooling air between entry and exit from the cowling was assumed in first approximation as mean temperature increment between cylinder and cooling air.

COOLING TESTS

These comprised chiefly the total change in cylinder temperature with increasing height in standard air and constant cylinder output, the cooling air temperature in standard air being varied in stages of 1,000 m from sea level to 8,000 m. To keep the indicated power constant the inlet temperature, the air-fuel ratio, the engine r.p.m., the charge pressure, and the back pressure were kept constant.

As the cylinder temperature drops the effective power drops despite constant charge pressure as a result of the increasing friction losses and the mixture temperature, thereby causing a reduction in indicated power.

This power loss can be avoided by so changing the inlet temperature that the volume and hence the indicated power remains constant. It was therefore assumed that at constant charge pressure the indicated horsepower could be considered constant. Moreover, the cited power changes are not so great as to cause an essential change in the obtained mean temperature records.

To afford at the same time the facility of exploring the effect of speed changes, the speed of the cooling air was changed in 25 km stages at every altitude between 200 and 350 km/h. The charge pressure was varied at every speed value and the correlated cylinder temperature recorded.

The execution of such tests is quite difficult and exacts great demands on the patience since the thermocouples used for the cylinder temperature records are very apt to yield errors of the order of magnitude of 2° to 3° and imperceptible changes in the constant factors can cause appreciable variation in the cylinder temperatures.

After tedious and exacting tests the curves (fig. 20) were obtained. They give the mean spark plug temperatures from sea level to 8,000 m in relation to the air speed at constant charge pressure (constant cylinder output) for all practical charge pressures of the A 80 engine.

From figure 20 follows figure 21, which gives the change in spark-plug temperature in relation to the air density at constant horsepower and constant speed. It will be noted that the temperature rise becomes so much greater as the air speed decreases. Moreover, it drops rapidly with the density. Figure 22 gives the temperature change at constant horsepower plotted against the air speed at different heights and standard air. The temperature decrease is seen to increase with altitude as a result of increasing speed.

In addition, we studied the actual cooling conditions in the engine with increasing height in standard air, constant charge pressure, and an effective output corresponding to curve B in figure 7. To simulate actual conditions as closely as possible the speed was changed proportionally to the third root of power and in the inverse ratio of the air density.

Figure 23 shows the temperature distribution of the rear spark plug of a cylinder which is characteristic of the mean temperature of all rear spark plugs.

The firs test was made by starting from normal charge pressure of 760 mm Hg and raising the altitude beyond the rated altitude up to 8,000 m with full throttle. Curve C in figure 23 indicates the computed speeds for each altitude stage.

The second test was made by starting from a 500 mm charge pressure and increasing the height, while keeping the charge pressure constant, until the throttle was wide open. The correlated speeds are shown as curve D.

The spark-plug temperature increases up to the rated power altitude where the peak output occurs; above it, it decreases.

Figure 24 gives instead of the spark-plug temperature the temperature increment between cylinder and air recorded in the test as difference between mean cylinder temperature and mean temperature difference of the air entering and leaving the cowling.

The mean temperature increment between air and cylinder is seen to increase steadily throughout the investigated height of 8,000 m. The change in the mean temperature increment between sea level and rated power altitude follows a law different from that between rated power altitude and the highest experimentally obtained altitude.

The change in mean temperature increment was studied for the normal as well as for 500 mm charge pressure. Figure 24 includes the temperatures recorded at entry and exit of the cowling. These curves give a complete picture of the engine behavior at altitude, so that no further cooling tests on the A 80 were necessary.

Mention should also be made of the change in spark-plug temperature in relation to the outside temperature at constant power, height, and speed, as obtained on single-cylinder models of the same design at 0.83° for 1° change in outside temperature. Although this law of change could not be checked very accurately in the engine test, various trial tests seem to confirm it.

As a result of these experiments on the altitude test stand it should be borne in mind that the power of an air-cooled engine is no little affected by the cooling conditions of the engine. Even though we are unable to give the laws governing the change in power in relation to spark-plug and oil temperature, it still remains a fact that under otherwise identical conditions the power of an engine in flight is dependent also on the type and the design of its cowling.

REMARKS AND CONCLUSIONS

In conclusion, it may be practical to touch upon the general points of view of the torque-stand engineer in his methods and means of defining the characteristic curves of altitude engines.

For moderately supercharged engines on which the determination of the power output with full throttle can be established at sea level, the experimental formulas of Gagg and Farrar, Fiat, and other give the horsepower curve with certain approximation; they can therefore be of practical use to the test engineer.

On fully supercharged engines where the direct determination of the sea-level power with full throttle is impossible, these formulas lead to uncertain results, unless the power can be exactly measured at any height in an altitude test chamber or, when in flight, by dynamometer hub.

The method employing an altitude depression tank and a corresponding correction formula does not appear to be quite suitable in its present form for altitude engine testing. As regards the applicability of the various coefficients contained in the correction formulas, the experiments on the altitude test stand manifest the following:

$$\left.\begin{array}{l}\text{Correction factor for the}\\ \text{effect of the lacking back}\\ \text{pressure on the power}\end{array}\right\} = 1 + \frac{1}{100} \times \frac{760 - p_z}{35}$$

This formula is applicable to altitudes up to 6,000 m and charge pressures of around 760 mm, but beyond these figures it makes no allowance for the change in charge pressure.

The numerical value in the denominator is dependent upon the charge pressure and on the type of supercharger.

$$\left.\begin{array}{l}\text{Correction factor for}\\ \text{inlet-air temperature}\end{array}\right\} = \sqrt{\frac{273 + t}{273 + t_z}} \quad \text{or} \quad \frac{529 + t}{529 + t_z}$$

This formula affords approximately correct values for pressures of around 700 to 760 mm and small temperature changes, but introduces great errors at other pressures and great temperature changes. The accuracy of the formulas varies, moreover, with the supercharger characteristics and the air temperature within which the engine operates.

$$\left.\begin{array}{l}\text{Correction factor for super-}\\ \text{charger compression ratio}\end{array}\right\} = 1 + 0.00063\ \rho\ (t - t_z)$$

The formula gives sufficiently exact values for heights up to 4,000 to 5,000 m. Above these the value of the numerical factor, which to a certain extent is dependent upon the type of supercharger and the compression ratio, varies.

The altitude chamber tests have made it possible to establish new formulas and factors which, when applied to the test values obtained from altitude depression-tank tests, give the altitude performance of an engine fairly accurately.

On the other hand, the Fiat experiments disclosed that the numerical values of the correction formulas change considerably with the peculiarities of different engines due to design.

Hence, to maintain the method involving the use of an altitude depression tank would necessitate the classification of the engines into several types (for instance, into liquid-cooled engines with 12 cylinders, air-cooled engines with 18 cylinders and superchargers of design x, as well as with superchargers of type y, etc.) and then write into the formulas for each class the numerical values previously obtained on the altitude test stand for an engine of this same class.

However, this method is not simple and is fraught with danger of dispute and controversial opinions between manufacturer and test stations.

Even though the obtained formulas are more accurate than those in the official test requirements, their potential use is limited and susceptible to error under different outside operating conditions of the engine. Hence it should not be hoped that altitude chamber tests could yield correction formulas of general applicability and precise accuracy.

But the method using an altitude depression tank should be abandoned in favor of direct tests on torque stands with reduced exhaust back pressure and cooled inlet air.

The costs of installing and operating such plants are not excessive; besides, it should be borne in mind that engine manufacturers will be forced to erect such plants within the next few years in order to be able to predict the characteristic curves of substratosphere engines.

The absence of exhaust back pressure and cooling of the air not only renders all studies about the cooling behavior at altitude difficult, but is also the source of many errors during the determination of the horsepower curves. The errors are in many cases negligible if an altitude test chamber is used, or at any rate substantially smaller than by the altitude depression-tank method.

Although no accurate and specific investigation has been made on the subject, it is nevertheless of interest to point out the discrepancies brought out in the Fiat altitude test chamber on operating the same engine once in cooled air at low pressure and then at normal sea-level pressure and temperature. The principal difficulties attributable to the absence of depression were as follows:

1. Penetration of oil in the cylinder at the piston rings and valve guides because of the greater outside pressure,
2. Leakage of oil past the labyrinth packing of the supercharger (may be eliminated by an energetic blast of compressed air through the air vents of the labyrinth packing),
3. Faulty operation of carburetor due to air seeping into the chamber of the membrane and into the casing, hence abnormal fuel consumption at altitude.

The absence of outside cooling had the following effect:

4. Change of mixture temperature at cylinder inlet as a result of less heat radiation from the supercharger casing and the mixture pipes. The result was higher mixture temperature than when the engine operates at correct air temperature at altitude. In consequence the recorded adiabatic efficiency of the supercharger is lower than under actual altitude conditions. The error varies for every engine and depends upon the location of the supercharger and the area exposed to the air. In general, it may be stated that this error is greater in liquid-cooled engines where the supercharger is more exposed to the outside air influences than on radial engines where the temperature of the supercharger walls is practically kept constant by the oil circulation and the cowling.

All these difficulties are avoided if the torque stand permits the production of depression and the cooling of the outside air. The expense of installation and operation is not very much greater than for a torque stand which permits only the production of depression in the inlet and exhaust.

At the present rate of development engines of 1,000 hp. at 10,000 km altitude are feasible within the near future.

The design of test plants where such engines could be tested under actual altitude conditions presents no difficulties so long as it relates to liquid-cooled engines. The air input of an engine of this horsepower is around 3,100 kg/h and the weight of exhaust gas about 3,250 kg/h.

The inducted air can be cooled to -50° (temperature of standard air at 10,000 km) in three stages - the first two - to about -35° - might be designed as spray cooler with intermediate refrigerating agent, the third, would raise the temperature to -50° by means of an expansion turbine.

The refrigerator for the first two stages would have to be designed to develop about 100,000 cal/h, requiring an input of around 80 to 100 hp. for cooling the intermediate agent.

The removal of the exhaust gases would require a multistage turboblower of about 400 hp.

To reproduce the atmospheric conditions the engine would have to be installed in a cooled depression chamber capable of evacuating the heat given off by the engine. The amount of heat removal depends on the design of the engine. By creating an energetic air current in the chamber the conditions encountered in free flight can be closely simulated, but the amount of heat removal is also increased considerably. It is therefore better to install a low-power air-agitating device designed simply to improve the heat transfer between engine and refrigerating elements. This would avoid abnormal changes in the heat balance of the cooling water and the oil between tests under sea-level and altitude conditions. The cooling of the engine chamber would have to be effected by direct expansion, by means of a central, noninflammable refrigerant, such as Freion, for instance. The theoretical maximum cooling power is about 250,000 cal/h, requiring around 150 hp.

But the conditions are altogether different for an air-cooled engine of the same horsepower. Based on the present installation of the Fiat company, the characteristics of a refrigerating plant for testing a 1,000-hp. engine in standard air at 10,000 m would be as follows:

To begin with, the pressure difference between air inlet and exit from the cowling must be great enough to be equivalent to a flying speed of at least 600 km/h (372 m.p.h.). This requires a fan-shaft power of about 700 hp.

for an air circulation of around 35 kg/s. With a fan having two adjustable propellers, the speed and volume of the air could be regulated at will. Assuming the test chamber to be made of metal and of the dimensions similar to that of the Fiat company, the refrigerating plant for the cooling of the circulating air in two stages would be about as follows:

The first stage with ammonia compressors and brine as refrigerant would lower the air temperature to about -20°; the second stage with a refrigerator with expansion direct in the refrigerating chamber would lower it from -20° to -50°. Figured on the basis of a heat removal of around 825,000 cal/h from engine to cooling air a heat production of around 450,000 cal/h due to the fan and a radiation loss of the engine chamber of around 40,000 cal/h the total refrigerating capacity to be supplied by the refrigerating plant is of the order of 1,315,000 cal/h. This corresponds to a power input of compressor and its auxiliaries of around 800 hp., with a first-stage refrigerating capacity of at least 1,900,000 cal/h and an engine output of 900 hp.

The maximum figures quoted above indicate that such a plant is far beyond the range of an industrial plant and can be owned and operated only by a large scientific institute.

With such experimental equipment it would be possible to study on different types of engines the laws of horsepower variation, the knowledge of which would enable the engineers of the various manufacturers to check their own data obtained on simple test stands operating only with inlet and exhaust depression. The same holds for the cooling data which could serve as standards for the preliminary calculation of the cooling capacity of newly developed engines as well as for the interpretation of flight tests. In flight tests the calibration curves obtained on depression test stands are particularly valuable for the computation of the power output to which the measurements of consumption, speed, temperature, etc., must be referred.

Dynamometer hubs and torque-reaction devices incorporated in the engine assure greater instrumental accuracy and represent a real progress in this direction. I would recommend these instruments to the particular attention of design engineers, since their application should increase within the next few years.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

REFERENCES

1. Ragazzi, P., and Righetti, F.: Le Prove in Quota dei Motori d'Aviazione. Rivista Aeronautica, vol. 10, no. 5, May 1934, pp. 268-325.

2. Kiel, G.: Total-Head Meter with Small Sensitivity to Yaw. T.M. No. 775, N.A.C.A., 1935.

3. Schedule of Standard Type and Production Tests for Aircraft Engines. Air Pub. 840, App. A, Air Ministry (British), May 1925 (4th ed.).

   Pettitt-Herriot, J.: Testing Supercharged Engines. Aircraft Eng'g., vol. 2, no. 22, Dec. 1930, pp. 300-04.

4. Gagg, R. F., and Farrar, E. V.: Altitude Performance of Aircraft Engines Equipped with Gear Driven Superchargers. S.A.E. Jour., vol. 34, no. 6, June 1934, pp. 217-25.

5. Ragazzi, Paolo, and Maiorca, Salvatore: Note on the Systems of Computing the Engine Power at Altitude. L'Aerotecnica, vol. 18, no. 5, May 1938.

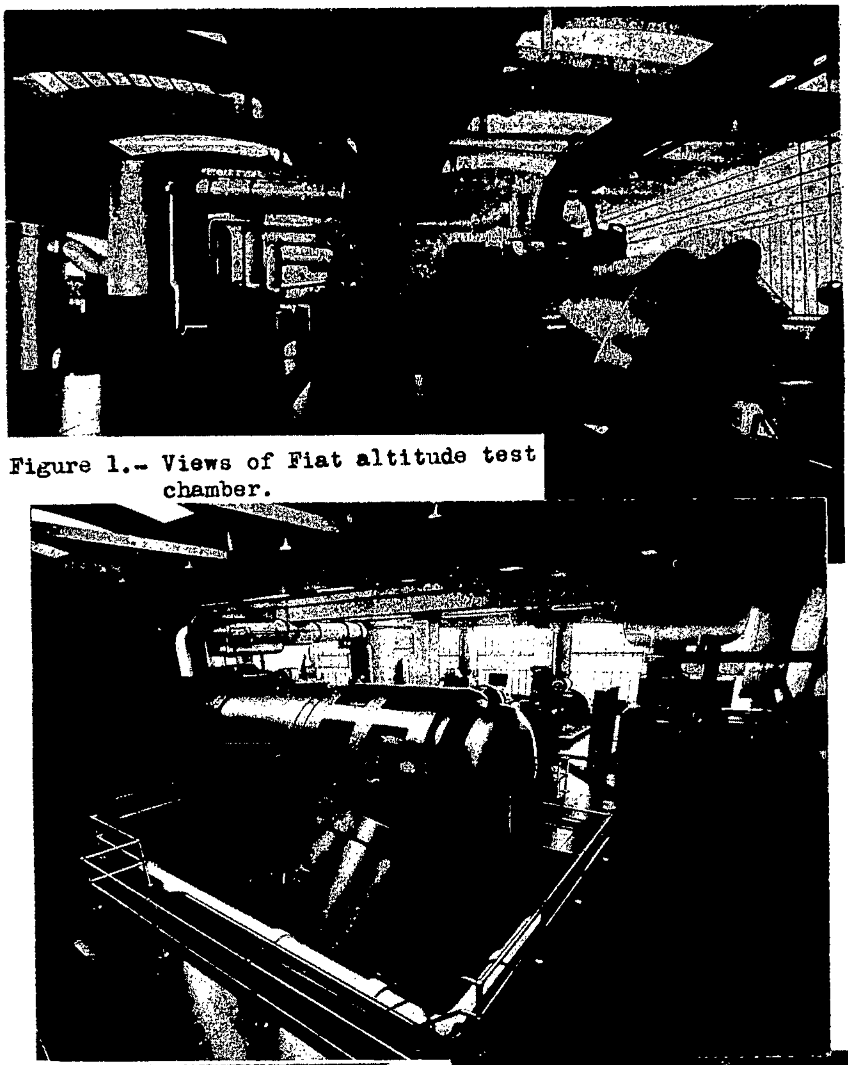


Figure 1.- Views of Fiat altitude test chamber.

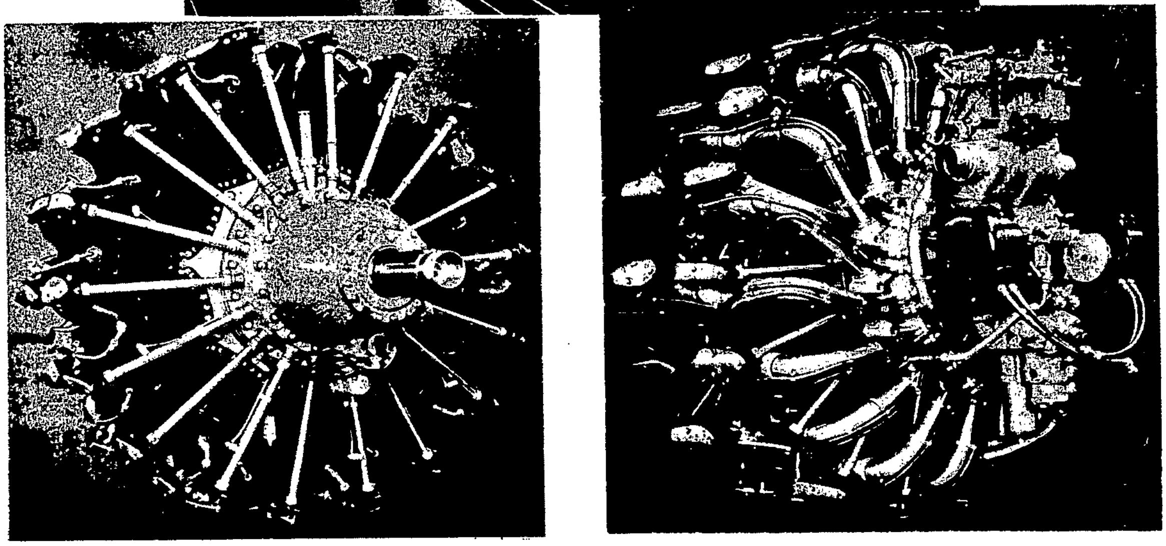


Figure 3.- The Fiat A80RC41 engine.

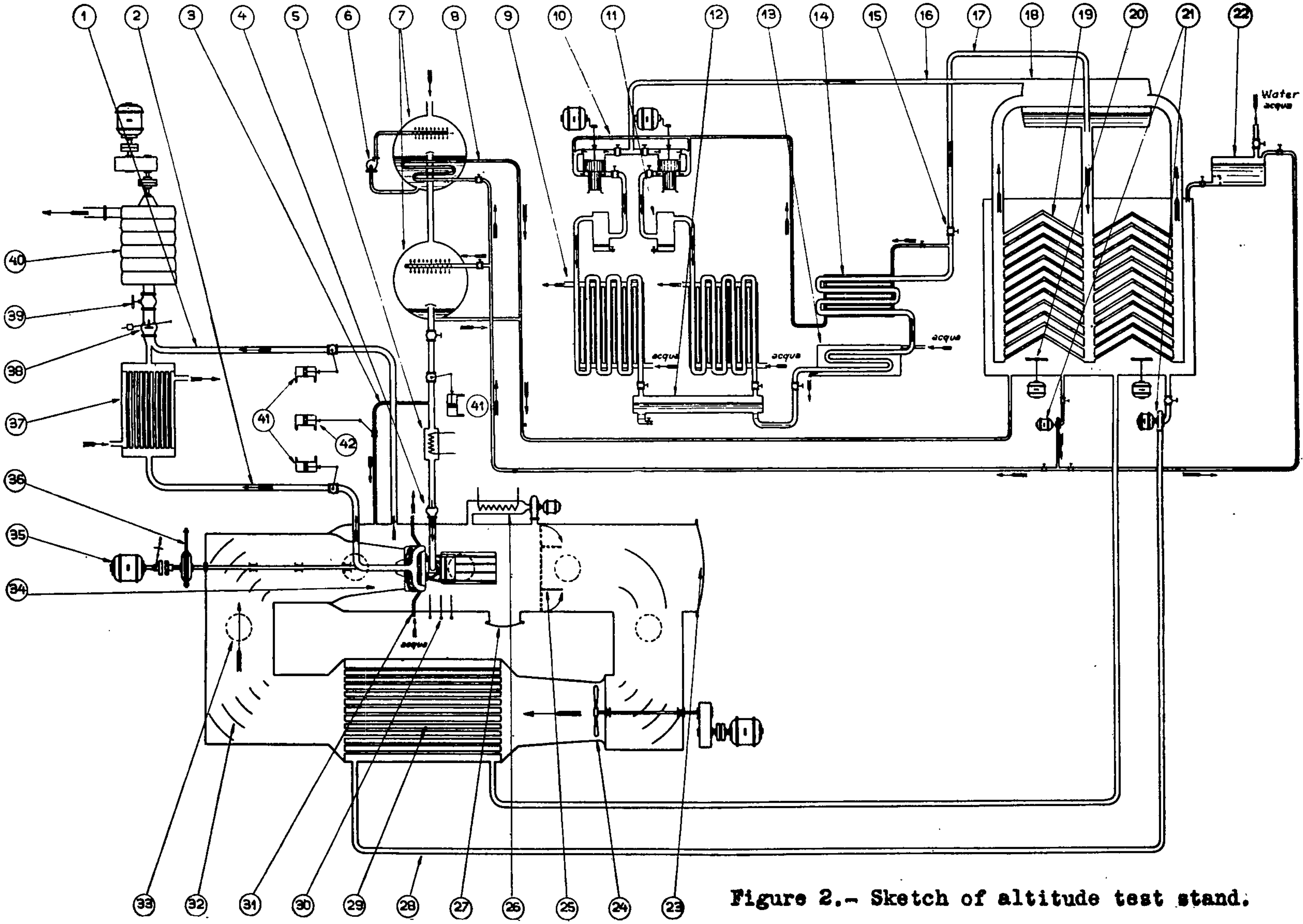


Figure 2.- Sketch of altitude test stand.

1. Test-chamber vent
2. Exhaust pipe
3. Supplementary air line for altitude change
4. Throttle valve
5. Rheostat for inlet air
6. Water circulation pump
7. Cooling towers for inlet air
8. Brine circulating pipe
9. Condenser
10. Compressors
11. Oil separator
12. Liquid ammonia tank
13. I additional condenser
14. II " "
15. Main regulator
16. Ammonia vapor pipe
17. Liquid ammonia pipe
18. Separator
19. Ammonia evaporator
20. Ventilator
21. Brine circulating pump
22. Brine filter and inlet
23. Main door
24. Blower
25. Movable partitions
26. Rheostat for outside air of engine
27. Manhole
28. Brine circulating line
29. Air cooler
30. Main operating post
31. Cooling-water collector pipe
32. Deflectors
33. Safety valve
34. Test chamber
35. Dynamometer brake
36. Hydraulic brake
37. Exhaust-gas cooling tower
38. Throttle valve
39. Starting valve for turboblower
40. Turboblower
41. Servomotors for altitude control
42. Servomotors for lowering the depression

Figure 2 (Parts)

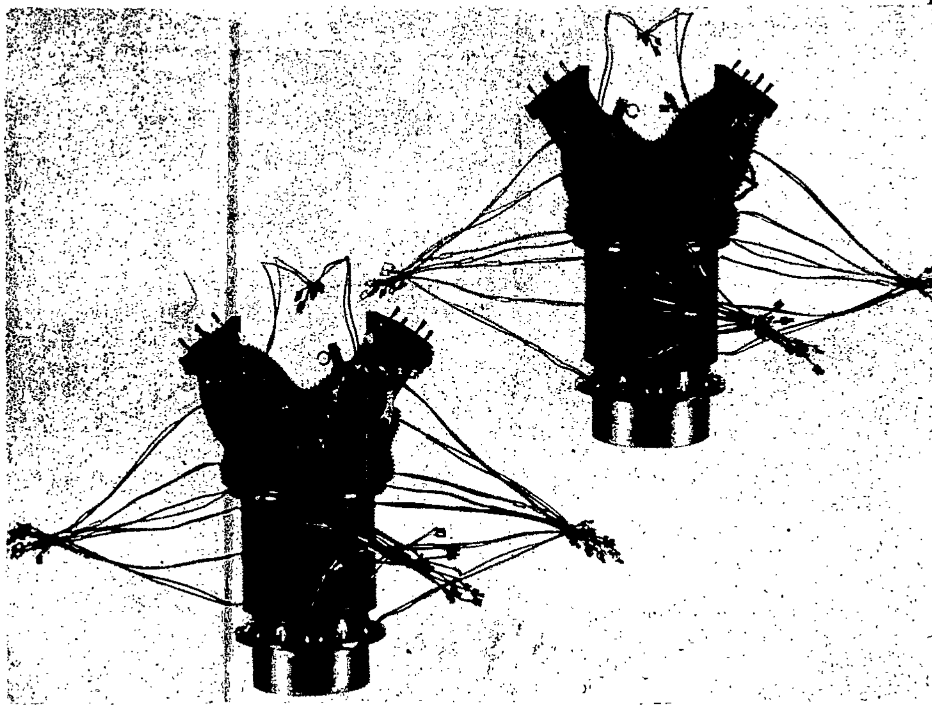


Figure 18.- Distribution of thermocouples for recording the mean cylinder temperature.

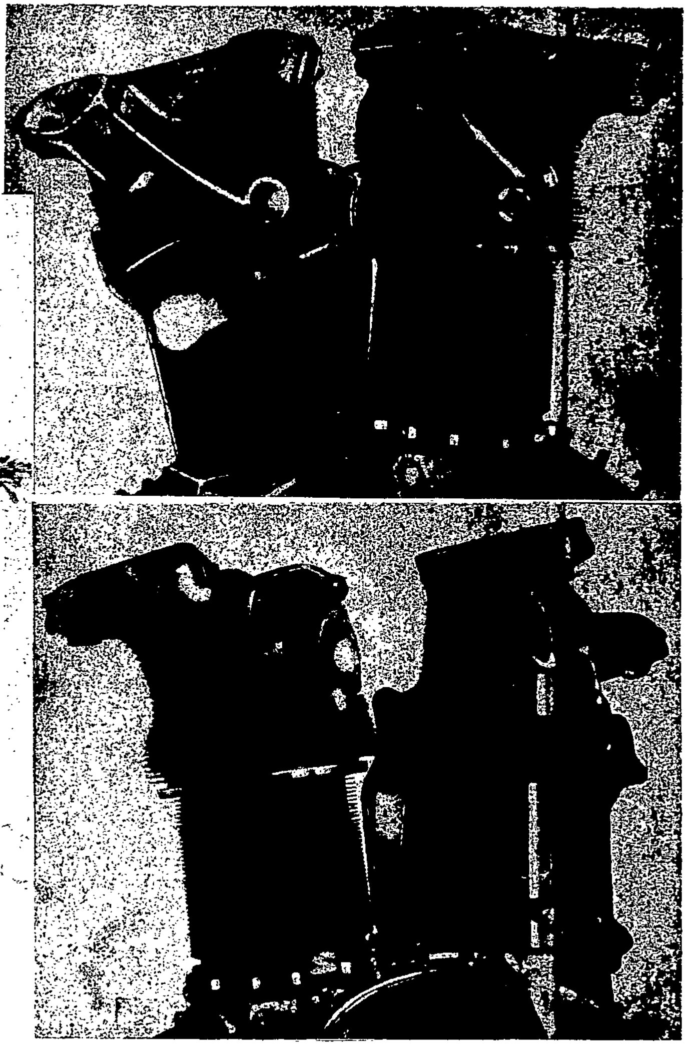


Figure 4.- Cylinder and baffles of the A80RC41 engine.

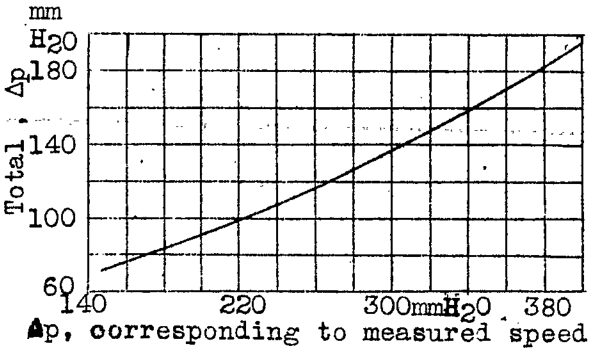


Figure 5.- Relation between pressure jump corresponding to the usual speed measured in the altitude test chamber and the total pressure jump between entry and exit from the cowling.

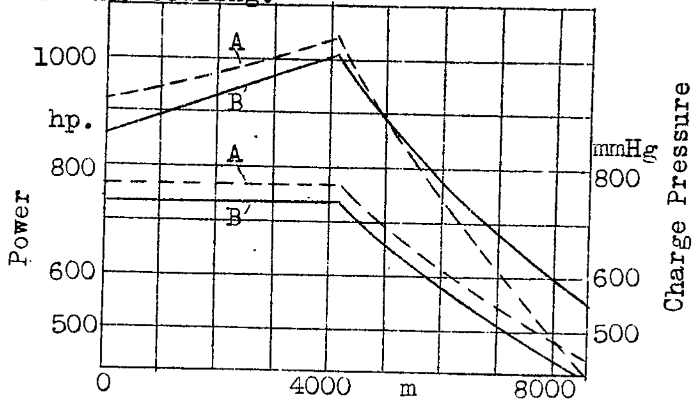


Figure 7.- Change of hp. and feed pressure at full throttle against altitude. Vacuum tank measurements versus altitude test chamber.

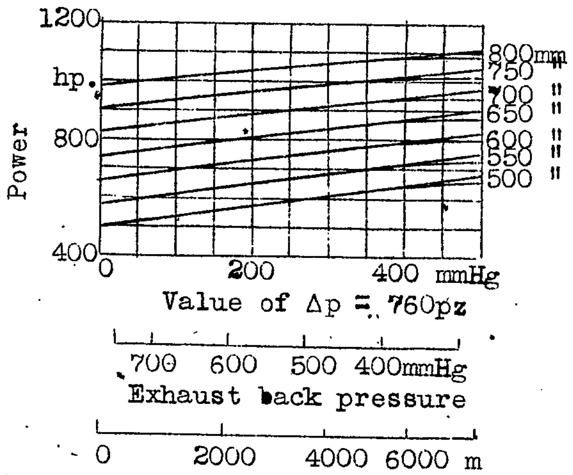


Figure 10.- Variation of power against exhaust back pressure.

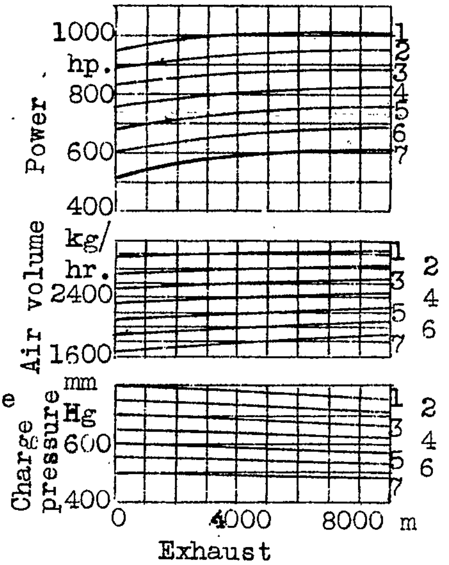


Figure 8.- Change of charge pressure against exhaust back pressure.

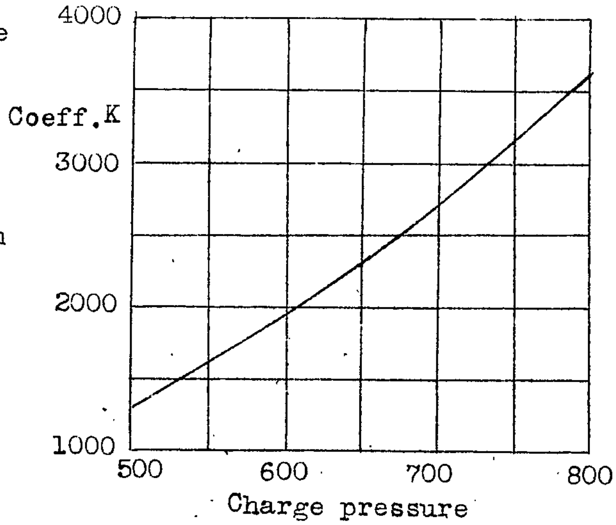
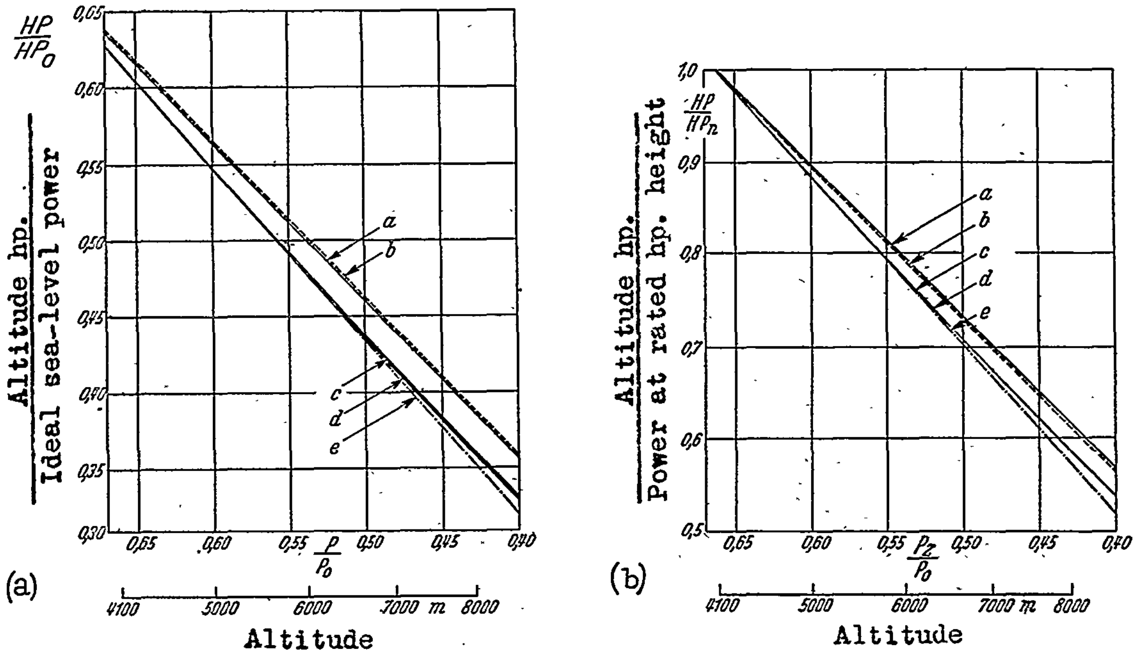


Figure 11.- Change in numerical value in the back pressure correction formula.



a) Devillers formula
b) Italian test specifications
c) Fiat formula
d) experimental curve
e) Hagg-Farrar formula

Figure 6a,b.- Comparison between actual power decrease at altitude and as computed by various formulas.

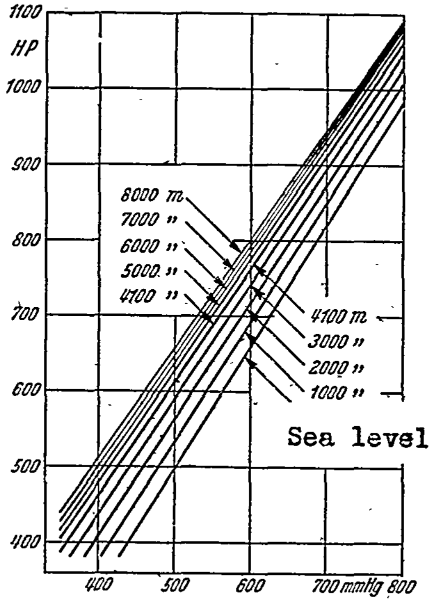


Figure 9.- Calibration curves - sea level to 8000m - at 2100 r.p.m. and constant inlet temperature.

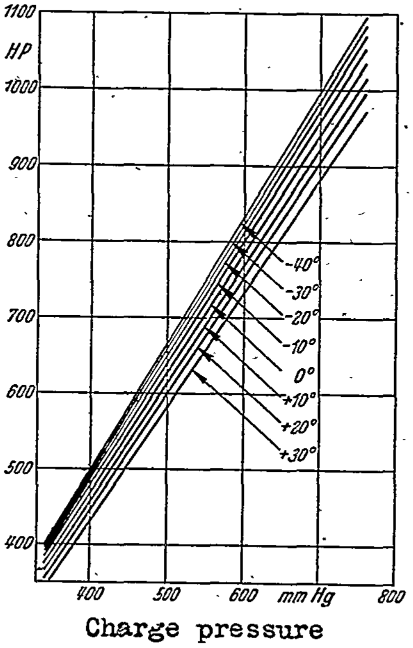
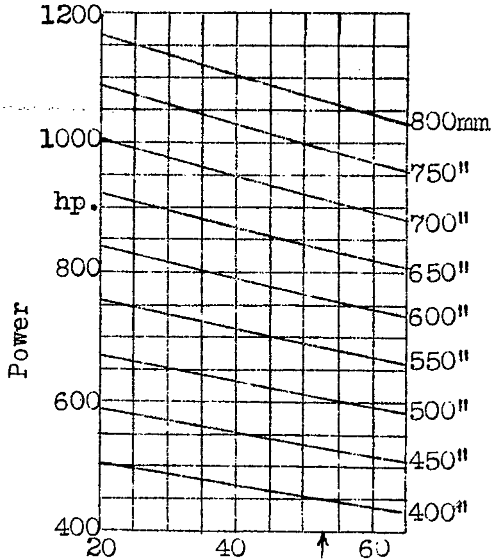


Figure 12.- Calibration curves of rated altitude at inlet temperatures ranging from -40 to +30°



Mixture temperature

Point corresponds to 15° inlet temperature

Figure 13.- Variation of power plotted against mixture temperature.

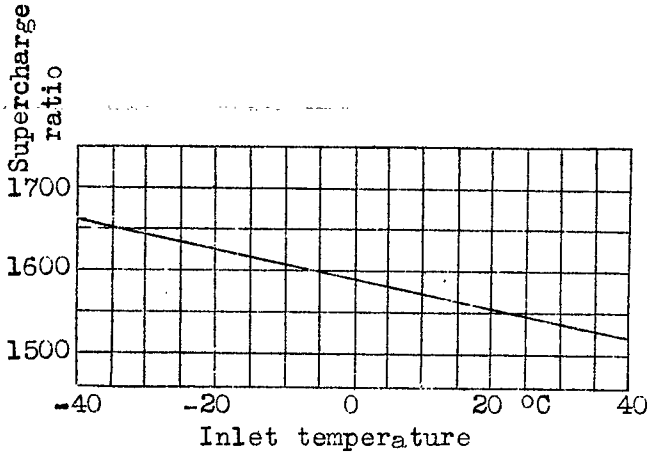


Figure 16.- Change of supercharge ratio at rated altitude plotted against inlet temperature.

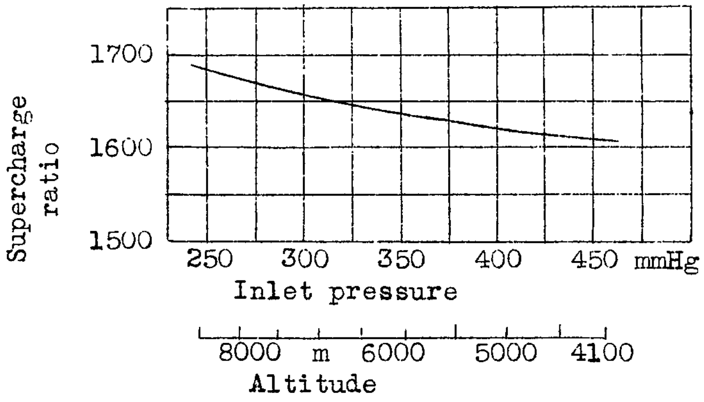
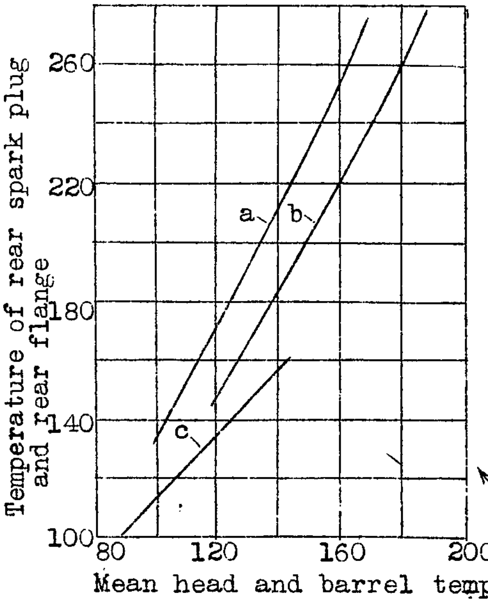


Figure 17.- Change of supercharge ratio plotted against inlet pressure for constant exhaust back pressure. and constant exhaust temperature.



(a) Rear spark plug to mean cyl. temp.
(b) " " " " " cyl. head temp.
(c) Flange to mean barrel temp.

Figure 19.- Relation between the temperature of the rear spark plug and the cylinder flange on one side and the mean temperature of cylinder head, flange and total cylinder.

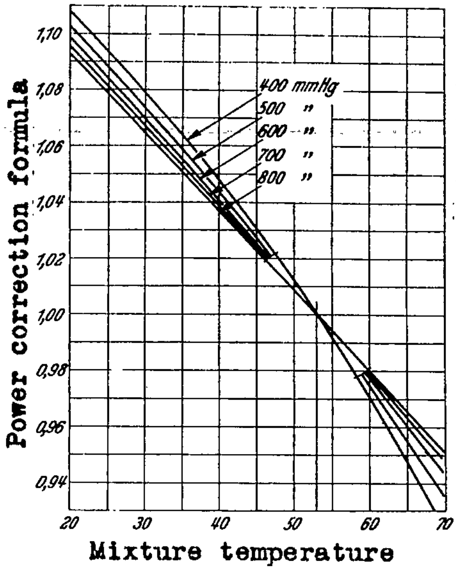


Figure 14.- Variation of power correction factor against mixture temperature.

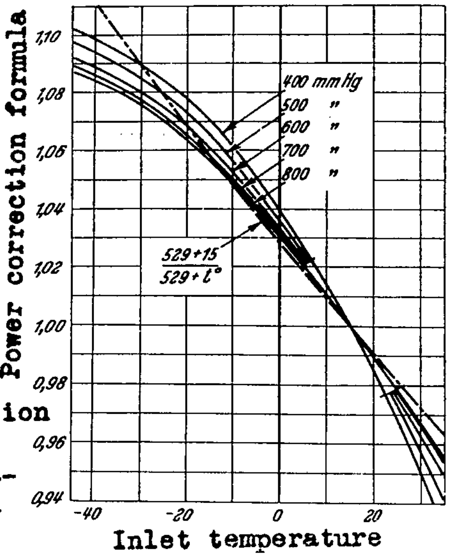


Figure 15.- Variation of power correction factor versus inlet temperature at rated altitude.

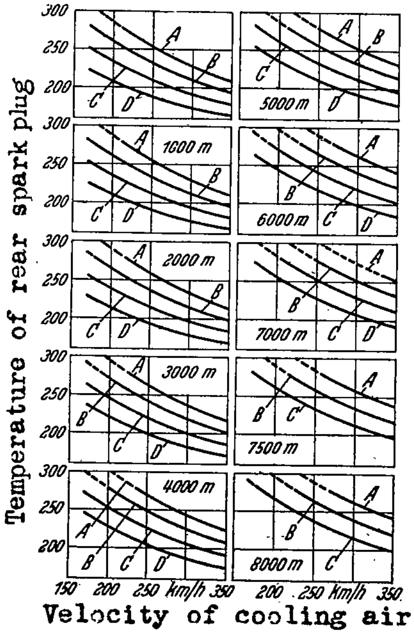


Figure 20.- Temperature variations of the rear spark plug at constant output at different heights and different wind velocities.

A. Measured at constant h p. and constant charge pressure of 800 mm(980 h p. at sea-level).

B. At constant h p. and constant pressure of 700 mm (822 h p. at sea-level)

C. Constant h p. and constant pressure of 600 m m (660 h p. at sea level)

D. Constant h p. and constant pressure of 500 m m(500 h p. at sea level.)

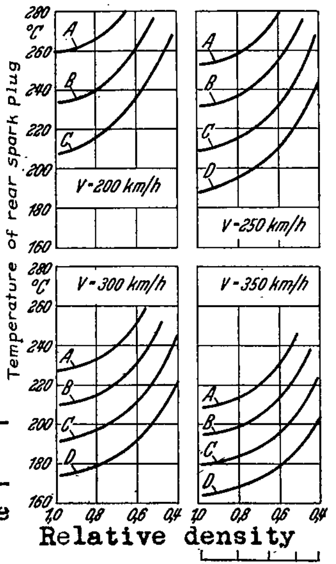


Figure 21.- Temperature variation of rear spark plug against air density(pressure and temperature equivalent to standard air) at constant hp. and constant speed.

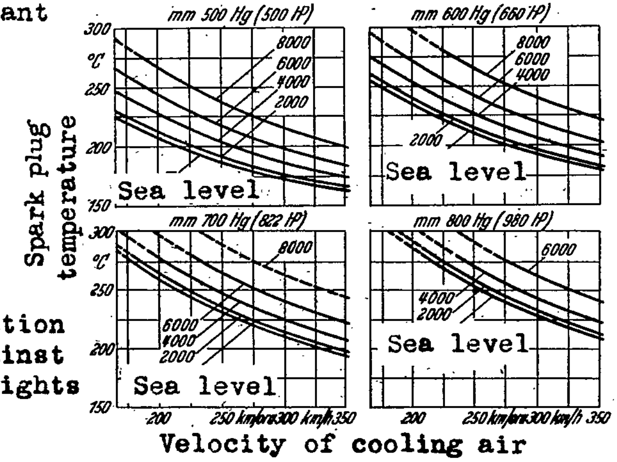
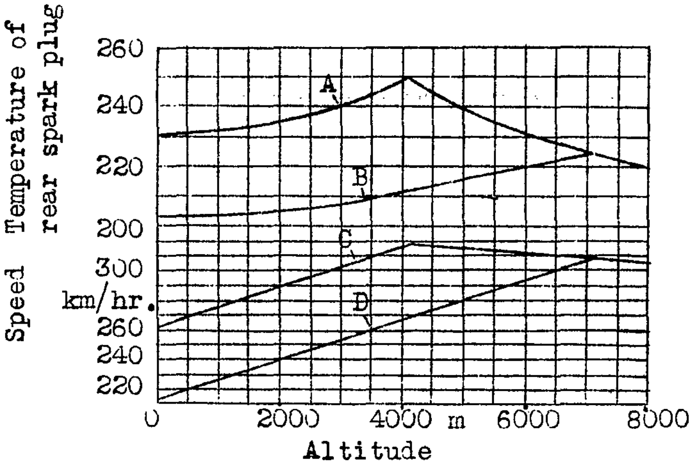


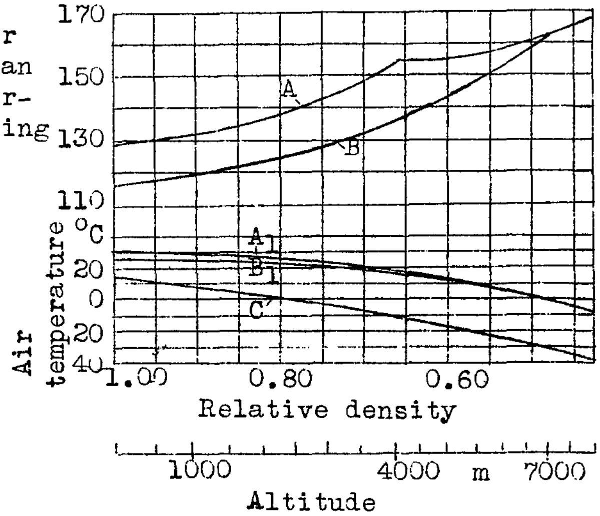
Figure 22.- Temperature variation in rear spark against wind velocity at different heights and constant h p.



A Spark plug temperature at 735 mm charge pressure
B " " " " 500 " " "
C Speed at 735 mm charge pressure
D " " 500 mm " "

Figure 23.- Temperature variation in rear spark plug in climb in standard air at constant charge pressure.

Δt = Mean cylinder temperature - (mean temperature difference of air entering and leaving the cowling).



A Average of Δt at constant pressure of 735 mm Hg
B " " " " " " " 500 " "
A_1,B_1. Air temperature on exit from cowling
C. Air temperature on entry into cowling

Figure 24.- Change in mean temperature jump between cylinder and air in climb in standard air at constant charge pressure.

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