REPORT No. 384

THE COMPARATIVE PERFORMANCE OF SUPERCHARGERS

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SUMMARY

This report presents a comparison of superchargers on the basis of the power required to compress the air at a definite rate, and on the basis of the net engine power developed at altitudes from 0 to 40,000 feet. The investigation, which was conducted at the Langley Memorial Aeronautical Laboratory, included geared centrifugal, turbine-driven centrifugal, Roots, and vane-type superchargers. It also includes a brief discussion of the mechanical limitations of each supercharger and explains how the method of control affects the power requirements.

The results of this investigation show that for critical altitudes below 20,000 feet there is a maximum difference of about 6 per cent between the amounts of net engine power developed by the various types of superchargers when ideal methods of control are employed, but for critical altitudes above 20,000 feet an engine develops considerably more power when equipped with a turbocentrifugal supercharger than with any other type. The Roots type gives the lowest net engine power of all at high critical altitudes, because it has the least efficient type of compression.

The throttling method of control used on the geared-centrifugal type of supercharger is very unsatisfactory at low altitudes from a net engine power standpoint when compared with the method used on the Roots or turbocentrifugal.

INTRODUCTION

The practice of supercharging has increased materially during the last few years. Superchargers now have the following uses: On automobile engines to supply air at pressures higher than atmospheric; on aircraft engines to compensate for diminution of atmospheric pressure at altitude as well as to boost the pressure slightly during take-off and during flight at low altitudes; on Diesel engines to supply the air for both combustion and scavenging.

The varied uses of superchargers have led to the development of several new types and to extensive improvements on the existing conventional types. In order to select the supercharger best fitted for a particular condition of service, a knowledge of the performance characteristics and the mechanical limitations of each type is essential.

During the last few years considerable flight and laboratory test data concerning the performance of the different types of superchargers have been collected. These data have not been, heretofore, reduced to a comparative basis.

The only well-known information available concerning the comparative performance of superchargers was published by the National Advisory Committee for Aeronautics. (References 1 and 2.) Reference 1 includes a theoretical analysis of the performance of supercharged engines, and Reference 2 includes the results of tests that were conducted to determine the comparative climb and high-speed performance obtained by the alternate use of a turbosupercharger and a Root supercharger for supercharging a Liberty engine that was installed in a modified DH-4 airplane. These tests showed that the climb performance obtained with the turbosupercharger was slightly better than that obtained with the Roots and that the high-speed performance obtained with the turbosupercharger was decidedly better than that obtained with the Roots. The difference in high-speed performance increased gradually with the altitude of operation, reaching a maximum of 20 m. p. h. at 20,000 feet.

The object of the present investigation is to compare the performance of the different types of superchargers to submit information that will permit the selection of the type of supercharger best fitted for a particular condition of service. The data were analyzed by the staff of the National Advisory Committee for Aeronautics.

GENERAL DESCRIPTION OF SUPERCHARGERS

For the supercharging of aircraft and automobile engines three types of superchargers have been used: The Roots, the vane, and the centrifugal. A sketch of each of these three types of superchargers is shown in Figure 1.

The Roots type consists essentially of two symmetrical rotating elements inclosed within a casing. The casing is usually made of an aluminum alloy ribbed for strength and cooling. The rotating elements or impellers have cycloidal contours except for the tip which forms the arc of a circle and for a narrow flat portion at the hub. The impellers are made from steel or a light alloy, the light metal being in more general use for aircraft-engine superchargers. The impellers are rotated in opposite direction by gears. They do not contact with each other nor the casing; the clearances, however, are reduced to a minimum in order to reduce the amount of air that slips back. This type of supercharger is driven directly by the engine and has been operated at speeds up to 7,000 r. p. m.

The principle of operation of the Roots type supercharger is as follows:

Low-pressure air enters at A and is trapped by each rotor in turn in the space B between the rotor and the casing. The instant the tip C of the rotor passes the corner D, the high-pressure air on the discharge side rushes back and compresses the low-pressure air in space B. Further rotation of the rotor for about 180° is against the discharge pressure. There are four discharge pulsations for each revolution or two for each of the two impellers.

The centrifugal supercharger consists of a rotating impeller inclosed within a casing. In well-designed superchargers both the impeller and the casing are provided with vanes to guide the entering and the discharge air. Alloys of aluminum and magnesium have been successfully employed for the construction of the casing and the impeller. In large capacity superchargers air is taken in at both sides and near the center of the impeller so as to eliminate the thrust on the

about the center, B, the vanes, C, move out against the casing under the action of springs and centrifugal force, or by mechanical means. If the vanes are moved by mechanical means, as has been found most satisfactory, they usually operate with a slight clearance rather than in contact with the casing.

The air enters the supercharger at D, and as the vanes revolve the air is trapped between two successive vanes. As this air moves toward the discharge side the volume betweent the vanes is decreased and thus the air is compressed. The high-pressure air is discharged through the opening E. This type of supercharger is driven directly by the engine.

METHOD

One of the most important characteristics of an aircraft-engine supercharger is the power required to compress air at a given rate for the desired range of altitudes; in other words, the percentage of engine power required by the supercharger to maintain sea-
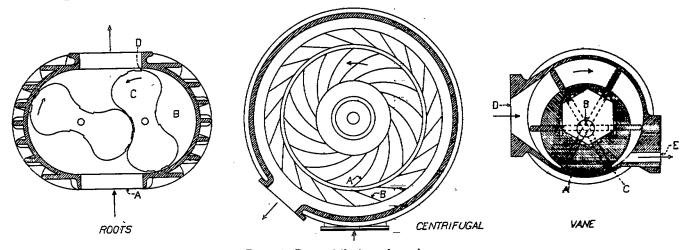

FIGURE 1.—Representative types of superchargers

bearings. In small superchargers, however, the air is taken in at one side of the impeller only.

The blades, A, are designed so as to receive the air without shock and to give maximum stiffness to the impeller. The rapid rotation of the impeller causes the air to have a high velocity at the impeller exit due to the action of centrifugal force. The high velocity air is discharged into diffuser vanes, B, which are so designed that the velocity head is efficiently changed to a pressure head.

This type of supercharger may be driven directly by the engine through gears of sufficient ratio to give the high rotative speeds necessary for this type of supercharger, or it may be driven by an exhaust-gas turbine. When driven by a turbine, the exhaust gases from the engine are collected in a nozzle box from which they pass through nozzles to the turbine wheel, which is coupled directly to the supercharger.

The vane type of supercharger consists of a series of vanes mounted on a drum which is eccentrically located within a cylindrical casing. As the drum, A, rotates

level pressure at the carburetor. In this investigation a rate of flow of 1 pound of air per second was assumed, the air required by a well-designed engine of 492 horsepower. The theoretical power required to compress air flowing at this rate from atmospheric pressure to 29.92 inches of Hg was computed for altitudes from 0 to 40,000 feet. These power requirements were computed for a series of compression exponents from 1 to 2.

When determining the power required for the compression of 1 pound of air per second for the range of altitudes and the pressure conditions mentioned above, the equation $\mathrm{hp} = CP_1 \, V_1 \log_e r$ was used for the isothermal condition, and the equation

$$\mathrm{hp} = C\frac{n}{n-1}P_1 \, V_1(r^{\frac{n-1}{n}}-1)$$ for the polytropic condition. In these equations:

P_1 = the intake or atmospheric pressure,
V_1 = the volume of intake air displaced per second,
r = the compression ratio,
C = a constant depending on the units used, and
n = the compression exponent.

The theoretical power required by a Roots supercharger to compress 1 pound of air per second was also computed for the range of altitude, pressure, and compression conditions mentioned above, using the equation

$$hp = C_1 V_1 (P_2 - P_1).$$

In this equation P_2 is the discharge pressure.

The effect of the compression exponent n on the discharge air temperatures was also determined for the range of altitudes, and for the pressure and compression conditions used in the power computations. The discharge air temperatures for polytropic compression were determined from the thermodynamic relation

$$\frac{(P_2)^{\frac{n-1}{n}}}{P_1} = \frac{T_2}{T_1},$$

in which

T_1 = the intake air temperature, degrees Fahrenheit abs.,

T_2 = the discharge air temperature, degrees Fahrenheit abs.

The pressures and temperatures for a standard atmosphere given in N. A. C. A. Technical Report No. 216 (Reference 3) were used in these computations.

The net engine power developed with each type of supercharger was computed for critical altitudes from 0 to 40,000 feet; the critical altitude is the maximum altitude to which sea-level pressure can be maintained at the carburetor. The unsupercharged engine power and the maximum developed engine power were also determined for the same range of altitudes. These computations were based on a hypothetical engine of good design developing 100 brake horsepower at sea level.

The determination of the power output of the unsupercharged engine for the range of altitudes investigated necessitated certain computations. The sea-level power was corrected according to the temperatures and pressures existing in a standard atmosphere. The assumption was made that the engine speed was constant and that the engine power varied according to the formula

$$hp\ altitude = hp\ sea\ level \left(\frac{P_2}{29.92}\right)^{1.15} \left(\frac{T_2}{518}\right)^{-0.5}.$$

The relation was arrived at by Diehl (Reference 4) after an analysis of a large amount of experimental data. Additional information verifying the temperature relation has since been obtained by the National Advisory Committee for Aeronautics and by the Bureau of Standards.

In the computing of the maximum brake horsepower developed by the supercharged engine, the assumptions were: The carburetor temperature at all altitudes was 59° F., the carburetor pressure was 29.92 inches of Hg, the engine speed was constant. The test data submitted in N. A. C. A. Technical Report No.

355 and the computations on discharge air temperatures submitted in this report indicate that, having a well-designed supercharger, one can use a cooler of sufficient capacity to maintain sea-level temperature at the carburetor. The engine speed could be maintained constant by the use of a variable-pitch or a variable-diameter propeller. The effect of reduced exhaust pressures on the power developed by an engine of 100 brake horsepower at sea level was computed for altitudes from 0 to 40,000 feet. These computations were based on the results of tests recently conducted by the Bureau of Standards on a Curtiss D-12 engine, in which it was found that there was an increase of 2.56 horsepower for 1 inch of mercury reduction in exhaust back pressure. Further discussion of the tests made by the Bureau of Standards and of other tests on the effect of exhaust back pressure on engine power will follow later in the report.

The power required by the supercharger was subtracted from the total power developed by the engine to obtain the net engine power in the case of the superchargers of the Roots, the geared centrifugal and the vane types. Before this value of supercharger power was used in the computations it was corrected for the increased volumetric efficiency of the engine operating with atmospheric pressure at the exhaust. This correction was based on the results of tests recently conducted by the Bureau of Standards.

The power developed by an engine equipped with a turbosupercharger was obtained by assuming that for any altitude the exhaust pressure was equal to the carburetor pressure, which was 29.92 inches of mercury. This assumption is supported by a large amount of experimental data. Assuming a constant carburetor air temperature of 59° F. and a constant engine speed, the engine equipped with a turbosupercharger has the same power at all altitudes up to the critical altitude.

Practical information regarding the respective merits of each type of supercharger was obtained by studying the various methods of controlling the quantity of air supplied at different altitudes. By controlling is meant the manner in which the supercharger capacity is varied so that the supercharger will supply carburetor air at a pressure of 29.92 inches of mercury within the range of altitudes for which it was designed.

The percentage of the engine power required by a Roots type of supercharger was obtained for four different capacities from values given in N. A. C. A. Technical Reports Nos. 284 and 327. (References 5 and 6.) The percentage of the theoretical engine power required by a Roots type of supercharger of 70 per cent over-all efficiency was also computed for comparison with the experimental values.

The values of the power absorbed in throttling, the method used on a geared-centrifugal supercharger, were obtained by computing the power required by superchargers having critical altitudes of the following

heights: 5,000, 10,000, 15,000, 20,000, 25,000, and 30,000 feet. In arriving at these values it was assumed that the pressure on the supercharger side of the throttle valve was equal to the atmospheric pressure at the critical altitude for which the supercharger was designed, that the throttled air was compressed from this pressure to 29.92 inches of mercury, and that the air was compressed by the polytropic process at a compression exponent of 1.6. These superchargers were assumed to have an over-all efficiency of 70 per cent and to be of sufficient size to supply air at a pressure of 29.92 inches of mercury up to the critical altitude for an engine developing 100 horsepower at sea level.

The net engine power developed at altitudes from 0 to 40,000 feet with each of these geared-centrifugal superchargers was also determined. In these compu-

tures below the critical altitude were corrected for the large increase in temperature caused by the compression of the throttled air and for the reduction due to drop in temperature as it passes through the cooler. Above the critical altitude the supercharger discharge air temperatures were corrected for the temperature drop through the cooler in order to arrive at the carburetor air temperatures. For the conditions with the Roots and geared-centrifugal superchargers, the engine and supercharger power were corrected for the increased volumetric efficiency at altitude.

RESULTS AND DISCUSSION OF RESULTS

The results of the computations on the theoretical power required to compress 1 pound of air per second from atmospheric pressure to 29.92 inches of mercury
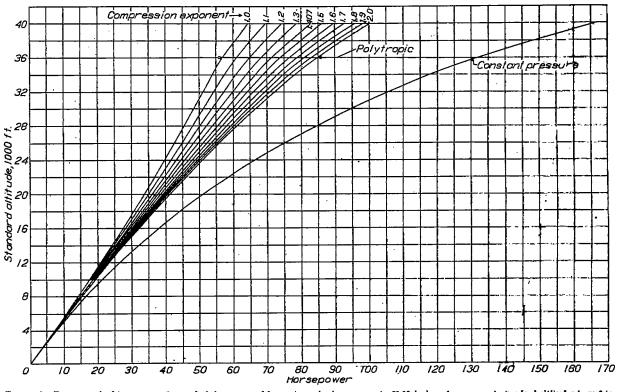

FIGURE 2.—Power required to compress 1 pound of air per second from atmospheric pressure to 29.92 inches of mercury at standard altitudes from 0 to 40,000 feet by a supercharger operating on a constant pressure card and one operating on polytropic card

tations it was assumed that the ratio of the atmospheric pressure to the carburetor pressure remained constant above the critical altitude. This assumption is not strictly correct, but the error introduced is small.

Additional computations were made on the net engine power developed, at altitudes from 0 to 40,000 feet, with 20,000-foot superchargers of each type. In these computations the effect of the method of control used on each type was considered. It was assumed, for the purpose of these computations, that the cooler used was of sufficient capacity to maintain a carburetor air temperature of 59° F. to the critical altitude for the condition with the Roots and the turbocentrifugal superchargers. For the conditions with the geared-centrifugal superchargers, the carburetor air tempera-

for altitudes from 0 to 40,000 feet for both a compressor operating on the polytropic process and one operating on a constant pressure process are presented in Table I. For the polytropic process, the ideal power was computed for a series of compression exponents from 1 to 2. Table II presents results of computations on the discharge air temperatures with these compression exponents, assuming standard atmospheric temperatures at the beginning of compression. These discharge air temperatures would be the same as the carburetor air temperatures if no cooling were provided between the supercharger outlet and the carburetor.

The curves in Figure 2 were obtained by plotting the information presented in Table I. If an over-all effi-

ciency of 70 per cent is assumed for each of the two types of compressors, then the power required to compress 1 pound of air per second is greater for the Roots type of supercharger by 3.49, 16.96, 47.35, and 111.32 horsepower at altitudes of 10,000, 20,000, 30,000, and 40,000 feet, respectively, than it is for a supercharger which operates with polytropic compression of exponent 1.6. In the study of these theoretical power curves remember that sea-level pressures are maintained at the carburetor for a large range of altitudes but that few supercharger installations maintain sea-level pressure at the carburetor for altitudes above 20,000 feet.

An analysis of the flight test data obtained with the turbosupercharger and with the Roots type of supercharger shows that these two superchargers heat the discharge air to a condition corresponding to that with a compression exponent of 1.6. (Reference 2.) If this compression exponent could be reduced to 1.235, for an engine consuming 1 pound of air per second, gains in engine power of 16.6, 33.8, 53.4, and 79.9 horsepower would be effected at altitudes of 10,000, 20,000, 30,000, and 40,000 feet, respectively. These figures are based on the temperatures given in Table II and on the assumption that the engine power varies inversely as the square root of the absolute temperature. The
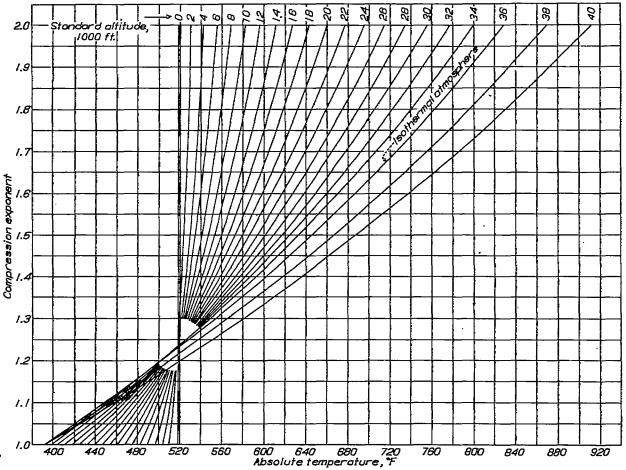

FIGURE 3.—Effect of compression exponent on discharge air temperatures when compressing air of standard temperature and pressure from atmospheric pressure to 29.92 inches of mercury at 0 to 40,000 feet, using a series of compression exponents from 1 to 2, inclusive

The curves in Figure 3 were obtained by plotting the information presented in Table II. A supercharger operating in a standard atmosphere and having a compression exponent of 1.235 gives a constant discharge air temperature up to the stratosphere (about 35,300 feet). Besides reducing the power required to compress the air, as shown in Figure 2, a supercharger having a low compression exponent gives lower discharge air temperatures, as shown in Figure 3. This reduction in supercharger discharge air temperatures increases the engine power, because a greater weight of charge can be inducted, and it also permits the use of a smaller cooler.

saving in supercharger power effected by the reduction of the compression exponent from 1.6 to 1.235 would be small compared to the gain in engine power due to the lower carburetor air temperatures; these gains for a supercharger of 70 per cent over-all efficiency amount to .94, 4.14, 9.86, and 19.71 horsepower at altitudes of 10,000, 20,000, 30,000, and 40,000 feet, respectively.

The design of a supercharger that would operate with a compression exponent as low as 1.235 and that would compress the large volume of air consumed by an aircraft engine would be difficult, if not impossible, because no satisfactory means for removing the heat of compression could be provided. An air cooler would,

therefore, be necessary in order to obtain a constant air temperature. The use of a small cooler would be possible if a supercharger of high efficiency were chosen, because low discharge air temperatures would then be obtained.

The power developed at standard altitudes from 0 to 40,000 feet by an engine developing 100 horsepower at sea level is shown by the curves in Figure 4. The total engine power supercharged is the maximum power developed by the engine with atmospheric pressure at the exhaust and 29.92 inches of mercury at the carburetor. When an exhaust turbosupercharger is used, the net engine power is the total engine power

net engine power of all at high critical altitudes, as would be expected from the fact that it has the least efficient method of compression.

One should remember that these curves represent the results that would be obtained if a series of superchargers of each type were used, in which each supercharger of the series was designed for one particular altitude. In practice it is necessary to consider, instead, the single supercharger that is best fitted for a range of altitudes. As this range of altitudes is increased, each supercharger will be affected; the size of the effect will depend principally on the method of control used.
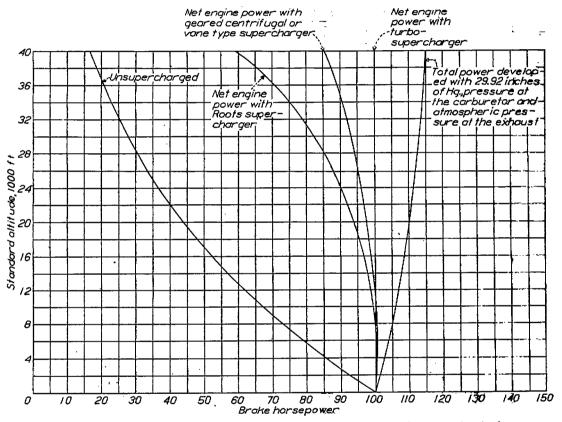

FIGURE 4.—Power developed by an unsupercharged and a supercharged engine of 100 horsepower at sea level

supercharged less the reduction in power due to increased exhaust back pressue. When a geared-centrifugal, a vane, or a Roots type of supercharger is used, the net engine power is the total engine power developed less the power required to drive the supercharger. The engine power unsupercharged is the power developed by the normal engine with standard atmospheric temperatures and pressures at the intake and exhaust.

These curves show that, regardless of the type of supercharger used, for altitudes below 20,000 feet the differences in net engine power are very small. However, as the altitude of operation increases above 20,000 feet, these differences in net engine power increase showing the exhaust turbosupercharger to be the most favorable. The Roots supercharger gives the lowest

The ideal method of control is one in which the quantity of air taken into the supercharger is varied, without throttling, to just enough to satisfy engine requirements. The use of discharge valves and an intake control to obtain this ideal method for varying the capacity of a Roots type of supercharger is discussed in N. A. C. A. Technical Report No. 303, Reference 7. With a vane type of supercharger, the ideal method of varying the capacity could be obtained by the use alone of the intake control, because the vanes would take the place of the discharge valves.

With the turbosupercharger, the method of control, though not ideal, is nevertheless very satisfactory. The quantity of compressed air and the amount of compression is regulated by the quantity of exhaust gas passing through the turbine wheel. The super-

charger is designed to supply enough air to satisfy engine requirements up to some definite altitude, that altitude at which all the exhaust gases pass through the turbine wheel.

Such an excellent method of control is used by the exhaust turbosupercharger that the curves shown in Figure 4 for a series of this type, each one being designed for one particular critical altitude, would probably closely represent the curve made by one supercharger used for the entire range. If this supercharger were designed, however, for a particular critical altitude, such as 20,000 feet, the power curves shown in Figure 4 would not then represent the actual power conditions above that altitude, because the carburetor pressures would be less than 29.92 inches of mercury and the effect of back pressure on power would increase as the carburetor pressure decreased.

The method of control used on the Roots supercharger is not so satisfactory as that used by the exhaust turbosupercharger. The Roots type is driven directly from the engine and is designed to maintain ground-level pressure up to some definite altitude. Too much air is supplied to the engine at altitudes below the critical altitude unless some of the air is by-passed. A supercharger designed for a critical altitude of 20,000 feet should by-pass at sea level about 40 per cent of the air. At low altitudes little energy has been expended in compressing the large amount of by-passed air, and near the critical altitude where the required energy is greater, only a small amount of air is by-passed. The lower the critical altitude for any supercharger the less air is by-passed at sea level, and proportionally less energy is wasted, below the critical altitude, in compressing air and then by-passing it.

The curves in Figure 5 show the percentage of the engine power required by a Roots supercharger of four different capacities. These four capacities were obtained by the variation of the gear ratio between the engine and the supercharger so that sea-level pressure would be maintained for ranges from 0 to altitudes of 7,000, 11,500, 17,000, and 22,000 feet. (Reference 6.) The curves show that as the critical altitude is raised, the deviation from the theoretical power curve is increased. This deviation would be expected on the Roots type owing to its method of control, explained in the preceding paragraph. The experimental results approximate more closely the theoretical values as the critical altitude is approached, because less compressed air is by-passed, therefore, less power is wasted. This condition is particularly well demonstrated by the curves of the superchargers of the lowest three capacities. The apparent discrepancy of the results from the supercharger having a critical altitude of 22,000 feet was due to the fact that the impeller clearances on the supercharger used in the tests were too great. The effect of large clearances is not so apparent at low alti-

tudes as at high altitudes, because the higher the altitude the greater the pressure difference across the impellers; the greater pressure difference causes more air to leak back past the impellers. The same amount of air must be supplied to the engine for a low range of altitude, such as 0 to 6,000 feet, by each supercharger; therefore, the supercharger of the lowest capacity requires the least power because it would need to by-pass the smallest amount of air. Consequently, the percentage of the engine power required for any altitude would increase with the capacity of the supercharger. The curves show that the difference in the percentage of engine power required is small near sea level, but is increasingly large as the critical altitudes are approached. For superchargers having critical altitudes of 7,000, 11,500, 17,000, and 22,000 feet, the percentage of the engine power required at 6,000 feet
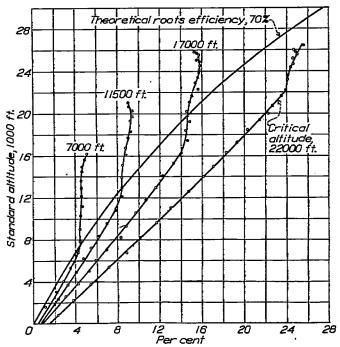

FIGURE 5.—Percentage of engine power required by the Roots supercharger

is 3.9, 4.75, 6.10, and 8.0, respectively. A Roots supercharger of 70 per cent over-all efficiency would require 2.75 per cent of the engine power at 6,000 feet. The large difference between this theoretical value and the results of experiment indicate that no single supercharger designed for a range of altitudes could approximate the theoretical curves of Figure 4. Consequently, the turbosupercharger appears to be even more advantageous than the curves in Figure 4 indicate, on account of its excellent method of control.

On the geared-centrifugal supercharger the throttling method of control is used. The air entering the supercharger at sea level and at low altitudes is throttled until just enough air is admitted to satisfy engine requirements at sea level. Throttling the air at the supercharger inlet to limit the quantity inducted makes it necessary to compress the throttled air so that it will

be discharged at sea-level pressures. Considering the net engine power this method is very unsatisfactory, because the engine power at sea level and at low altitudes is greatly reduced by two factors; the loss of the
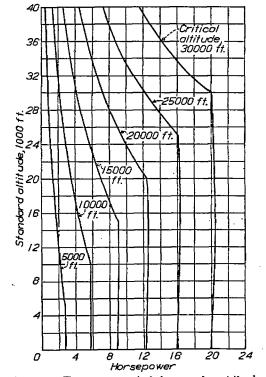

FIGURE 6.—Horsepower required by geared centrifugal superchargers of different capacities to supply air to 100-horsepower engine using throttling method of control

power used in compressing the throttled air, and the loss in power due to the decreased weight of the charge caused by the high carburetor air temperatures resulting from the compression. Figure 6 shows the power required by geared-centrifugal superchargers of six different capacities to supply sufficient air to maintain sea-level pressure on a 100-horsepower engine to critical altitudes of 5,000, 10,000, 15,000, 20,000, 25,000, and 30,000 feet. The large amount of power required at low altitudes by a geared-centrifugal supercharger is a serious disadvantage. This type of supercharger compares unfavorably, in this respect, with either the Roots or the turbo-supercharger, because neither of these require at sea level more than 2 per cent of the total engine power, nor do they heat the carburetor air.

The curves of Figure 6 show that the results obtained by using a geared-centrifugal supercharger for a large range of altitudes will deviate considerably from the results of the curves shown in Figure 4. This deviation at low altitudes is so large that the use of geared-centrifugal superchargers for high critical altitudes is not justified without providing two or more stages and some method for disengaging the supercharger or reducing its speed at low altitudes.

The net engine power developed by a 100-horsepower engine when equipped with geared-centrifugal superchargers of several different capacities is shown by the curves in Figure 7. Although a cooler of sufficient capacity to maintain, at the critical altitude, a carburetor air temperature of 59° F. was assumed to have been used for each condition, there would nevertheless be considerable heating of the carburetor air at low altitudes because of the large amount of throttling. This increase in carburetor air temperature with a 20,000-foot critical altitude supercharger would reduce the engine power about 7 per cent at sea level. The advantage of using a compressor of one or more stages is illustrated by the serrate curve ABCD for a 20,000-foot critical altitude supercharger and the serrate curve ABCDEF for a 30,000-foot critical altitude supercharger. For the 30,000-foot supercharger at least two stages of compression would be necessary, as the high pressure ratio could not be obtained in one stage, while for the 20,000-foot, the saving in power could be accomplished by using one stage and increasing the rotative speed, at the higher altitudes, by means of a gear shift between the engine and the supercharger.

The comparative performance obtained with 20,000-foot critical altitude superchargers of different types

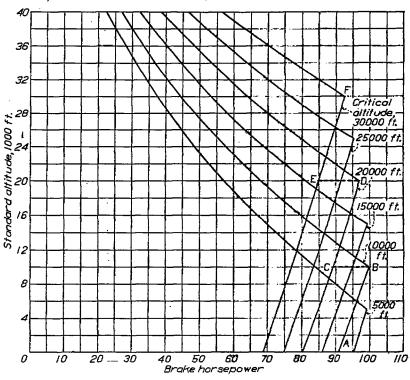FIGURE 7.—Net engine power obtained at altitudes from 0 to 40,000 feet when supercharging a 100-horsepower engine with geared-centrifugal superchargers of six different capacities

(fig. 8) indicates that there is very little difference in the performance above the critical altitude. Below the critical altitude the geared centrifugal gives the lowest net engine power because of its very inefficient

method of control. With superchargers of higher critical altitude, the best performance above and below the critical altitude would be obtained with a turbo-centrifugal supercharger. The Roots would be the least efficient at the critical altitude and above the critical altitude.

Mechanical features and limitations.—Although it is not the purpose of this report to discuss in detail the mechanical features of the various types of super-chargers, a brief discussion of some of the limitations seems quite appropriate. The analysis submitted in this report assumed that sea-level pressure was main-tained at the carburetor for critical altitudes up to 40,000 feet. This would be a very severe condition of

tained in the gears when the engine is accelerated rapidly. In order to obtain a gain in critical altitude, the speed must be increased or the diameter of the rotors must be enlarged. Either change increases the force due to rapid acceleration, consequently placing an additional load on the gears. The geared-centrif-ugal supercharger will, therefore, probably not be used for high altitudes until further improvements are made, or until these compressors are designed with two or more stages of compression.

The turbosupercharger weighs more than the geared-centrifugal supercharger, and it can not be compactly installed. The supercharger increases the drag of the airplane, because the turbine must be placed in the
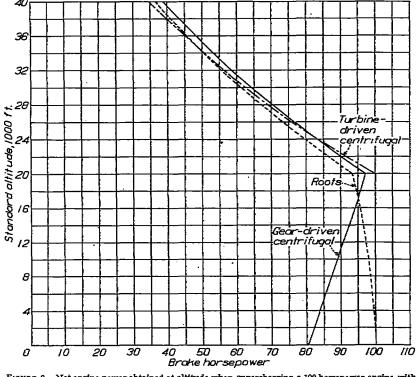

FIGURE 8.—Net engine power obtained at altitude when supercharging a 100-horsepower engine with different types of superchargers of 20,000-foot critical altitude

service because of high temperatures and high mechan-ical stresses. Although the performance of the Roots supercharger has been satisfactory for critical alti-tudes up to 22,000 feet (Reference 4), and the one used by the United States Navy when establishing the world's altitude record had a critical altitude above 30,000 feet, the design of a supercharger of this type that would operate satisfactorily at 40,000 feet would be very difficult.

The geared-centrifugal supercharger has the ad-vantage of low weight and compactness, and it lends itself to a particularly clean installation, especially on radial engines. Gear ratios higher than 10 : 1 are seldom employed on these installations, although gear ratios as high as 13 : 1 have been used. Using the latter ratio, a spring coupling or friction clutch should be provided to reduce the high stresses that are ob-

air stream so that sufficient cooling may be obtained to prevent the turbine buckets and nozzles from warping. Some time is required to bring the rotor up to speed. For this reason an engine equipped with a turbosuper-charger responds sluggishly to the throttle. Difficulty has also been experienced in the warping of valves in engines equipped with this type of supercharger, be-cause the valves are continually surrounded by hot gases.

The vane type of compressor has been little used as an aircraft engine supercharger, though it has the funda-mental advantage of the centrifugal type in that it handles large volumes of air and operates on the poly-tropic process. It is driven directly from the crank-shaft of the engine and can be located so that the drag of the airplane is not increased. In a vane type of supercharger, the continual shifting of the center of

gravity of the rotating parts introduces inertia forces which must be carefully considered in the design. The fact that this difficulty has been overcome in small machines is encouraging. It indicates that it will not be long before vane type superchargers of sufficient size for aircraft service can be operated at speeds of 5,000 r. p. m. and above.

The Roots supercharger has the advantage of simplicity and it is equal to any of the others in reliability. In this type of supercharger the size of the mechanical clearances between the impellers and between the impellers and the case is very important. These clearances should be kept at the lowest practicable limit in order to reduce the amount of air that can flow
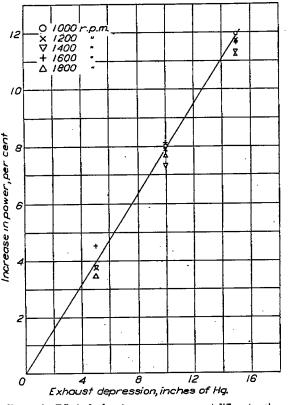

FIGURE 9.—Effect of exhaust pressure on power at different engine speeds. At 0 inches depression the exhaust pressure equals 29.92 inches of Hg

back to a minimum, because this air must be recompressed with a resultant increase in temperature.

Effect of exhaust back pressure on engine power.—Inasmuch as the exhaust back pressure affects the weight of the charge inducted by the engine and the friction losses of the engine, it must be considered in the determination of the engine power developed at different altitudes, and also in the determination of the power required by the supercharger to supply the combustion air. An analysis of the flight test data from an investigation in which a Roots type supercharger was used to supply and to meter the carburetor air showed that there was an increase of approximately 8 per cent in the volumetric efficiency of a supercharged engine at 20,000 feet altitude as compared with the volumetric

efficiency of the normal engine at sea level. This increase in volumetric efficiency was principally due to the better scavenging obtained with the reduced exhaust back pressures. Another advantage of the reduced exhaust back pressures is the decrease in the engine pumping losses on account of the engine exhausting against a lowered pressure.

To determine the power output of a supercharged engine at altitude, the effect of the exhaust back pressure on the engine power must be known. This knowledge is required regardless of the type of supercharger used, for the ability to compute the power at altitude with a turbosupercharger, a type that inherently increases the exhaust back pressure, is as necessary as the ability to compute the power at altitude with a mechanically driven supercharger, a type that produces no pressure at the exhaust.

Several investigations have been conducted to determine the variation of engine power with exhaust back pressure. Although the results of these investigations are not in exact agreement, they are probably as good as may be expected considering that the many factors involved—compression ratio, carburetor pressure, valve timing, and manifolds—simultaneously influence the results obtained.
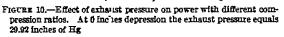
The first experimental tests to determine the effect of exhaust back pressure on engine power were conducted in the altitude chamber of the Bureau of Standards. (Reference 8.) This investigation was conducted on a 150-horsepower Hispano-Suiza engine of 5.3 compression ratio, and included a range of exhaust back pressures from 29.92 inches of mercury to 13.38 inches of mercury. The data were corrected to a constant intake temperature of 32° F. and to a constant engine speed of 1,500 r. p. m. These data show a rate of change in power at sea level of 0.6 horsepower for each inch of mercury change in exhaust back pressure when sea-level pressure is maintained at the carburetor. With the pressure at the carburetor equal to the pressure at sea level, but with the exhaust back pressure reduced to the atmospheric pressure at an altitude of 25,000 feet, the rate of change in power increases to 1.9 horsepower for each inch of mercury change in exhaust back pressure.

An investigation recently conducted by the National Advisory Committee for Aeronautics to determine the best valve timing for supercharged engines provided a large amount of information concerning the effect of exhaust back pressure on engine power. (Reference 9.) The tests were conducted on a single-cylinder Universal test engine of about 35 horsepower. Figure 9 shows the percentage increase in power obtained in these tests with various reductions in exhaust back pressure at engine speeds of 1,000, 1,200, 1,400, 1,600, and 1,800 r. p. m. The plotted points indicate that the effect of the exhaust back pressure on the engine power is influenced almost negligibly by the engine

speed. Figure 10 shows how the variation in exhaust back pressure affects the engine power at several compression ratios. The curves represent the results obtained, using the best valve timing for each compression ratio. If the same valve timing had been used for all compression ratios the curves would not have crossed each other, and the curves for the 7.35 ratio would have been lowest for all pressure conditions. The curves show that an engine should be of high compression ratio in order to give the minimum reduction in power with increase in the exhaust back pressure when operating at altitude.
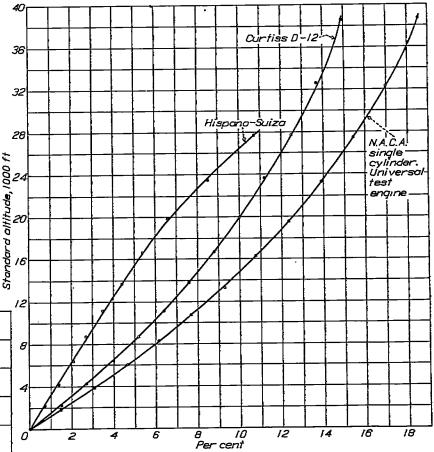
Very comprehensive tests on the effect of exhaust back pressure on engine power were recently conducted by the Bureau of Standards on a Curtiss D–12 engine. These tests indicate that a straight-line relation exists between the engine power and the exhaust back pressure, and that with a carburetor pressure of 29.92 inches
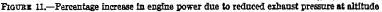
FIGURE 11.—Percentage increase in engine power due to reduced exhaust pressure at altitude

As the data for these three investigations were obtained on engines of different size, the results were reduced to a percentage basis, as shown in Figure 11,

to make a comparison possible. Inasmuch as the tests made by the Bureau of Standards on a Curtiss D–12 engine were the most comprehensive of the three, and the results seemed to represent a fair average, these results were used to obtain the values used in Figure 3 of this report. These tests by the Bureau of Standards are also in exact agreement with tests conducted by the French (Reference 10), in which it was found that the percentage increase in power at altitude with respect to power at ground is equal to 0.62 P. P is the difference between intake manifold pressures and exhaust manifold pressures expressed in pounds per square inch.

All the data that have been shown on the effect of exhaust back pressure on engine power have been for carburetor pressures of 29.92 inches of mercury. This fact must be borne in mind when the results are applied to other problems; reducing the pressure at the carburetor decreases the total amount of power remaining to be affected, therefore, the decrease in horsepower for each inch reduction in exhaust back pressure becomes an increasingly large percentage of

FIGURE 10.—Effect of exhaust pressure on power with different compression ratios. At 0 inches depression the exhaust pressure equals 29.92 inches of Hg

of mercury a gain of 2.56 horsepower is obtained for each inch of mercury reduction in exhaust back pressure. In these tests the carburetor air temperature was 59° F. and the engine speed 2,000 r. p. m.

the total power. At altitudes of 20,000 feet and above one may expect conditions in which an exhaust back pressure of 4 inches of mercury reduces the power 15 per cent as compared with a reduction of 2½ per cent when the carburetor pressure is 29.92 inches of mercury.

CONCLUSIONS

The results of this investigation show that for altitudes up to 20,000 feet, when ideal methods of control are employed, there is very little difference in superchargers from the point of view of net engine power, while for critical altitudes over 20,000 feet an engine develops more power when equipped with an exhaust turbosupercharger than with any other type. The Roots supercharger, because of its less efficient type of compression, gives the lowest engine power.

The method of control used on a geared-centrifugal type of supercharger is very unsatisfactory from the standpoint of net engine power when compared with the method used on the Roots or turbocentrifugal superchargers. A geared-centrifugal supercharger of 20,000-foot critical altitude would reduce the engine power 20 per cent at sea level as compared with less than 2 per cent for a Roots or turbocentrifugal supercharger.

In regard to mechanical limitations, the geared centrifugal has the advantage of low weight and neat installation, the Roots type would rank next in these points, and the exhaust turbosupercharger would be the least desirable.

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LANGLEY FIELD, VA., *January 13, 1931.*

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TABLE I.—THEORETICAL POWER REQUIRED TO COMPRESS 1 POUND OF AIR PER SECOND FROM ATMOSPHERIC PRESSURE TO 29.92 INCHES Hg., FOR STANDARD ALTITUDES FROM 0 TO 40,000 FEET, USING THE POLYTROPIC AND CONSTANT PRESSURE PROCESS

| Standard altitude 1,000 feet | Atmospheric pressure in Hg. | Pressure ratios | Pressure difference | Horsepower required to compress 1 pound of air per second by the polytropic process for the following compression exponents | | | | | | | | | | | Constant pressure |
				1.0	1.1	1.2	1.3	1.407	1.5	1.6	1.7	1.8	1.9	2.0	
0	29.92	1.000	0.00	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	27.82	1.075	2.10	3.61	3.611	3.630	3.631	3.634	3.645	3.649	3.658	3.660	3.664	3.670	3.742
4	25.84	1.158	4.08	7.17	7.208	7.247	7.289	7.320	7.335	7.366	7.387	7.405	7.422	7.432	7.719
6	23.98	1.248	5.94	10.67	10.766	10.877	10.947	11.017	11.065	11.118	11.170	11.206	11.247	11.282	11.942
8	22.22	1.347	7.70	14.14	14.230	14.452	14.637	14.750	14.852	14.947	15.035	15.116	15.176	15.242	16.461
10	20.58	1.454	9.34	17.53	17.829	18.044	18.308	18.509	18.662	18.807	18.952	19.066	19.174	19.271	21.254
12	19.03	1.572	10.89	20.88	21.317	21.677	22.012	22.300	22.535	22.744	22.948	23.119	23.280	23.430	26.397
14	17.57	1.703	12.35	24.18	24.785	25.266	25.726	26.131	26.452	26.752	27.039	27.280	27.504	27.710	31.923
16	16.21	1.846	13.71	27.43	28.203	28.861	29.450	29.993	30.418	30.824	31.198	31.521	31.814	32.091	37.836
18	14.94	2.003	14.98	30.61	31.558	32.414	33.187	33.882	34.427	34.940	35.435	35.844	36.236	36.596	44.177
20	13.74	2.178	16.18	33.74	34.957	36.028	36.951	37.829	38.512	39.171	39.777	40.296	40.801	41.239	51.042
22	12.63	2.369	17.29	36.80	38.252	39.553	40.711	41.787	42.625	43.430	44.184	44.832	45.451	45.996	58.396
24	11.59	2.582	18.33	39.82	41.559	43.120	44.491	45.799	46.823	47.798	48.710	49.511	50.264	50.936	66.375
26	10.62	2.817	19.30	42.76	44.863	46.638	48.312	49.846	51.059	52.230	53.322	54.296	55.197	56.016	75.001
28	9.72	3.078	20.20	45.66	48.059	50.186	52.130	53.928	55.374	56.765	58.059	59.208	60.284	61.270	84.362
30	8.88	3.369	21.04	48.48	51.232	53.709	55.958	58.069	59.755	61.390	62.910	64.265	65.538	66.696	94.537
32	8.10	3.694	21.82	51.25	54.393	57.220	59.809	62.249	64.196	66.101	67.871	69.454	70.944	72.301	105.61
34	7.35	4.054	22.54	53.93	57.510	60.703	63.653	66.460	68.713	70.902	72.952	74.782	76.510	73.094	117.64
36	6.71	4.459	23.21	56.95	61.006	64.633	68.001	71.212	73.809	76.335	78.704	80.836	82.541	84.684	131.72
38	6.10	4.905	23.82	60.58	65.159	69.344	73.186	76.891	79.881	82.818	85.553	88.047	90.388	92.543	148.71
40	5.54	5.401	24.38	64.18	69.357	74.063	78.464	82.700	86.118	89.493	92.658	95.537	98.250	100.75	167.41

TABLE II.—THEORETICAL DISCHARGE AIR TEMPERATURES OBTAINED BY COMPRESSING AIR FROM ATMOSPHERIC PRESSURE TO 29.92 INCHES Hg., USING SEVERAL COMPRESSION EXPONENTS FOR STANDARD ALTITUDES FROM 0 TO 40,000 FEET

| Standard altitude, 1,000 feet | Atmospheric pressure in Hg. | Atmospheric temperature, °F. Abs. | Pressure ratios | Pressure difference | Discharge air temperature (°F. Abs.) obtained in compressing air by the polytropic process for the following compression exponents | | | | | | | | | | |
					1.0	1.1	1.2	1.3	1.407	1.5	1.6	1.7	1.8	1.9	2.0
0	29.92	518.40	1.000	0.00	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40	518.40
2	27.82	511.27	1.075	2.10	511.27	513.08	517.51	519.91	522.10	523.80	525.38	526.81	528.04	529.16	530.19
4	25.84	504.13	1.158	4.08	504.13	510.89	516.58	521.47	525.96	529.33	532.61	535.49	538.06	540.38	542.44
6	23.98	497.00	1.248	5.94	497.00	507.09	515.69	523.04	529.85	535.02	539.99	544.41	548.34	551.91	555.15
8	22.22	489.87	1.347	7.70	489.87	503.29	514.75	524.70	533.86	540.91	547.67	553.70	559.14	563.99	568.45
10	20.58	482.74	1.454	9.34	482.74	499.44	513.73	526.28	537.92	546.84	555.44	563.16	570.07	576.34	582.04
12	19.03	475.61	1.572	10.89	475.61	495.59	512.85	527.97	542.10	553.04	563.55	573.01	581.53	589.28	596.37
14	17.57	468.47	1.703	12.35	468.47	491.71	511.90	529.70	546.42	559.40	571.96	583.29	593.50	602.83	611.35
16	16.21	461.34	1.846	13.71	461.34	487.77	510.93	531.42	550.79	565.88	580.55	593.79	605.79	616.73	626.78
18	14.94	454.21	2.003	14.98	454.21	483.78	509.94	533.15	555.23	572.49	589.29	604.60	618.41	631.12	642.75
20	13.74	447.08	2.178	16.18	447.08	479.85	509.00	535.02	559.92	579.46	598.60	615.99	631.77	646.39	659.71
22	12.63	439.94	2.369	17.29	439.94	475.80	507.91	536.81	564.58	586.44	607.91	627.53	645.39	661.93	677.07
24	11.59	432.81	2.582	18.33	432.81	471.76	506.91	538.68	569.41	593.73	617.66	639.61	659.69	678.30	695.40
26	10.62	425.68	2.817	19.30	425.68	467.73	505.84	540.66	574.37	601.19	627.71	652.10	674.53	695.31	714.50
28	9.72	418.55	3.078	20.20	418.55	463.59	504.77	542.57	579.36	608.82	638.04	664.99	689.81	712.92	734.35
30	8.88	411.42	3.369	21.04	411.42	459.43	503.70	544.56	584.59	616.76	648.81	678.47	705.87	731.46	755.20
32	8.10	404.28	3.694	21.82	404.28	455.26	502.60	546.58	589.93	624.90	659.91	692.41	722.53	750.75	776.99
34	7.35	397.15	4.054	22.54	397.15	451.04	501.44	548.58	595.33	633.26	671.30	706.81	739.77	770.74	799.66
36	6.71	392.40	4.459	23.21	392.40	449.53	503.37	554.07	604.61	645.85	687.37	726.25	762.51	796.65	828.59
38	6.10	392.40	4.905	23.82	392.40	453.42	511.45	565.58	621.52	666.69	712.40	755.29	795.51	833.46	869.05
40	5.54	392.40	5.401	24.38	392.40	457.42	519.69	579.14	639.10	688.43	733.58	785.86	830.28	872.34	911.90