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PERFORMANCE CHARACTERISTICS OF AN AIRCRAFT ENGINE WITH EXHAUST TURBINE SUPERCHARGER

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SUMMARY

The Pratt & Whitney Aircraft company and the Naval Aircraft Factory of the United States Navy cooperated in a laboratory and flight program of tests on an exhaust turbine supercharger. Two series of dynamometer tests of the engine-supercharger combination were completed under simulated altitude conditions. One series of hot gas-chamber tests was conducted by the manufacturer of the supercharger. Flight demonstrations of the supercharger installed in a twin-engine flying boat were terminated by failure of the turbine wheels.

The analysis of the results indicated that a two-stage supercharger with the first-stage exhaust turbine driven will deliver rated power for a given indicated power to a higher altitude, will operate more efficiently, and will require simpler controls than a similar engine with the first stage of the supercharger driven from the crankshaft through multispeed gears.

INTRODUCTION

It is the function of superchargers in general to augment the performance of an internal-combustion engine by increasing the pressure of the air or the air-fuel mixture as it enters the combustion chamber. In the exhaust turbine supercharger (see fig. 1) this function is accomplished with a two-unit machine consisting essentially of a centrifugal blower driven by an impulse turbine that derives its motive power from the energy of the engine exhaust gas. With this arrangement of supercharger installed on a conventional aircraft engine there results a two-stage supercharger consisting of the first, or auxiliary, stage and the second, or last, stage; the second stage is internal and integral with the engine and is driven from the crank-shaft by gears.

The operation of the exhaust turbine supercharger and the engine is dependent upon a number of variables that, to a large extent, are interdependent; atmospheric pressure, which affects both the pressure of the engine air entering the blower and the pressure differential across the turbine wheel; the brake horsepower required from the engine, which dictates the quantity and the pressure of the air supplied to it by the blower; the indicated horsepower developed by the engine, which dictates the flow of exhaust gas available for utilization by the turbine; and several less obvious factors, including efficiencies of the turbine and the blower, air-consumption rates of the engine under varying load conditions, efficiencies of the exhaust and intake manifold systems, atmospheric temperature, etc.

As the operating altitude of the exhaust turbine supercharger and engine combination is increased, or the atmospheric pressure is reduced, the air consumption of the engine, to maintain a constant power, is substantially constant, while the work required of the blower as a compressor to maintain this flow of air to the engine rapidly increases. At the same time, however, this reduction in atmospheric pressure has increased the differential across the turbine wheel, thereby increasing the energy available to the wheel for transmission to the blower. Hence, it is seen that, up to the arbitrary design limit of the turbine and blower combination, the unit should be capable of maintaining approximately sea-level operating engine characteristics.

This constant power characteristic appears to be a condition that is desired from power-plant units for our present-day high-performance aircraft in order that advantage may be taken of the increase in speed, comfort, and safety resulting from flight at high altitudes. In addition to this fundamental requirement, it is also necessary to provide an apparatus that will permit the operator, the pilot, the engineer, or the mechanic to control the power plant in any necessary manner. In other words, the flexibility of engine operation must not be impaired by the addition of the exhaust turbine supercharger. Furthermore, the unit must not detract from the present standards of safety and economy of operation that have been established with engines not equipped with exhaust turbine superchargers.

The development of the exhaust turbine supercharger has met with numerous disappointments and failures, some of which have been described in references 1 and 2. It is only necessary to mention here a few of the chief problems related to the design, the installation, and the operation of the exhaust turbine supercharger; namely, handling combustible gases at high temperature; high rotational speeds of turbine wheels and the resultant stresses induced in the blade material, which must of necessity operate at high temperatures; and controls properly designed to match the requirements and the characteristics of the engine, the propeller, and the exhaust turbine-supercharger combination. These problems account for many of the difficulties and the disappointments that have come to some of the country's most brilliant and thorough engineers in their endeavor to meet the standards required of aviation.

During the latter part of 1937, the Pratt & Whitney Division of United Aircraft entered into a contract with the U. S. Navy requiring the installation of exhaust turbine superchargers in a twin-engine flying boat. In conjunction with the contract, the Navy carried on an extensive laboratory test program. When the contract was finally abandoned late in 1939, two series of dynamometer tests under simulated altitude conditions had been completed on the engine and exhaust turbine supercharger combination involved; one series of hot-gas chamber tests had been conducted by the exhaust turbine supercharger manufacturer; and two flight demonstrations were attempted. Although these flight tests were terminated by failure of the turbine wheels, the efforts are considered well spent in view of the data made available.

DESCRIPTION

Engine and exhaust turbosuperchargers.- The airplane in which the exhaust turbine superchargers were installed was a PBY flying boat, a type that has had several years of service to its credit and a reputation for its long-range mass maneuvers. The engine, a Pratt & Whitney Twin Wasp type, likewise has proved performance and reliability through years of service operation. The only modification to the engines in adding the exhaust turbine superchargers was the reduction in the internal supercharger gear ratio to effect a reduction in its critical altitude from 8000 to approximately 6000 feet.

Engine and exhaust turbosupercharger controls.- The exhaust turbosuperchargers were of a conventional impulse type, single-stage turbine with the turbine wheel mounted directly on the supercharger impeller shaft. The units were complete with pressure and scavenging oil pumps, intercooler, and exhaust waste gate.

The control used was the standard Pratt & Whitney Aircraft power and mixture control, as normally used on the airplane and as described by Beardsley (reference 3), with modification to incorporate a double-acting hydraulic servocylinder and changes necessary to match the response characteristics with those of the propeller control. (See fig. 1.) Since the successful operation of an exhaust turbine supercharged engine is definitely affected by the type of control used, as will be discussed later, it is well to describe briefly the function of this control, which was selected for its simplicity of operation. As far as the operator was concerned, the control of the engine with the exhaust turbine supercharger installed was the same as it was previous to the installation of the exhaust turbine supercharger. The two piston rods at opposite ends of the servocylinder were connected to the automatic throttle gates at the carburetor entrance and to the exhaust waste gate. The engine had a critical-altitude functioning on its gear-driven supercharger of approximately 4000 feet with the exhaust turbine supercharger installed, and during full-throttle operation up to this altitude the automatic throttle gates were actuated by one side of the servocylinder piston to throttle the engine down to rated power while the exhaust turbine supercharger waste gate remained wide open. At 4000 feet both the automatic and the manual throttles and waste gate were wide open. Then with increasing altitude the waste gate, actuated by the opposite side of the servocylinder, closed, causing the exhaust turbine supercharger to function and thereby maintain the rated power pressure at the entrance to the carburetor. When the critical altitude of the engine and the exhaust turbine supercharger was reached, the manual and the automatic throttles were still wide open and the exhaust waste gate was fully closed.

The automatic pressure control operated to maintain as desired either one of two pressures at the entrance to the carburetor: that required for rated power or cruising power. Combined with this pressure control was a means of adjusting the fuel flow as adapted to power output. The carburetor was equipped with three main fuel jets, all of which were in operation when the automatic power control was made inoperative by placing the selector lever in the emergency position. As the selector lever was placed to maintain rated-power carburetor pressure, one of the fuel jets was blanked off to produce a fuel flow equivalent to a rich best-power setting. As the selector lever was placed in the position to maintain cruise-power carburetor pressure, the second fuel jet was blanked off, reducing the fuel flow as near to best economy as operating conditions warranted.

Operation of the engine and the exhaust turbine supercharger was remarkably simple for both dynamometer and flight tests because the operator had no controls to adjust other than those used in the normal installation without the exhaust turbine supercharger. A preheater control was provided on the airplane, as on conventional installations, to prevent icing at low altitudes; it was interconnected with a control to vary the amount of cooling air passing through the intercooler. With constant air pressure and reasonably constant air temperature at the carburetor inlet, the power and the fuel consumption for a given engine speed remained almost constant up to the critical altitude of the engine and exhaust turbine supercharger combination. For optimum use of this or any type of control system, the engine should be operated with the manual throttle wide open at all times except when the carburetor-air pressure exceeds the rated-power setting. This arrangement not only reduces the losses in the air system by maintaining the minimum restriction through the carburetor but also allows the automatic features to function with the greatest accuracy and permits the engine to deliver cruising power at relatively high brake mean effective pressures. When the control system is operating in this manner, the pilot must rely upon change in engine speed to effect a change in the power output. The shortcomings of this type of control, discussed in a later section, may be largely overcome by the use of improved carburetion devices recently made available.

INSTALLATION

The installation of the engine and exhaust turbine supercharger combination on the laboratory altitude stand is shown in figure 2. In view of certain physical limitations and structural restrictions present, both the dynamometer and the airplane installations were quite efficient in that the pressure losses were reasonable and the intercooler heat-dissipating capacity was ample. The airplane installation was reproduced as closely as practicable, especially with regard to the control and linkage mechanism.

Operation of the exhaust turbine supercharger under simulated altitude conditions on the altitude stand resulted in external pressures equal to the difference between sea-level and altitude atmospheric pressures. This condition necessitated venting the under side of the turbine wheel, to equalize thrust and balance pressures, and venting the exhaust turbine supercharger lubrication system, to assure normal lubrication. These vents were connected into the exhaust disposal hood, which was designed to fit over the turbine wheel.

PERFORMANCE

<u>Definition of critical altitude</u>.- Before the performance characteristics can be discussed, it is necessary to define the term, "critical altitude." Normally, critical altitude refers to the altitude at which the engine develops rated power with wide-open throttle. For these tests, however, the critical altitude was considered as the maximum altitude to which the rated-power carburetor pressure could be maintained at the entrance to the carburetor or as indicated by the complete closing of the waste gate. Although the power at critical altitude was less than rated power, for reasons that will be apparent, this definition of critical altitude was accepted because of control and operating limitations.

<u>Power obtained</u>.- During the operation on the altitude test set-up, where close control of operating conditions was possible, complete performance data were obtained. The most important results are shown in figure 3 for rated-power condition and in figure 4 for cruise-power condition. The primary purpose for adding the exhaust turbine supercharger in this case was to improve the altitude performance of the relatively low-performance engine that had been thoroughly proved in service and of which the characteristics were well known. The extent to which this result was accomplished is shown in figure 5, where the original engine guaranteed power is compared with the output of the same engine modified by the installation of lower ratio blower drive gears and operated with and without the

exhaust turbine supercharger. The normal rating of this engine was 850 brake horsepower at 2450 rpm and, as originally operated in service, this power could be maintained to an altitude of 8000 feet. The modification of the engine for operation with the exhaust turbine supercharger, by reducing the internal supercharger gear ratio from 11.9 to 10, lowered the critical altitude of the engine to 6000 feet and, with 90° F carburetor-air temperature, this altitude is lowered to approximately 4000 feet. Then with the exhaust turbine supercharger installed, the increased exhaust back pressure and the increased restriction of the carburetor air, the critical altitude of the engine was approximately 3000 feet. The addition of the exhaust turbine supercharger, however, permitted rated power to be maintained to approximately 20,000 feet. Above this altitude, it will be noted that, while the carburetor and the manifold pressure remain constant, the power decreases to 820 brake horsepower, or 96.5 percent of rated power at 26,000 feet. This result was somewhat disappointing, as it was established in the beginning of the project that 25,000 feet would be the altitude to which 100 percent of rated power could be maintained. As a result of the attachment of the exhaust turbine supercharger, however, the output of the engine was increased at 26,000 feet from 47 percent of rated power with the original engine to 96.5 percent of rated power. A study of the results shows the decrease in brake horsepower above 20,000 feet to be caused by the increased exhaust back pressure.

Operation of the engine and exhaust turbine supercharger combination at 100 percent of rated power at 25,000 feet was possible by increasing the control setting. Later phases of the testing included 25 hours of endurance operation at these conditions. Important endurance data are shown in table I. It will be noted that the exhaust back pressure remained at approximately 38.0 inches of mercury absolute. Because of this high exhaust back pressure and the fact that the brake horsepower would have exceeded rated power for all altitudes below 25,000 feet, the performance data were obtained on the basis of the carburetor pressure required to give rated power at sea level.

It is not known whether the sharply rising exhaust back pressure above 20,000 feet, as just discussed, is common to all exhaust turbine supercharger installations. It is expected that the over-all efficiency characteristics of the exhaust turbine supercharger unit would affect the exhaust back pressure obtained and, for this particular unit, the desired requirements relative to minimum powers at high altitudes made it necessary to design the supercharger with maximum efficiency at an altitude considerably below the critical altitude. This condition may account for the increase in exhaust back pressure.

Power limitations.- The results shown in figures 3 and 4 indicate two distinct and separate power limitations; first, that resulting from critical altitude where the exhaust turbine supercharger can no longer deliver the required carburetor pressure and, second, that resulting from a condition of surging in the supercharger of the exhaust turbine supercharger unit. The limitation of power due to critical-altitude conditions can be compared with the corresponding condition for gear-driven supercharged engines, except that the rate at which the power decreases with further increase in altitude is apparently a function of exhaust turbine supercharger design. This characteristic appears to be mainly a function of nozzle area and, from the results of tests of variable nozzle area (fig. 6), the rate at which the power decreases with altitude exceeds that obtained with gear-driven supercharged engines. The operation above critical altitude, as indicated by complete closure of the waste gate, was found to be very stable even though the power appears to drop off sharply.

It is believed possible that the indication of instability in some installations may have been the result of surging, definitely a condition of instability. A study of figures 3 and 4 will reveal the limitations effected by each of the conditions and show that at some engine speeds and power it may be possible to encounter a reduction of power, as limited by the critical altitude, before encountering a condition of instability or surging. During subsequent calibrations, several tests were run under varying conditions of power and speed at and above the critical altitude and at no time was any evidence noted of instability other than that caused by surging of the compressor. In fact, the engine and exhaust turbine supercharger operation seemed to be more stable under those conditions than below the critical altitude because, above the critical altitude, the engine and exhaust turbine supercharger responded directly to the operating conditions without variations due to response of the control.

In order to make an accurate determination of the critical altitude, it was found desirable to make separate runs with the waste gate fully closed to obtain the intersection of the absolute manifold pressure line when operating at these conditions and the absolute manifold pressure line maintained constant by the control for the same speed and power setting. Figure 6 shows an example of such results that were obtained in an investigation of the effect of change in nozzle area on critical altitude. These results are considered important because they show the effect of change in nozzle area on the slope of the brake horsepower curve with closed waste gate, the critical altitude, and the exhaust back pressure. It must be admitted, however, that operation with closed waste gate, especially at altitudes below the critical, is a procedure fraught with much danger to the exhaust turbine supercharger because of possible failure of the turbine wheel, owing to over-speeding.

<u>Power control</u>.- In figure 7 are shown the operating characteristics of the engine and exhaust turbine supercharger at constant altitudes of 10,000 and 20,000 feet. It is interesting to note that, whereas the brake horsepower varies from 845 at an engine speed of 2450 rpm to 360 at an engine speed of 1350 rpm, a change of 57.4 percent, the brake mean effective pressure varies from 149 to 115 pounds per square inch, a change of but 22.6 percent. This reduction in brake mean effective pressure is the result of the reduced absolute manifold pressure caused by the reduction in pressure ratio of the internal-geared supercharger at reduced engine speeds. The variation in exhaust back pressure and engine speed has some effect on the available brake mean effective pressure, but these causes are unimportant compared with the change resulting from change in absolute manifold pressure with engine speed.

This engine was operated in service at a maximum cruising power and speed of 70 percent normal rated power, 600 brake horsepower, and an engine speed of 2150 rpm, respectively. (See fig. 4.) The brake mean effective pressure for this condition is 120 pounds per square inch. The development of more modern engines, constant-speed propellers, and the availability of fuels with higher octane ratings has permitted operators to increase the brake mean effective pressure for cruising, thereby increasing the airplane efficiency. Figure 7 shows that, with this engine and exhaust turbine supercharger combination, power varying from 70 to 53 percent of rated power is obtained with a brake mean effective pressure range from 137 to 126 pounds per square inch with wide-open throttle at engine speeds from 1900 to 1550 rpm. This change in power is effected by adjustment of the engine speeds by means of the constant-speed propeller control.

Since the variation in brake mean effective pressure is a function of absolute manifold pressure, which is in turn a function of the gear-driven engine supercharger design, this condition can be controlled within certain limits. Reducing the losses in air and exhaust systems to a minimum, thereby reducing the amount of supercharging required by the gear-driven engine supercharger, will decrease the variation in brake mean effective pressure and permit operation over a required cruising power range at conditions corresponding more nearly to present air-line practice.

The amount that the supercharging from the gear-driven engine supercharger can be reduced is also limited by the manifold pressure required for take-off power. Some of this required supercharging can be obtained from the exhaust turbine supercharger, and such an arrangement has been considered by some engineers and is being used in one successful installation. It is not believed desirable for the following reasons: If the engine and exhaust turbine supercharger combination are designed for high-altitude operation, the range of pressures and volumes at which the turbine-driven supercharger must operate will limit its efficiency and reduce the critical altitude and the altitude at which surging will be encountered. For safety reasons, it seems desirable to incorporate sufficient gear-driven supercharging to permit development of take-off horsepower without dependence upon the exhaust turbine supercharger. Also, it must not be forgotten that the gear-driven engine supercharger serves a secondary purpose in radial aircraft engines, that is, improving distribution. For engines with fuel-injection systems, this disadvantage does not exist.

Another method of maintaining a more nearly constant brake mean effective pressure is by using a variable amount of exhaust turbine supercharging. With this method, the exhaust turbine supercharger would be required to maintain increasing pressures at the outlet of the compressor with decreasing engine speed. This method also has a limitation, as shown by the curves of waste-gate position in figure 7. The exhaust turbine supercharger operates progressively closer to its limit; that is, the critical altitude for a given cruise power decreases as the amount of supercharging from the exhaust turbine supercharger is increased.

<u>Power recovery</u>.- One of the critical features of any exhaust turbine supercharger control system is ability of the engine to recover power at altitude after complete throttling or a condition of surging has been induced. This surging may be encountered due to complete throttling, reduction in power by decreasing engine speed, or by increasing altitude. Surging occurs at low air flow but, since it is a characteristic of the supercharger alone, it may occur with or without closed waste gate. In order to stabilize operation and thereby regain power, one of two conditions must be altered: increase the air-flow requirements or reduce the supercharger pressure rise. The air-flow requirements can be increased by increasing the engine speed or decreasing the operating altitude, and the supercharger pressure rise can be reduced only within the limits of the operating control or by reducing the operating altitude. For obvious reasons, increasing the engine speed and decreasing the operating altitude are not always desirable but are a means by which engine power can be regained after a condition of surging has been encountered.

Owing to the difference in inertia loads and the difference in controlling the artificial altitude conditions provided at the supercharger inlet and the turbine exhaust outlet, it was impossible to determine accurately the ability of the control system to recover power on the dynamometer. Some attempts were made but with little success. During the flight tests made with the flying boat, this characteristic was checked at altitudes up to the critical altitudes. In all cases, power recovery was obtained and, after some practice, an effective method was devised to reduce the time lag inherent in the engine and exhaust turbine supercharger combination. This method consisted in starting the recovery from idling or closed throttle with the automatic control in the cruise position and the propeller set for low engine speeds. As the engine and the exhaust turbine supercharger began to accelerate slowly, the propeller blade-angle setting was decreased, allowing the engine to accelerate under light load. This condition supplied the exhaust turbine with sufficient exhaust gas to permit the supercharger to build up a pressure. As the output of the exhaust turbine supercharger approached that required for cruising, the control was shifted into the rated-power position and the propeller setting was increased to rated engine speed. This procedure resulted in complete regaining of power in a relatively short interval of time. Recovery of power was also possible with the control in the rated-power position and the propeller control set for rated engine speed, but the time for complete recovery was considerably longer than required by the first procedure.

Control improvement.- It is desired to point out the desirability of using the more modern carburetion devices now available because of possible improvements in the type of control that can be used. The pressure control could have infinitely selective pressure settings that would simplify the procedure of regaining power after complete throttling, and stabilization of conditions after a condition of surging is encountered without appreciably sacrificing operating altitude or without manipulation of the propeller control. Such a control system, operating from manifold pressure, would also permit cruising operation approaching more nearly the present practice of high brake mean effective pressure and low engine speeds. In some types of aircraft where maneuverability is of importance, a completely manual control, in conjunction with an automatic carburetor, may suffice; such a control might be so designed that the first part of the quadrant opened the carburetor throttle and the remaining portion of the quadrant closed the waste gate. Dynamometer and flight tests indicated that the exhaust turbine supercharger responds very rapidly to changes in waste-gate position.

Stability.- A second objectionable characteristic of great importance that has resulted in unsatisfactory performance of many exhaust turbine supercharger installations is the inherent instability of the exhaust turbine supercharger control, which causes violent hunting. This characteristic has, in most cases, been due to the use of controls possessing insufficient damping to compensate for the slight response lag of the exhaust turbine supercharger. This characteristic of exhaust turbine supercharger installations has been further exaggerated in the more recent installations by the use of constant-speed propellers, in which the slope of the propeller-governor response curve has been nearly the same as the slope of the pressure-control response curve. When this result occurs, both controls may be stable in themselves but the combination will result in an unstable combination. The typical cycle of operation of such a combination might be briefly described as synchronized out-of-phase. When this cycle occurs, both controls react violently, and the cycle may continue indefinitely; if allowed to continue, the action may result in detrimental power surges. For a satisfactory installation, such fluctuations should be limited to not more than one complete cycle, with preferably but half a cycle.

In these tests, both the carburetor-pressure control and the propeller control were individually tested prior to their installation in the flying boat to make sure that neither possessed inherent hunting characteristics. The pressure control was then reworked to provide the minimum response lag possible because it was known that the response of the propeller control was relatively slow and it was desired to make their rate of response as different as possible. In combination, the result was excellent in that not only was there no hunting present under any operating condition but the rate of pressure response was so far in excess of that of the propeller control that the desired pressure was attained long before the governor revolution speed was reached and then remained constant during the interval of time required for the governor to stabilize the engine speed.

It has been previously mentioned that the control and the carburetor combination was selected for its simplicity, ease of control, and automatic-control features. The results of specific fuel consumption and fuel-air ratio shown in figures 4 and 7, respectively, indicate the extent to which this combination fulfilled the expectations upon which the selection was based. The fuel-air ratios obtained relative to engine power or speed are typical metering characteristics of the float-type carburetor and were satisfactory for all operating conditions except above critical altitude, where the fuel-air ratio rapidly increased. Control of carburetion on the basis of the fuel-air ratio is essential because it is not affected by changes in mechanical efficiency as is the specific fuel consumption.

Here again the use of recently developed carburetion devices offers the advantage of better control of the fuel-air ratio inherent in the design. These carburetion devices can be very similar to the conventional type used on engines with gear-driven supercharger including automatic rich and lean settings but with compensation functioning on the basis of carburetor-entrance pressure rather than on the basis of air flow. The compensation on the basis of carburetor-entrance pressure is essential in order that the carburetor shall operate to best advantage with the type of control having infinite variable-pressure settings as previously described and also to prevent the possibility of the engine and exhaust turbine supercharger operating at its critical altitude with high carburetor pressures, causing high turbine wheel speeds, and with lean mixtures, resulting in high exhaust temperatures; the combination of the two conditions might possibly exceed the safe operating limits of the turbine wheel.

Fuel economy and efficiency.- The degree of economy that can be obtained with an engine equipped with an exhaust turbine supercharger has long been the subject of controversy between the engine and the exhaust turbine supercharger manufacturers; this point of difference has arisen mainly because the exhaust turbine supercharger manufacturers have been reluctant to sanction operation at exhaust temperatures resulting from lean mixtures. In the present installation it was essential that the exhaust turbine supercharger have no deleterious effect on the fuel economy at cruising powers because the airplane involved was designed and intended for extended cruising. The carburetor settings were therefore adjusted to operate the engine at a mixture as close to best economy as practical. Because the specific fuel consumption obtained with the cruise-power control setting (fig. 4) was 0.460 pound per brake horsepower per hour or less for most of the altitude and the power range, and approximately 0.440 pound per brake horsepower per hour during the 25-hour endurance operation at maximum cruise power, this installation is considered to demonstrate that this engine and exhaust turbine supercharger combination is inherently capable of operating at cruise powers at all altitudes with specific fuel consumptions equal to the minimum obtainable on the same engine at sea level without the exhaust turbine supercharger installed. A determination of the corresponding exhaust-gas temperatures for these specific fuel consumptions from figures 8 and 9 show that the temperatures were maximum and the operation was therefore not limited in this respect for cruise-power conditions. It should be noted here that the temperatures encountered exceeded the maximum limits established by the turbine manufacturer. Owing to this fact, it is improbable that the maximum cruising power could have been increased at the same fuel-air ratio without damage to the turbine.

Of less importance is the specific fuel consumption required for rated-power conditions because normally the engine requirements are far in excess of best economy.

For these tests, the carburetor settings gave an average fuel-air ratio and specific fuel consumption for rated power of 0.090 and 0.590 pound per brake horsepower per hour, respectively, which was comparable with that obtained on the same engine without the exhaust turbine supercharger installed. It is important, however, to note that, if of necessity or by accident, the fuel-air ratio had been reduced to correspond to the maximum exhaust temperature while operating at rated power, the safe operating temperature of the turbine wheel would have been exceeded. Such a condition at rated altitude, where the turbine is operating at or near its maximum safe operating engine speed, would cause damage or complete failure to the turbine buckets.

The curves shown in figures 10 and 11 are an attempt to compare, on the basis of equal carburetor-entrance pressure, the engine performance obtained using the exhaust turbine supercharger with the estimated performance of the same engine using a two-stage gear-driven supercharger. It was assumed that, in each case, the mechanical friction horsepower was equal and need not be considered. The upper curve AC of horsepower against altitude obtained with the exhaust turbine supercharger removed with standard altitude exhaust pressure and for a carburetor-entrance pressure equal to that obtained with the engine and exhaust turbine supercharger combination, represents the brake horsepower of the engine without any deduction for horsepower required to drive the supercharger. The middle curve AB is the horsepower output of the engine equipped with exhaust turbine supercharger. Then, from the pressures and the air flows obtained for the AC run and an assumed adiabatic shaft efficiency, the horsepower required for the gear-driven supercharger was calculated. Subtracting those values from the upper curve resulted in the curves ADEFG and ADEHIG, which estimated the performance of the engine with the gear-driven supercharger.

These curves indicate that less power is absorbed from the engine by the exhaust turbine supercharger than by the gear-driven type for a given amount of supercharging. They therefore substantiate the claim that the use of an exhaust turbine supercharger will result in a reduced minimum specific fuel consumption, provided that such operation can be conducted within the operation limits of the exhaust turbine supercharger and engine. From the same curves, it can be seen that the engine with the exhaust turbine supercharger has a greater advantage when compared with the engine with gear-driven supercharger operating at part throttle because the exhaust turbine supercharger has infinitely variable-speed control that varies to suit the air-consumption and the pressure requirements, without loss due to throttling, as is the case with the gear-driven supercharged engine. This advantage in net brake horsepower available has a proportional effect on the minimum specific fuel-consumption requirements.

This comparison is not on the basis of equal indicated performance because the volumetric efficiency and the air flow at a given brake horsepower of the engine varies with the exhaust back pressure. For a more accurate comparison, the run represented by the curve of brake horsepower without deduction for supercharger horsepower should therefore have been for the same air consumption as was obtained during the run represented by the curve of brake horsepower for the engine with the exhaust turbine supercharger. Such a comparison would show an even greater advantage, approximately 10 to 7 percent, for the exhaust turbine supercharger in net brake horsepower and fuel economy, as is apparent from the specific air consumption curves shown in figures 10 and 11.

A comparison of shaft efficiencies for the two types of supercharger, gear-driven and exhaust turbine-driven, is of little value since the method of driving, in each case, is different. For the gear-driven supercharger, adiabatic shaft efficiency does represent a figure of interest to the engine manufacturer because it is a measure of power required from the engine for supercharging. This efficiency is fairly simple of determination, and much reliable and accurate information has been obtained on the subject. This value can be compared with what might be called the "effective efficiency" of the exhaust turbine-driven supercharger shown in figure 12. The effective efficiency is the ratio of the power required for adiabatic compression of the air consumed to the power lost by the engine resulting from the increase in the exhaust back pressure due to the use of the exhaust turbine supercharger. This value is not a true measure of the efficiency of the exhaust turbosupercharger because no attempt is made to measure the power input to the turbine. It is significant, however, as a measure of effectiveness of the exhaust turbine supercharger as a method of supercharging to a given carburetor pressure in comparison with other methods.

The effective efficiencies shown in figure 12 cover operation at rated and cruising powers and speeds with the turbine as modified for this installation. It is noteworthy that the exhaust turbine supercharger appears to possess an advantage at high power but a disadvantage at low power in comparison with typical gear-driven superchargers. The compressors of both the turbine-driven and the gear-driven types are of the same general character and should have approximately the same shaft efficiencies at their design operating conditions. It is therefore evident that the difference in effective efficiency of the exhaust turbine supercharger and the gear-driven supercharger lies in the method of driving and the effect that each method has on engine operation.

The relation of the curves shown in figure 12 does not mean that the exhaust turbine is a less efficient method of supercharging for cruising power but indicates that it has a greater effect upon engine performance for a given degree of supercharging or for a given carburetor pressure. An analysis on the basis of equal indicated performance, as indicated by the specific air-consumption values in figures 10 and 11, shows the exhaust turbine method of supercharging to be more efficient than the gear-driven method of supercharging by approximately 10 and 7 percent for rated-power and cruise-power conditions, respectively. In the comparison of efficiencies it must be remembered that the use of the exhaust turbine supercharger largely eliminates the propulsive thrust available from the engine exhaust so that the true picture can be obtained only after a thorough study of the relative total propulsive efficiencies obtainable from propellers and engine exhaust jets for the particular condition involved.

The increase in effective efficiency shown as the result of increased turbine nozzle area is indicative of the importance of correlation of turbine design with the engine and the aircraft operating conditions to be met. The increase in nozzle area in this case was accompanied by a decrease in critical altitude and a decrease in range of operating conditions at cruising powers. This result also points to the necessity of turbine design correlation with engine and aircraft requirements because it affects engine reliability as well as performance. Although limits are not definitely established, the general belief is that high exhaust back pressures are detrimental to engine life. It appears, then, that the application of an exhaust turbine supercharger would hinge upon a decision of the most desirable compromise between efficiency, operating conditions, and reliability.

Buck (reference 4) discusses the relationship between load coefficient (Q/N, where Q is the volume of air in cu ft/min and N is the impeller rotational speed) and adiabatic efficiency; Buck indicates that, for a given supercharger and impeller design, there is a relatively narrow range of load coefficient at which the maximum adiabatic efficiencies may be obtained. The results of these tests indicated that the load coefficient varies over a wide range with engine power and speed for a given altitude and carburetor pressure. Since the normal efficient range does not usually exceed 20 percent, it is obvious that the supercharger of this exhaust turbine supercharger unit contributes to the high exhaust back pressure at rated power and altitude as previously discussed.

This condition also offers an explanation for the surging condition encountered at high altitudes and powers. Since the phenomenon of surging may be explained as intermittent aerodynamic stalling of the impeller blades, it would be expected to occur at low values of the load coefficient. This result is evidently the case because the load coefficient decreases with increasing altitude at any given engine speed and carburetor pressure. By reference to figures 3 and 4, it will be seen that this explanation is in agreement with the general trend of the power calibration.

Reliability.- As the result of the failure of the turbine wheels during the first attempted flight tests, two series of ground tests were conducted to determine and prove safe operating limits. The first of these tests consisted in operating the exhaust turbine supercharger with a supply of hot gases generated in a closed chamber by the combustion of oil and air in a suitable burner. The turbine was loaded by the supercharger operating at conditions equivalent to the rated-power engine requirements for an altitude of 25,000 feet. Tests were run in 1-hour periods and the wheel diameter was measured, after cooling, following each run. The tests consisted in runs at constant engine speed and increasing temperature and runs at constant temperature and increasing engine speed. The results of the two tests follow:

(a) Constant engine speed of 22,000 rpm - several buckets failed after 59 minutes' operation at 1750° F.

(b) Constant temperature of 1600° F - one bucket failed after 52 minutes' operation at engine speed of 22,000 rpm.

The limits established were as follows:

	Nozzle-box exhaust temperature (°F)	Turbine-wheel rotational speed (rpm)
Rated power	1600	21,000
Cruise power (limited duration)	1700	18,000
Cruise power (extended duration)	1650	18,000

The second series of tests was conducted on a dynamometer installation in which the exhaust turbine supercharger was equipped with a turbine wheel of improved material, a cooling cap of the same design as the one used in the airplane installation, and an exhaust disposal hood of approximately the same shape and dimensions as the hood used on the airplane installations. The endurance test consisted of two 25-hour periods, the first period at rated power and altitude and the second period at maximum cruising power and rated altitude. The important results of the endurance test are given in table I.

Examination of the results in table I shows that the endurance test was conducted at conditions exceeding the specified safe limits. Throughout the tests, measurements of the turbine wheel were obtained and the only measurable blade stretch indicated was the initial set that occurred during the first 3 hours of operation preliminary to the endurance run. Furthermore, the flow of air through the cooling cap of the turbine wheel was gradually reduced and completely shut off during the last 11 hours of the test at the higher exhaust temperature. The cooling air blast to the engine was also reduced to what was considered to be the minimum safe limit. Since the turbine-wheel measurements indicated no deterioration of the buckets, everything was done to test the turbine under the most severe conditions that it might encounter in service; it finished all the tests in excellent condition.

As a result of these dynamometer tests, it was concluded that the exhaust turbine supercharger as now constructed, with the wheel of improved material and with the cooling cap, was satisfactory for tests in the airplane.

Failure of the turbine wheel during the first attempted flight test was attributed to excessive temperature caused by afterburning. Afterburning tests were conducted with the new turbine, cooling cap, and exhaust disposal hood on the altitude dynamometer to establish the limiting fuel-air ratio productive of afterburning. Because of the differences in test and flight conditions, the results obtained were inconclusive.

The second attempted flight test was terminated by failure of one turbine wheel, although operating conditions had been maintained within the maximum limits established during the dynamometer operation. The airplane installation and the dynamometer installation were as similar as it was possible to make them and yet simulate altitude conditions on the dynamometer. In view of the failure, however, it is obvious that one or more of the assumptions made in this regard were unjustified or had an unsuspected effect on turbine operation. It is apparent that further tests should be conducted in which the temperatures of the turbine wheel and buckets are measured because these appear to be the critical members of the unit and the measurement of surrounding temperature is of little or questionable value.

In general, it can be said that these tests have proved that exhaust turbine superchargers of the design and material similar to that used in the units tested operate too near their maximum safe operating conditions. The fact that some successful exhaust turbine supercharger installations have been made indicates that conditions can be controlled and the following suggestions for controlling the operating conditions may have merits worthy of investigation:

(a) Cooling of exhaust gas

(b) Direct air cooling of turbine buckets

(c) Reduction in turbine speed by using a two-stage compressor

(d) Reduction in exhaust-gas temperature by increasing engine compression ratio

Method (d) is of particular interest because such an engine would be suitable for high-altitude long-range aircraft on account of the inherent low specific fuel consumption characteristics.

The ideal engine and exhaust turbine supercharger combination, with regard to reliability, is one that would permit operation at all conditions of power, engine speed, fuel-air ratio, and altitude without danger of failure caused by exceeding the limits of the exhaust-gas temperature and the turbine-wheel rotational speed. In other words, the exhaust turbine supercharger turbine buckets must be constructed of a material with sufficient strength, when operating with exhaust-gas temperatures at the maximum value, to withstand the stresses resulting from the maximum turbine-wheel rotational speed. Until such a time as bucket material with these properties is available, some foolproof means of limiting the exhaust-gas or turbine-bucket temperature by cooling or by control of the fuel-air ratio is a necessity.

The exhaust-gas temperature and the mass-flow data plotted in figures 8 and 9 should be of value for the analysis of the exhaust turbine supercharger design and installation problems. An analysis of these data reveals that the exhaust-gas temperature varies noticeably as a direct function of the engine speed; the values shown can therefore be considered only as indicative. From this result it would appear that the exhaust turbine supercharger manufacturer's problem is becoming more severe because the demands of industry for increased engine output are in many cases being met by increasing the engine speed. The availability of fuels of high knock rating and the demand for lower specific fuel consumption have resulted, however, in some increase in compression ratio, which lowers the exhaust-gas temperature and compensates to some extent for the increase resulting from the increased engine speed.

These data also indicate that the specific weight of exhaust gas is a minimum at a mixture strength slightly richer than that for best economy and maximum temperature. This weight was also found to be independent of operating altitude. By use of such data and the information presented in reference 5, the turbine manufacturer is able to calculate the total gas energy available at any condition. It should be noted here that cruising at high brake mean effective pressures by reduction of engine speed to obtain low specific fuel consumption, imposes the most severe condition on the turbine because it is the condition at which the exhaust-gas temperature is a maximum and the turbine rotational speed is relatively high.

CONCLUSIONS

The analysis of the dynamometer and flight test results indicates that an engine with a two-stage supercharger in which the first stage is exhaust turbine driven will deliver rated power for a given indicated power to a higher altitude, will operate more efficiently, and will require simpler controls than a similar engine in which the first stage of the supercharger is driven from the crankshaft through multispeed gears. This efficiency of operation is more pronounced at altitudes and powers where the maximum safe output of the engine with the gear-driven supercharger is restricted by throttling.

The selection of the most desirable type of supercharging will depend upon the type of operating conditions involved rather than upon the aircraft design because the main factors involved are: critical altitude required, relative flying time spent at rated and cruising power, and the relative importance and efficiencies available from propeller and exhaust-jet propulsion.

The stability of operation of an engine with an exhaust turbine supercharger is entirely satisfactory if the turbine-driven supercharger is not permitted to operate beyond the surging point and if the response of the pressure control and propeller-speed control are properly matched. The availability of fully automatic carburetion devices will permit the use of an infinitely variable pressure control, which will simplify and improve exhaust turbine supercharger operation. The reliability of the turbine of present-day exhaust turbine supercharger units is questionable because they operate at speeds and temperatures that allow an insufficient margin of safety.

Extensive flight testing will be required to show the extent to which the advantages of an engine with exhaust turbine supercharger can be realized. The inherent disadvantages of the exhaust turbine supercharger weight and installation problems resulting from the necessity of handling exhaust gas are the chief problems. Weighing the advantages and the disadvantages indicates that there is an altitude below which the use of the exhaust turbine supercharger is not warranted.

It is believed that the main aerodynamic disadvantage in using the exhaust turbine supercharger can be overcome by the use of an exhaust-disposal hood. The use of the exhaust turbine supercharger will partly, if not completely, eliminate any possible thrust from exhaust-jet propulsion.

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TABLE I

	Nozzle-box exhaust temperature (°F)	Turbine-wheel rotational speed (rpm)	Fuel-air ratio	Specific fuel consumption (lb/bhp/hr)	Absolute pressure (in. Hg)	
					Nozzle box	Super-charger outlet
Rated power:						
Average	1490	22,000	0.090	0.59	37.8	28.0
Maximum	1525	22,400	.095	.61	38.2	28.6
Minimum	1400	21,200	.087	.575	37.5	27.0
Cruise power:						
Average	1675	18,700	.071	.445	27.7	23.0
Maximum	1715	19,100	.073	.450	29.0	23.4
Minimum	1600	18,400	.069	.440	26.5	22.5

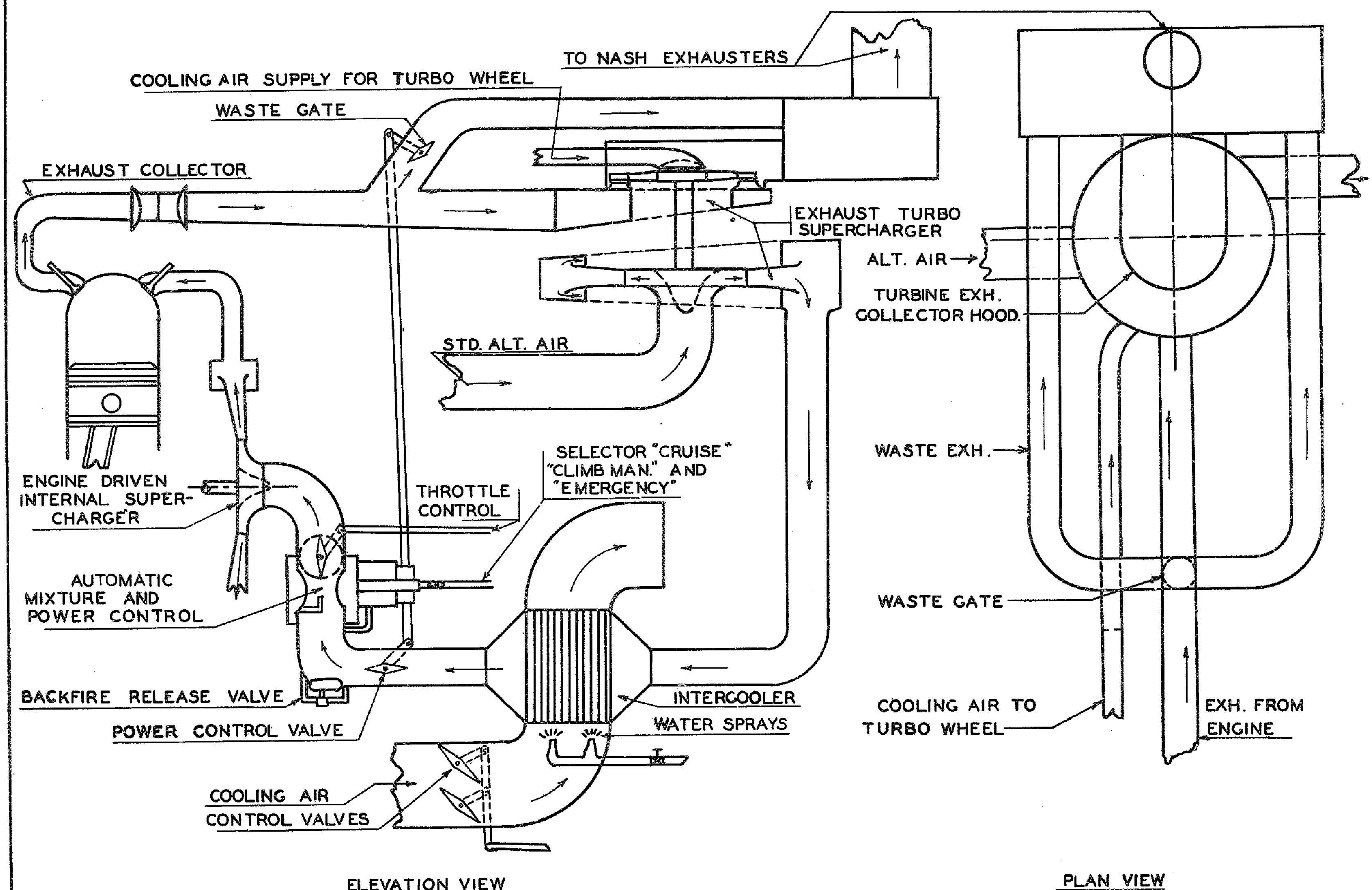

Figure 1.- Diagrammatic sketch of engine and exhaust turbine supercharger installation on the laboratory altitude stand.

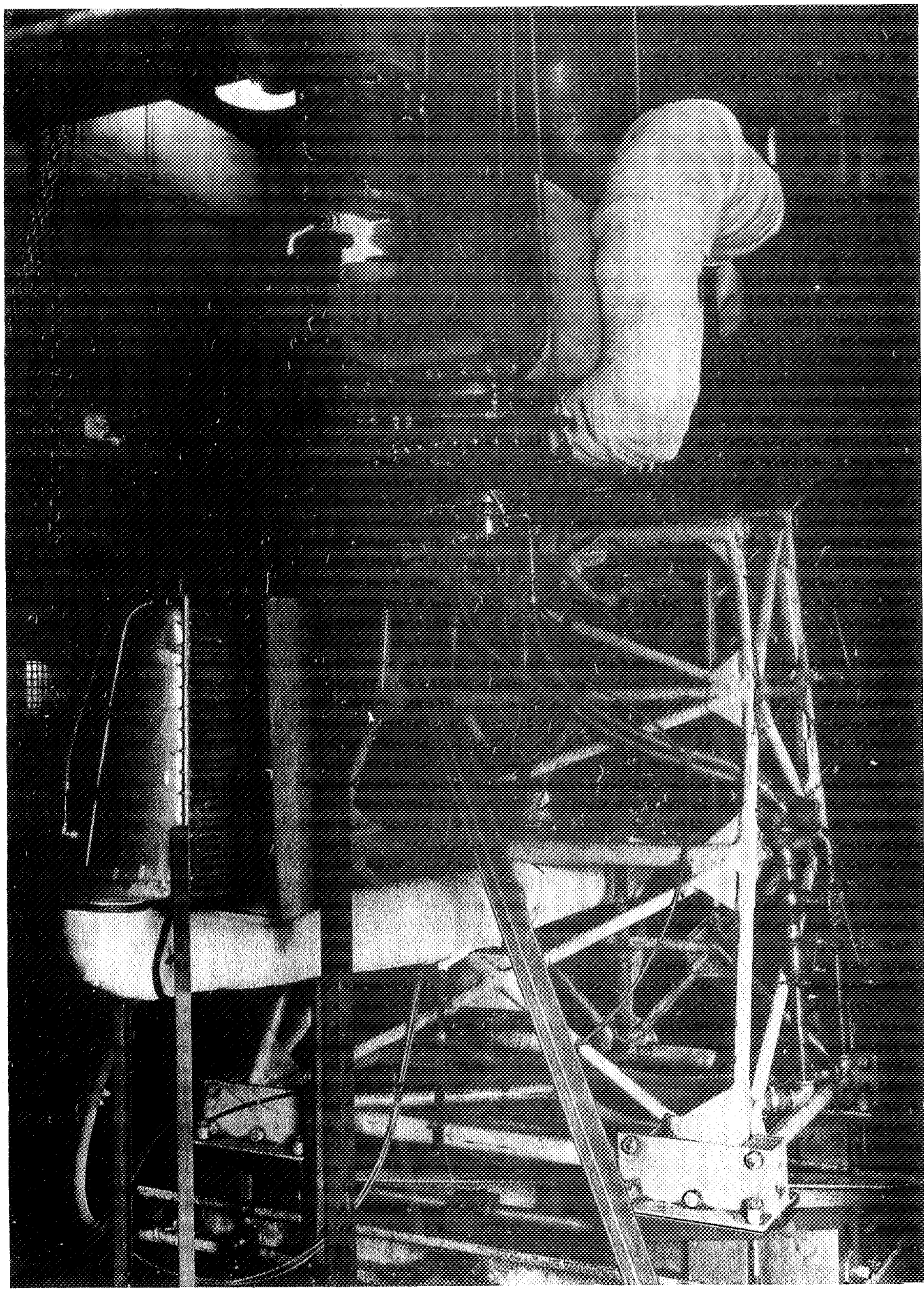

Figure 2.- The engine and the exhaust turbosupercharger installation on the laboratory altitude stand.

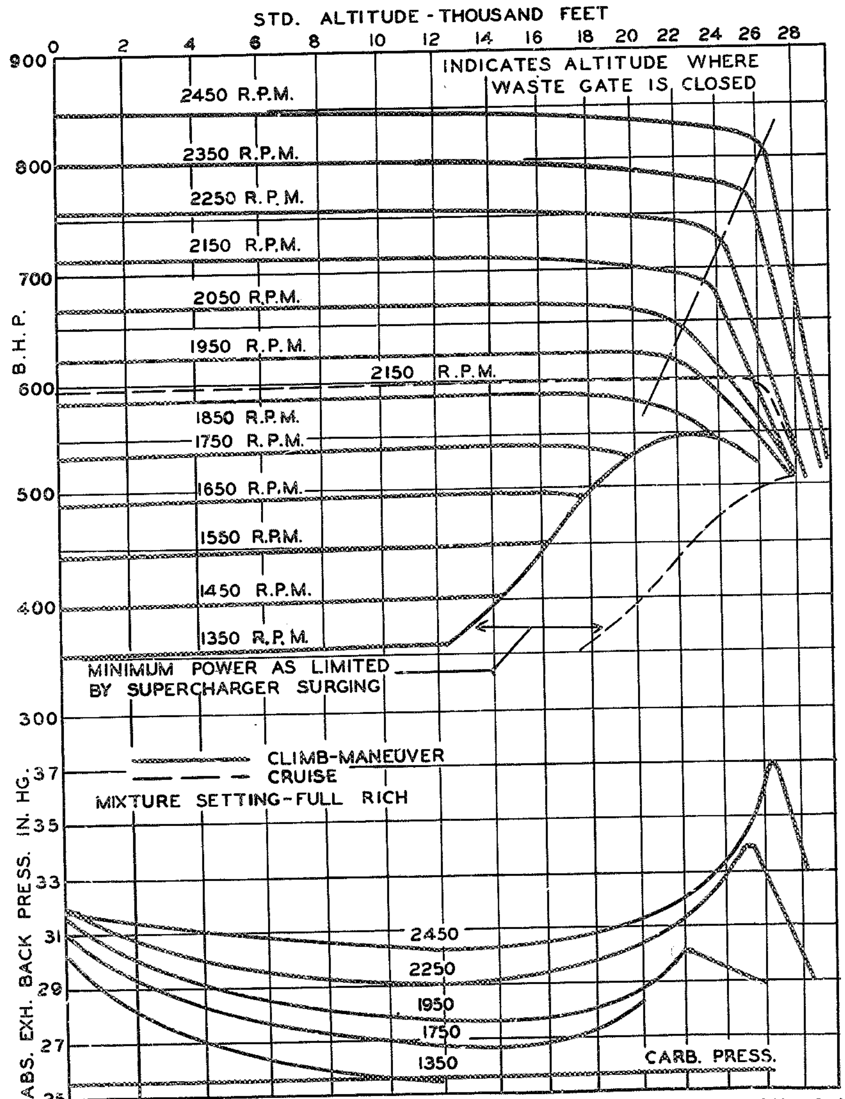

Figure 3.-Variation of brake horsepower and exhaust back pressure with altitude for engine and exhaust turbine supercharger installation. Rated-power carburetor pressure.

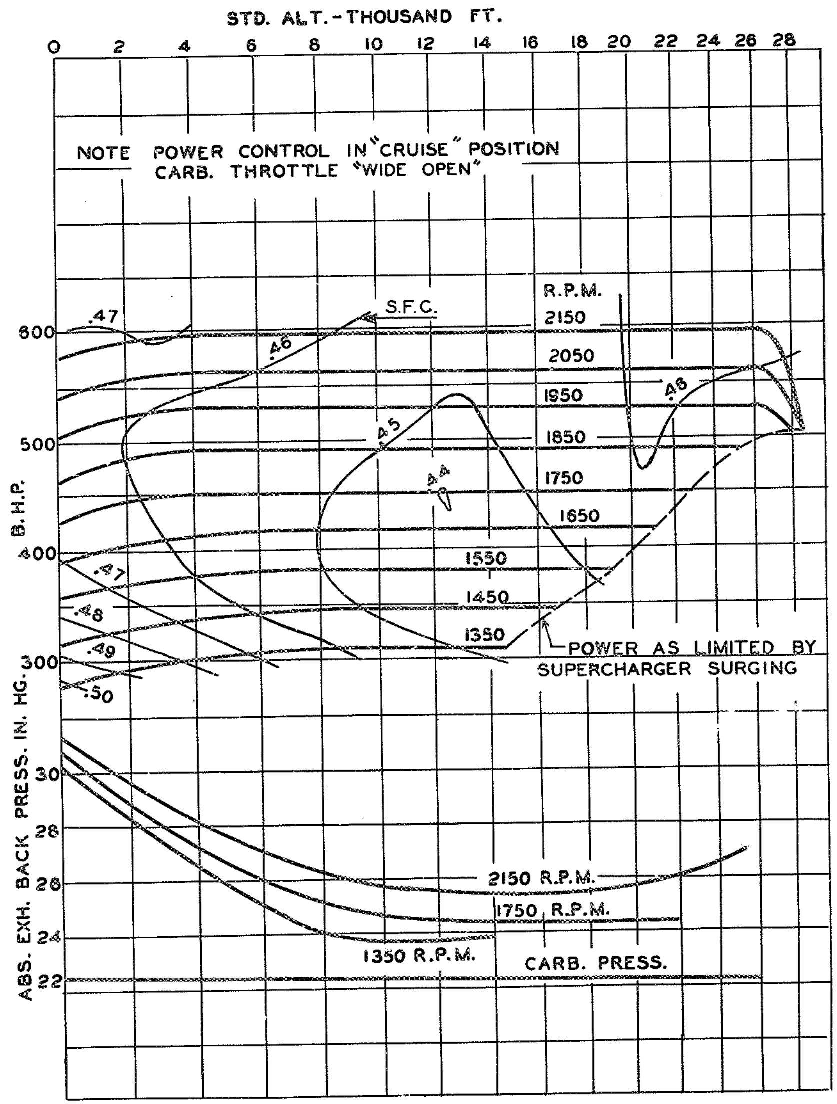

Figure 4.-Variation of brake horsepower, specific fuel consumption, and exhaust back pressure with altitude for engine and exhaust turbine supercharger installation. Cruise-power carburetor pressure.

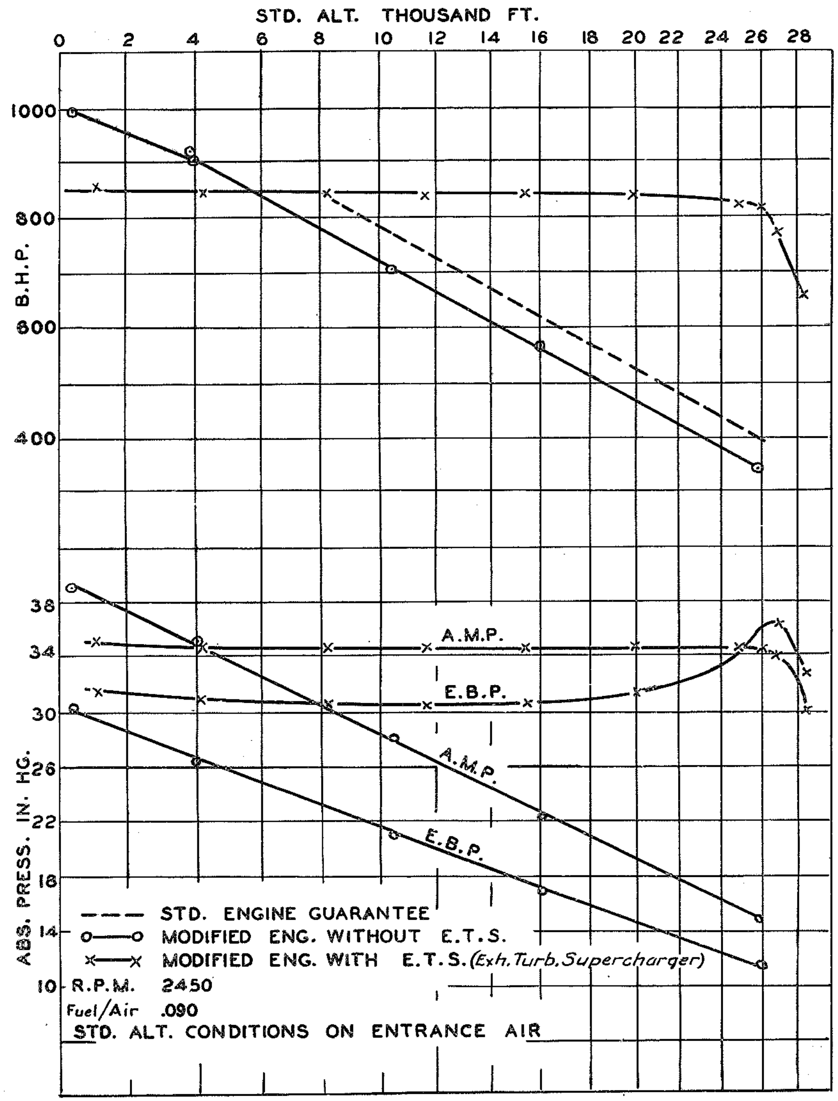

Figure 5.- Variation of brake horsepower, exhaust back pressure, and absolute manifold pressure with altitude for rated engine speed before and after installation of exhaust turbine supercharger. Engine speed, 2450 rpm; fuel air ratio, 0.090; standard altitude conditions on entrance air.

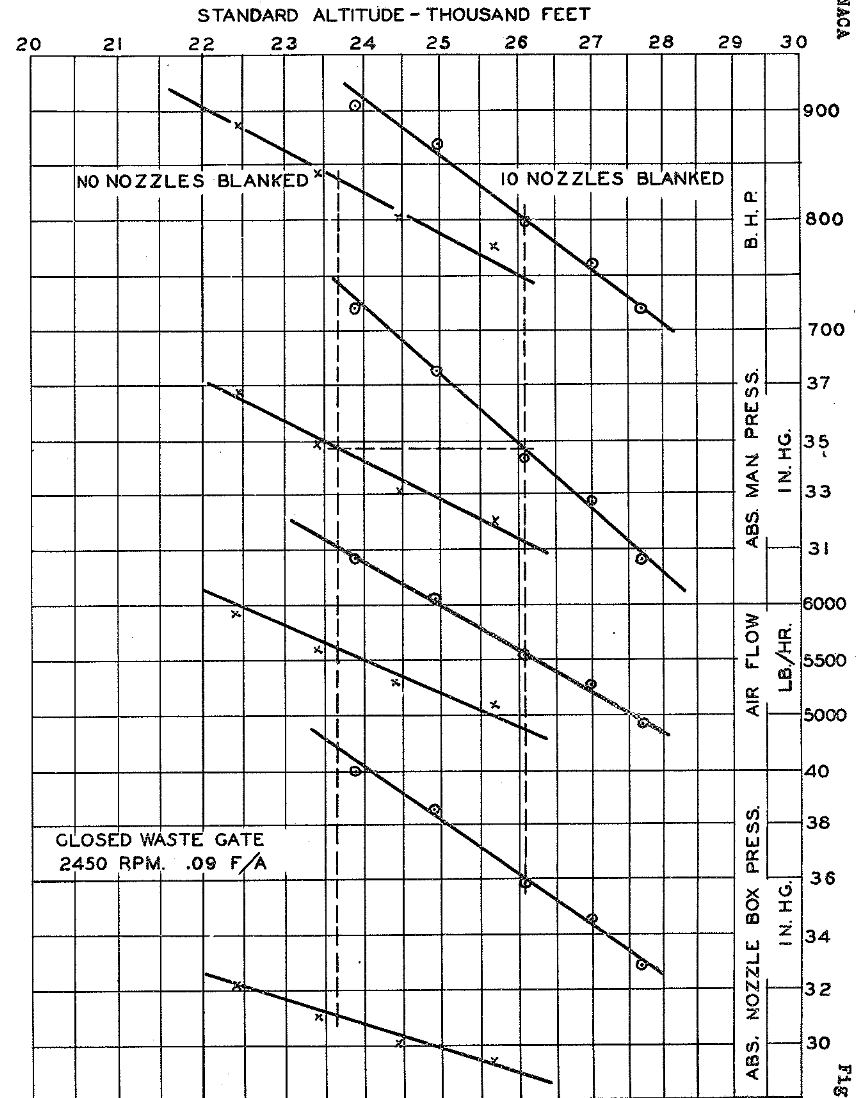

Figure 6.-Variation of brake horsepower, exhaust back pressure, and absolute manifold pressure with altitude. Effect of nozzle area on critical altitude and exhaust back pressure. Engine speed, 2450 rpm; fuel-air ratio, 0.090; closed waste gate.

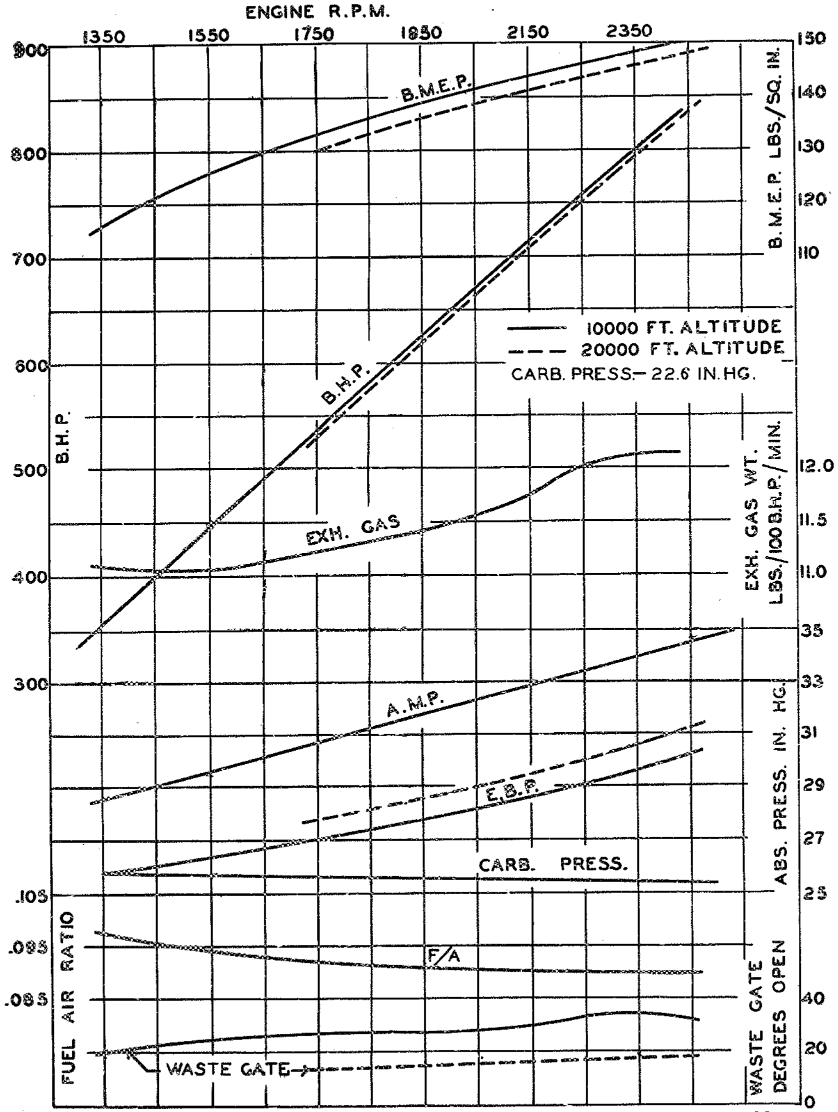

Figure 7.-Variaiton with engine speed of brake horsepower, brake mean effective pressure, absolute manifold pressure, exhaust back pressure, fuel-air ratio exhaust-gas weight, and waste-gate position for 10,000-and 20,000-foot altitudes.

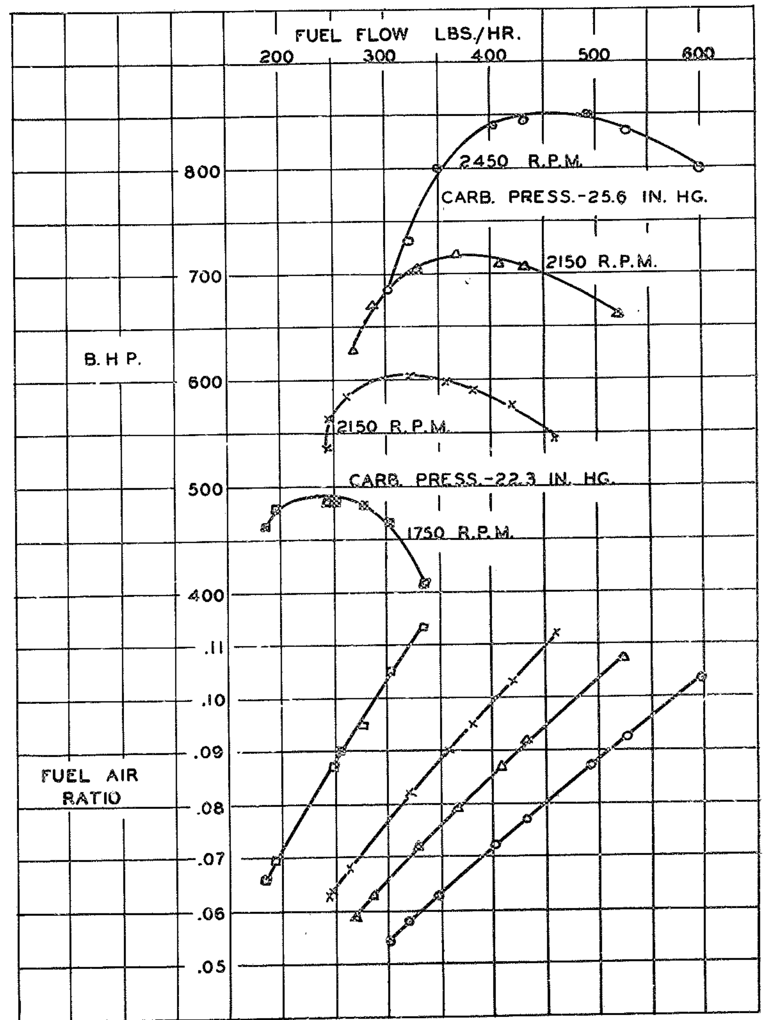

Figure 8.-Variaiton with fuel flow of exhaust gas temperature and weight and specific fuel consumption for several engine operating conditions.

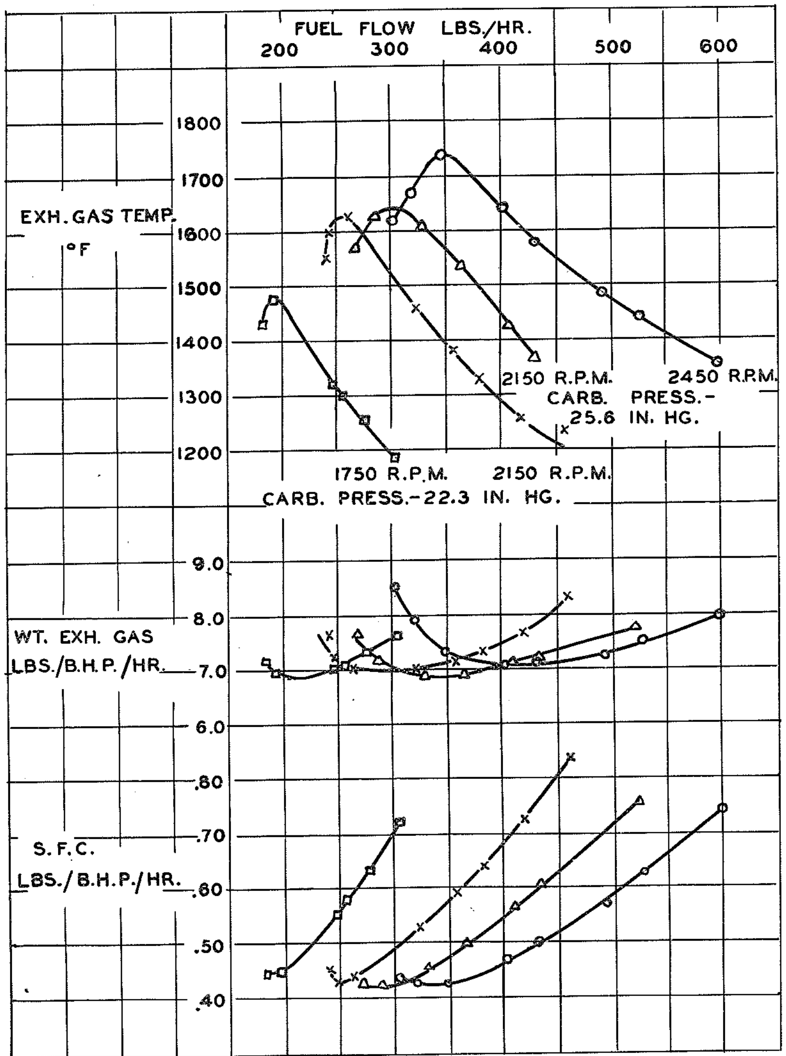

Figure 9.-Variation with fuel flow of brake horsepower and fuel-air ratio for several engine operating conditions.

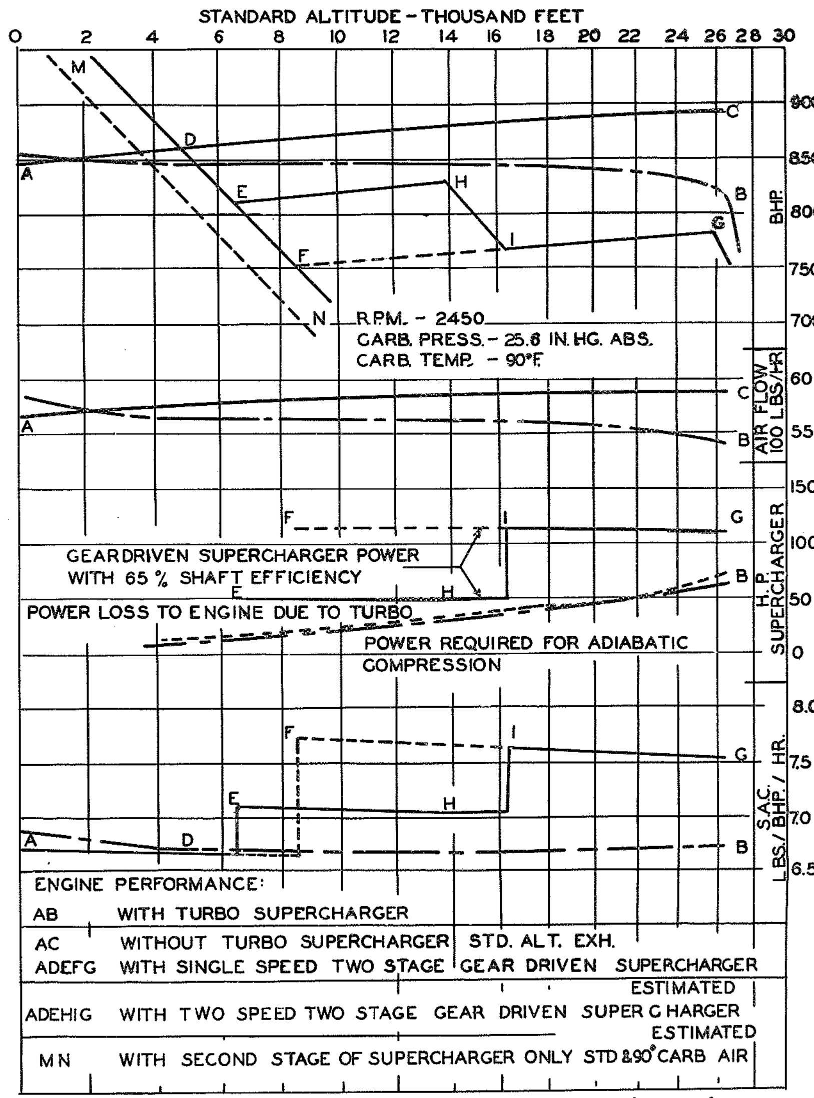

Figure 10.-Variation with altitude of brake horsepower, supercharger horsepower, and specific air consumption. Comparison of engine performance with exhaust turbine and gear-driven superchargers for a condition of rated-power carburetor pressure.

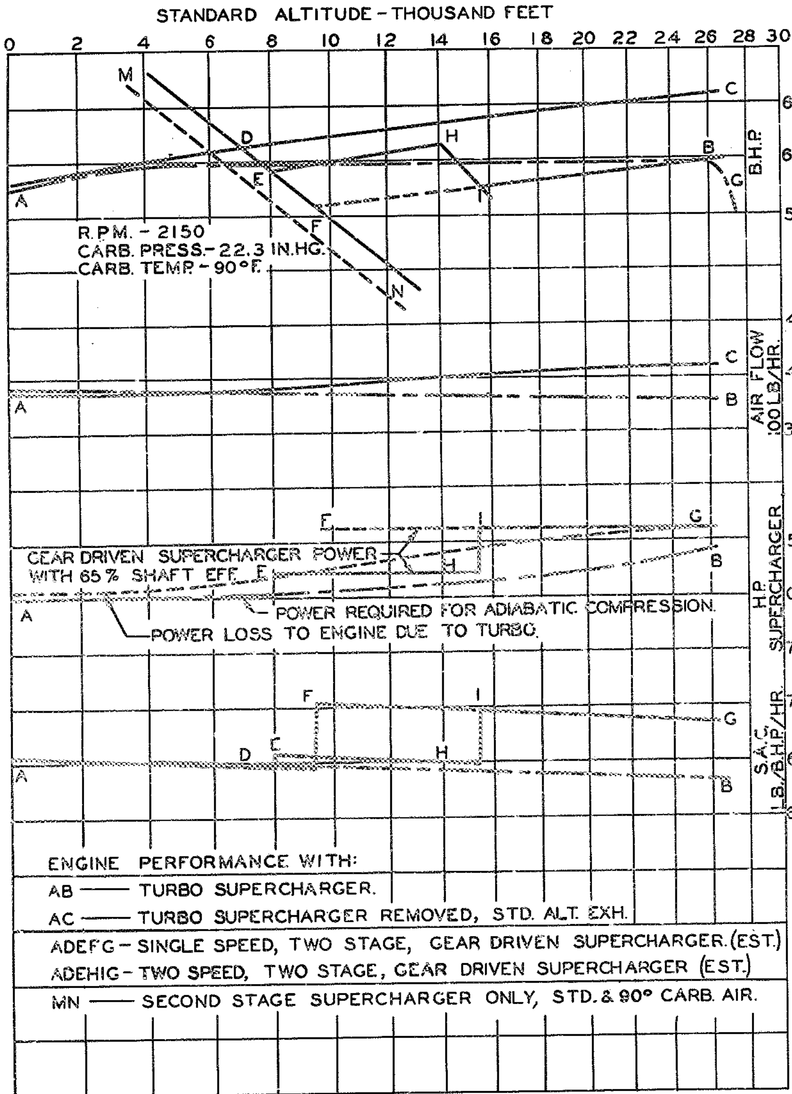

Figure 11.-Variaiton with altitude of brake horsepower, supercharger horsepower, and specific air consumption. Comparison of engine performance with exhaust turbine and gear-driven superchargers for a condition of cruise-power carburetor pressure.

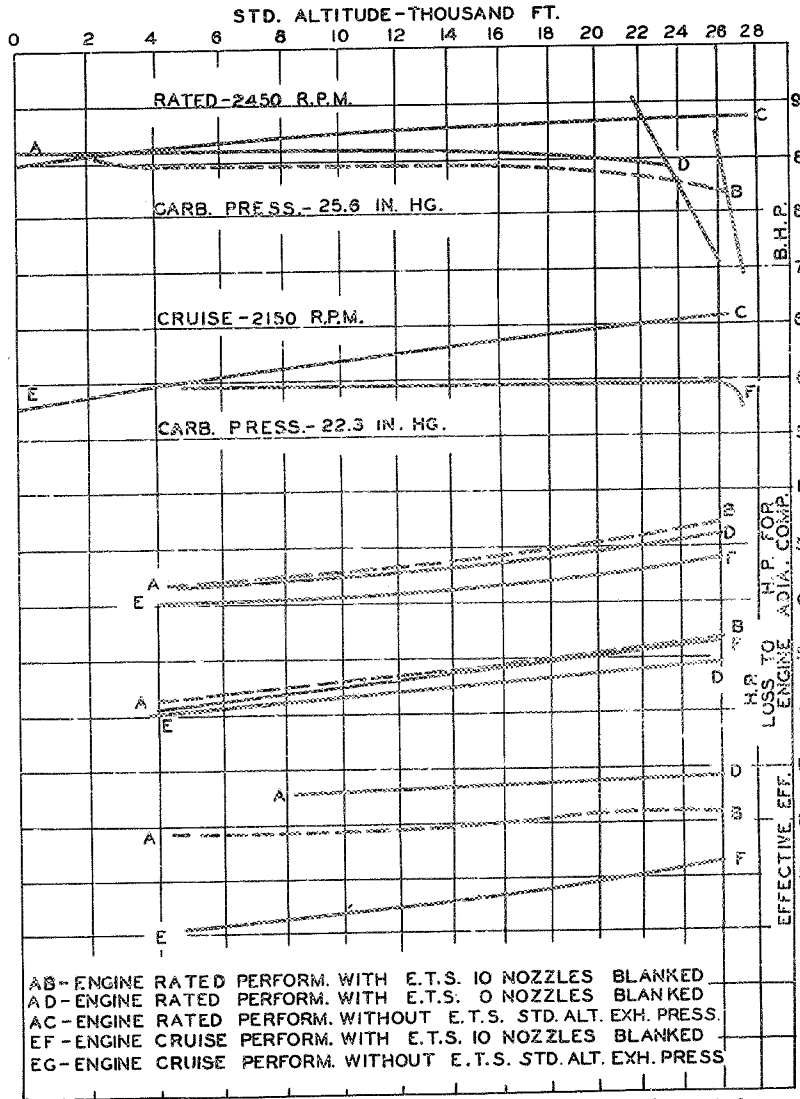

Figure 12.-Variation of effective efficiencies with altitude for rated-power and cruise-power conditions and for rated power with two nozzle areas.