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PERFORMANCE OF EXHAUST-GAS BLOWDOWN TURBINE AND VARIOUS ENGINE SYSTEMS USING A 12-CYLINDER LIQUID-COOLED ENGINE

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SUMMARY

An experimental investigation of a blowdown turbine installed in the exhaust stream of a 12-cylinder liquid-cooled engine of 1710-cubic-inch displacement was conducted at the NACA Cleveland laboratory. Exhaust stacks from pairs of cylinders with nonoverlapping exhaust strokes were joined and connected to the six turbine-nozzle segments.

The blowdown turbine and the reciprocating engine were each loaded with separate dynamometers and data were obtained for engine speeds of 2000, 2400, and 3000 rpm, engine inlet-manifold pressures of 30 and 40 inches mercury absolute, fuel-air ratios of 0.063, 0.069, and 0.085, and a range of ratios of exhaust to inlet-manifold pressure from 0.3 to 0.9. At each set of engine conditions, a range of turbine speeds sufficient to define the peak value of turbine horsepower was investigated.

The data obtained are correlated and compared with data obtained from a smaller NACA blowdown turbine previously investigated. The effect of the presence of the turbine on engine power and volumetric efficiency is shown. Calculated compound-engine performance is presented for a system incorporating a blowdown turbine and for a system incorporating a blowdown and a steady-flow turbine in series. Included for comparison is the calculated performance of an engine system with all-geared supercharging, one with turbosupercharging, and a compound engine with a steady-flow turbine.

The calculations indicated that under certain conditions, the blowdown-turbine compound engine produced more power than the steady-flow-turbine compound engine for the altitude range from sea level to 31,000 feet.

INTRODUCTION

At the time of exhaust-valve opening, the pressure of the gas in the cylinder of an internal-combustion engine is considerably above atmospheric pressure, and the gas is therefore capable of doing an appreciable amount of work by further expansion. If a steady-flow turbine is operated in conjunction with an internal-combustion engine, most of the kinetic energy associated with the blowdown period (the portion of the exhaust stroke from exhaust-valve opening until cylinder pressure has decreased to exhaust-collector pressure) is largely dissipated as heat in the exhaust-gas collector and nozzle box. This kinetic energy may be partly converted to useful work, however, by jet stacks or a suitably designed turbine. Two turbines, similar to Büchi turbines, have been constructed at the NACA Cleveland laboratory for this purpose. The results of the investigation of the performance of the first of these two NACA blowdown turbines operating in conjunction with a nine-cylinder radial engine are presented in reference 1, where it is shown that a considerable amount of kinetic energy was converted to shaft work and that the presence of the turbine caused no appreciable engine power loss.

Inasmuch as the investigation of reference 1 was conducted over a limited range of conditions with a comparatively small turbine and a low-powered engine, an investigation was accordingly conducted at the NACA Cleveland laboratory over a greater range of variables on a larger blowdown turbine installed on a high-powered engine. Each unit was loaded with a separate dynamometer. Engine speeds of 2000, 2400, and 3000 rpm, engine inlet-manifold pressures of 30 and 40 inches mercury absolute, a range of fuel-air ratios from 0.063 to 0.085, and a range of ratios of exhaust- to inlet-manifold pressure from 0.3 to 0.9 were covered. At each set of engine conditions, a range of turbine speeds sufficient to define the peak value of turbine horsepower was investigated.

The experimental performance of the blowdown turbine is presented along with a method of correlating the data. Calculated compound-engine performance is presented for a system incorporating a blowdown turbine and for a system incorporating a blowdown and a steady-flow turbine in series. Included for comparison is the calculated performance of an engine system with all-geared supercharging, one with turbosupercharging, and a compound engine with a steady-flow turbine.

SYMBOLS

The following symbols and abbreviations are used in this report:

A	effective nozzle area, square feet
f	fuel-air ratio
g	mass ratio, 32.17 pounds per slug
M_a	mass flow of air, slugs per second
M_e	mass flow of exhaust gas through turbine, slugs per second
n	engine speed, rps
nbhp	net brake horsepower
nthp	net thrust horsepower
ntsfc	net thrust specific fuel consumption, pounds per net thrust horsepower-hour
P_t	turbine power output, horsepower
p_e	system-exhaust pressure, pounds per square foot absolute
p_m	engine inlet-manifold pressure, pounds per square foot absolute
Δp	pressure drop, pounds per square foot
R_e	gas constant for exhaust gas (from reference 2), foot-pounds per slug per $^{\circ}F$
T_e	effective turbine-inlet temperature, $^{\circ}R$
ΔT_e	temperature increment equivalent to turbine power output, $^{\circ}F$
u	turbine pitch-line velocity, feet per second
$\overline{V}_e$	mean jet velocity at turbine-nozzle exit, feet per second
V_j	exhaust jet velocity, feet per second
V_o	airplane velocity, feet per second

v_d engine displacement volume, cubic feet

γ_e ratio of specific heats for exhaust gas (from reference 2)

η_p propeller efficiency, assumed to be 85 percent

$\overline{\eta}_t$ mean turbine efficiency

η_v volumetric efficiency

APPARATUS AND PROCEDURE

Construction of blowdown turbine. - The nozzle assembly of the blowdown turbine was constructed in six segments, each covering an arc of 60° of the nozzle periphery. Front and rear views of the assembled nozzle box are shown in figure 1. Each nozzle segment had an exit area of 2.83 square inches in a plane perpendicular to the gas flow and accommodated the gas from a pair of cylinders with non-overlapping exhaust periods. The actual area of 17 square inches thus corresponds to a total effective area of 34 square inches. The choice of nozzle area is discussed in the appendix. In order to insure even distribution of gas entering the turbine, each nozzle segment was fitted with nine equally spaced guide vanes set at angles of 24° with respect to the plane of the wheel.

The turbine wheel had a pitch-line diameter of 13.2 inches, was primarily of the impulse type, and included a shroud ring permanently fixed to the individual blades. The wheel and the shaft, the bearing housing, and the oil system were obtained from a commercially manufactured turbosupercharger.

A labyrinth-type seal was placed between the nozzle diaphragm and the bearing housing to prevent leakage into or out of the turbine gas system, and compressed air was used to balance the seal pressures and cool the enclosed part of the bearing housing. Provision was made for cooling both upstream and downstream sides of the turbine wheel.

Reciprocating engine. - The V-type, 12-cylinder, liquid-cooled reciprocating engine used in the installation was the same as that used in reference 3 and had the following pertinent specifications:

Bore, inches 5.50
Stroke, inches 6.00
Displacement volume, cubic inches 1710
Compression ratio 6.65
976 Valve overlap, degrees 74
Supercharger-impeller diameter, inches 9.5
Supercharger-gear ratio 8.1:1

Additional information concerning the engine and its installation are contained in reference 3.

Test setup. - A photograph of the blowdown-turbine installation showing the turbine with its dynamometer and the accessories section of the reciprocating engine is presented in figure 2. The turbine power was absorbed by a 300-horsepower, manually-controlled, high-speed water dynamometer; the engine power was absorbed by a 2000-horsepower, electronically-controlled, eddy-current dynamometer.

Part of the program was conducted with the engine drawing the charge air from the room. When the desired inlet-manifold pressure was unattainable in this way, the laboratory combustion-air system was used to increase the pressure at the carburetor inlet. A butterfly valve located in the charge-air intake pipe between the air-measuring orifice and the engine was used to adjust the carburetor-inlet pressure.

Exhaust pipes from pairs of cylinders with nonoverlapping exhaust periods (cylinders 1 and 6, 2 and 5, and 3 and 4 in each bank) were joined and connected to six turbine-nozzle-inlet pipes. Bellows-type expansion joints were located in the engine-exhaust pipes to permit expansion while insuring a gas-tight system. The exhaust gas from the turbine was collected in an annular hood of circular cross section and discharged through four radial pipes to the laboratory exhaust system.

Turbine and engine torque were each measured with a balanced diaphragm-type torquemeter and a mercury manometer. Turbine and engine speed were each measured with a chronometric tachometer.

An estimate of the mean turbine-inlet pressure (mean engine-exhaust pressure) was obtained by conducting static-pressure tubes to a small surge tank from each of the six pipes that connected the engine-exhaust ports to the turbine-inlet pipes and then measuring the pressure therein. These pressure tubes were placed downstream of the junction of the two individual cylinder-exhaust streams but upstream of the bends in the turbine ducting. Turbine-exhaust pressure was obtained by two piezometer rings, one located just upstream and one, downstream of the four discharge pipes in the turbine hood.

Turbine-exhaust temperatures were obtained by four quadruple-shielded chromel-alumel thermocouples, one in each of the four turbine-exhaust pipes. Turbine-exhaust temperature was measured instead of turbine-inlet temperature because of the cyclic nature of the flow in the turbine-inlet pipes. At any given set of conditions, the turbine discharged to a substantially constant pressure thus permitting greater reliability of the temperature measurements.

Test methods. - The investigation was conducted with the engine throttle fully open for all runs, the combustion-air throttle upstream of the carburetor being used to adjust the engine inlet-manifold pressure to the desired value. Engine speed, inlet-manifold pressure, fuel-air ratio, and turbine-exhaust pressure were held at constant values while turbine speed was varied in increments through a range sufficient to define the peak values of turbine horsepower. Sufficient time was allowed at each turbine speed for the measured variables to reach equilibrium.

The investigation was made at the following conditions:

Engine speed, rpm	2000, 2400, 3000
Engine inlet-manifold pressure, inches mercury absolute	30, 40
Fuel-air ratio	0.063, 0.069, 0.085
Ratio of turbine-exhaust to engine inlet-manifold pressure	0.3 to 0.9

Engine speed was held within ±5 rpm, manifold pressure within ±0.1 inch mercury, and fuel-air ratio within ±0.001 of the respective desired values. As in reference 3, the carburetor-inlet temperature was $90^\circ \pm 15^\circ$ F, the engine oil-inlet temperature was maintained at $150^\circ \pm 5^\circ$ F by automatic control, and the coolant-outlet temperature was held constant at $220^\circ \pm 5^\circ$ F.

METHODS OF CALCULATION

The reduction of turbine data as well as the calculations of complete engine systems is presented.

Reduction of Turbine Data

Turbine power. - The power of the blowdown turbine may be expressed, as in references 1 and 4, in terms of the available kinetic energy by the relation

$$P_t = \frac{1}{2} \frac{M_e \overline{V}_e^{\,2} \,\overline{\eta}_t}{550} \tag{1}$$

It is shown in equation (1), however, that calculation of the efficiency $\overline{\eta}_t$ requires knowledge not only of the measurable quantities, turbine power and mass flow, but also of the mean jet velocity at the turbine-nozzle exit. In a steady-flow turbine, the theoretical nozzle-exit velocity is easily computed from theory and measurable quantities. For the case of intermittent flow such as occurs in the blowdown turbine, the instantaneous velocity is not constant throughout the blowdown process and the mean jet velocity $\overline{V}_e$ is difficult to determine analytically. It can be experimentally determined, however, (reference 5) by directing the exhaust gas from an engine cylinder through a nozzle against a pivoted target, thus permitting measurement of the jet thrust. The mean jet velocity $\overline{V}_e$ is the thrust per unit mass flow. Reference 5 reports the results of such an investigation wherein the thrust available from a single cylinder of an 1820-cubic-inch-displacement engine was determined for several exhaust-stack shapes, lengths, and nozzle areas.

In reference 5, it was shown that the mean jet velocity from an individual cylinder jet stack could be expressed by a relation of the form

$$\overline{V}_e = f_1 \left(\frac{p_e A}{M_e}\right) \tag{2}$$

It was also indicated that $\overline{V}_e$ should be a function of exhaust-gas temperature, but no data showing the relation are given.

In order to correct turbine output and efficiency for variations in gas temperature, the assumption was made in reference 1 that the following relation between $\overline{V}_e$ and temperature applied:

$$\frac{\overline{V}_e}{\sqrt{R_e T_e}} = f_2 \left(\frac{p_e A}{M_e \sqrt{R_e T_e}}\right) \tag{3}$$

The mean jet velocity as given in equation (2) was used in reference 1 to calculate the mean efficiency of a blowdown turbine (equation (1)). However, as the exact functional relation between $\overline{V}_e$ and p_eA/M_e may be expected to vary from engine to engine, it is undesirable to apply data obtained on one engine to others, particularly when the valve timings are appreciably different. Also, any small error in $\overline{V}_e$ would approximately double the error in estimated turbine power because the power varies as $\overline{V}_e^{\,2}$. The uncertainty would be decreased, however, if the turbine data could be correlated in such a manner as to minimize the importance of the need for exact data on $\overline{V}_e$. That this correlation can be made approximately is shown as follows: Rearranging equation (1) and dividing through by R_eT_e gives

$$\frac{550\ P_t}{M_eR_eT_e} = \frac{\overline{V}_e^{\,2}\ \overline{\eta}_t}{2R_eT_e} \tag{4}$$

The turbine efficiency was found in reference 1 to be a function of blade-to-jet speed ratio $u/\overline{V}_e$ and $p_eA/M_e\sqrt{R_eT_e}$ so that from equations (3) and (4),

$$\psi = \frac{550\ P_t}{M_eR_eT_e} = f_3\left(\frac{p_eA}{M_e\ \sqrt{R_eT_e}}, \frac{u}{\overline{V}_e}\right) \tag{5}$$

Equation (5) indicates that for constant values of $u/\overline{V}_e$, ψ should be a function of only the parameter $p_eA/M_e\sqrt{R_eT_e}$. Inasmuch as $\overline{V}_e$ is also a function of $p_eA/M_e\sqrt{R_eT_e}$ (equation (3)), it is possible to plot ψ instead of efficiency against u for various constant values of $p_eA/M_e\sqrt{R_eT_e}$ in order to illustrate turbine performance. On the assumption that the turbine efficiency becomes a maximum at a constant value of $u/\overline{V}_e$ regardless of the value of $p_eA/M_e\sqrt{R_eT_e}$, it should be possible to plot the maximum values of ψ obtained from variable-speed runs at constant values of $p_eA/M_e\sqrt{R_eT_e}$ against $p_eA/M_e\sqrt{R_eT_e}$ and obtain a single curve regardless of how the individual quantities in the parameter are varied. It might also be expected from a consideration of the similarity of turbine-efficiency curves that if ψ/ψ_{max} for each of the constant $p_eA/M_e\sqrt{R_eT_e}$ runs were plotted against $u/\overline{V}_e$, a single curve would result for all values of $p_eA/M_e\sqrt{R_eT_e}$.

Although $\overline{V}_e$ is still involved in the method of correlating ψ/ψ_{max}, it is not expected that the scatter in the data will be as great as would result from the use of an efficiency that involves the square of $\overline{V}_e$.

Effective turbine-inlet temperature. - The effective turbine-inlet temperature T_e was obtained by adding the temperature increment equivalent to the measured turbine power per pound of exhaust gas to the turbine-exhaust temperature, as obtained from the quadruple-shielded thermocouples. The temperature increment equivalent to the turbine power output ΔT_e was calculated by the relation

$$\Delta T_e = \frac{550\ \dot{P}_t}{M_eR_e}\left(\frac{\gamma_e - 1}{\gamma_e}\right) \tag{6}$$

The value of γ_e was chosen at turbine-exhaust temperature to simplify the calculation of ΔT_e. The values of turbine-inlet temperature obtained in this way for any given set of variable-turbine-speed runs at fixed engine conditions should theoretically be a constant. In this investigation, the values of T_e were essentially constant for constant engine conditions.

Turbine speed and blade-to-jet speed ratio. - The effect of turbine speed on turbine power is shown by plots of the parameter $550\ P_t/M_eR_eT_e$ against turbine speed. In order to determine whether the individual power-speed curves all conformed to a single characteristic shape, the ratio of turbine power at any value of turbine speed to the maximum faired value of turbine power for the run was plotted against the calculated value of blade-to-jet speed ratio $u/\overline{V}_e$, which is the ratio of turbine-pitch-line velocity to mean jet velocity at the turbine-nozzle exit. Values of $\overline{V}_e$ from reference 5 were used in the absence of a similar $\overline{V}_e$ correlation for the engine investigated. The error introduced by use of these values is negligible, as will be subsequently shown.

Complete Engine-System Calculations

Best power and best economy of the five engine systems are compared in order to determine the relative value of the blowdown-turbine performance.

Net thrust horsepower and specific fuel consumption were calculated for the following five engine systems:

System	Description
A	Compound engine with geared blowdown and steady-flow turbines
B	Compound engine with geared steady-flow turbine
C	Compound engine with geared blowdown turbine
D	Turbosupercharged engine
E	Engine with all-geared supercharging and individual jet stacks

Each system incorporates, in addition to a 1710-cubic-inch-displacement engine (with engine-stage supercharger), an auxiliary-stage supercharger with an efficiency of 80 percent, an intercooler with a cooling effectiveness of 50 percent, and a propeller with an efficiency of 85 percent. In systems A, B, and C, the turbine (turbines in system A) drives the auxiliary supercharger, and the excess turbine power is geared to the engine crankshaft through a gearbox with an efficiency of 95 percent. An efficiency of 80 percent was assumed for the steady-flow turbine. An effective nozzle-exit area of 0.236 square foot (the same as that of the investigation) was used for the blowdown turbine. The turbine-exhaust gas passes through an exhaust-discharge nozzle with an assumed velocity coefficient of 0.96. For the case of the turbosupercharged engine (system D), the steady-flow turbine provides just enough power to drive the auxiliary supercharger; the remainder of the energy in the exhaust gas becomes available to the exhaust-discharge nozzle.

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In system E, the engine power necessary to drive the auxiliary supercharger is transmitted through the gearbox; the engine exhaust gas expands through individual exhaust stacks to the atmosphere.

The calculations were made for an airplane velocity of 400 miles per hour, an engine speed of 2600 rpm, an engine inlet-manifold pressure of 40 inches mercury absolute, and a fuel-air ratio of 0.069 for a range of engine exhaust-to-inlet-manifold pressure ratios p_e/p_m sufficient to define both best power and best economy at each of several altitudes from 0 to 45,000 feet. The effects of flight ram on engine inlet-manifold pressure and temperature were not considered because they influence each system in a similar manner. The required specific-heat data were obtained from reference 2.

Engine data from reference 3 were used as the basis upon which the performance of the various systems was calculated because the scope of these data was greater than that of the present investigation. Thus all the systems could be evaluated with the same basic engine. Auxiliary supercharger power was calculated assuming the charge air was compressed from ambient altitude conditions to carburetor top-deck pressure. Blowdown-turbine power was computed from the correlation curves here included assuming an engine-exhaust pressure equal to turbine-inlet pressure, no pressure drop through the turbine, and optimum turbine speed. The exhaust-gas temperature drop equivalent to the power extraction of the blowdown turbine was subtracted from the engine-exhaust temperature and the resulting temperature was assumed to be that at the inlet of the next exhaust-energy-recovery device. Steady-flow-turbine power was assumed to be that obtained by expanding all the exhaust gas from engine-exhaust pressure and temperature (blowdown-turbine exhaust temperature in system A) to exhaust-discharge nozzle-inlet pressure.

In systems A, B, C, and D, the turbine-leaving velocity was taken into account when computing the exit velocity of the exhaust-discharge nozzle. In addition, the nozzle-inlet pressure was maintained at the value that would provide maximum net thrust horsepower for the complete engine system. For system E, the exit velocity of the individual exhaust stacks was obtained from the correlation in reference 5, exhaust-stack-exit area being assumed equal to engine-exhaust-port area.

The net brake horsepower of each system is considered to be the horsepower at the propeller shaft after the contributions of the turbine (or turbines) and that of the auxiliary supercharger have been taken into account.

Net thrust horsepower nthp was assumed to be

$$\text{nthp} = \eta_p \, \text{nbhp} + \frac{M_a \left[(1 + f) \, V_j - V_o\right] V_o}{550} \qquad (7)$$

where the fuel-air ratio f is 0.069 and airplane velocity V_o is 587 feet per second (400 mph). 976

Net thrust specific fuel consumption ntsfc is

$$\text{ntsfc} = \frac{3600 \, f g M_a}{\text{nthp}} \qquad (8)$$

RESULTS AND DISCUSSION

Turbine performance and the performances of the complete engine systems are presented.

Turbine Performance

Turbine power. - Representative blowdown-turbine data are shown in figure 3 where turbine horsepower is plotted against turbine speed for ranges of engine speed, engine inlet-manifold pressure, fuel-air ratio, and nominal turbine-exhaust pressure.

The effect of engine speed on turbine power is presented in figure 3(a). Turbine power increased with engine speed as would be expected inasmuch as the charge flow and the mean-jet velocity at the turbine-nozzle exit $\overline{V}_e$ both increase with engine speed. The turbine speed at which turbine power is maximum also increased with engine speed as is characteristic for a given impulse-type turbine. (Maximum power occurs at a constant value of blade-to-jet speed ratio independent of other operating conditions.)

The effect of engine inlet-manifold pressure on turbine power is shown in figure 3(b). Turbine horsepower again increased with engine inlet-manifold pressure because of the increase in charge flow and $\overline{V}_e$. The turbine speed corresponding to maximum turbine horsepower also increased with engine inlet-manifold pressure.

The effect of fuel-air ratio on turbine power is presented in figure 3(c). As fuel-air ratio was increased from 0.063 to 0.069, turbine power increased slightly because of an increase in turbine-inlet temperature (engine exhaust-gas temperature). Although no data were obtained at higher fuel-air ratios for the conditions of this figure, it is expected that turbine power would decrease slightly as fuel-air ratio is enriched from 0.069 because the engine exhaust-gas temperature would decrease.

The effect of turbine exhaust pressure on turbine power is presented in figure 3(d). Turbine power increased as turbine-exhaust pressure decreased because the mean jet velocity $\overline{V}_e$ increased, and the charge flow increased. The change in the turbine speed at which maximum turbine power occurs is again due to change in $\overline{V}_e$.

The maximum turbine power shown on figure 3 is 134 horsepower and was developed at an engine speed of 2000 rpm, an engine inlet-manifold pressure of 40 inches mercury absolute, a fuel-air ratio of 0.085, and an average turbine-exhaust pressure of 14.4 inches mercury absolute. A slightly larger power (142 horsepower) was obtained at other conditions, however.

All the turbine data obtained throughout the investigation are presented in figure 4 where the variation of the turbine-power parameter $550\ P_t/M_eR_eT_e$ with turbine speed is shown for various engine inlet-manifold pressures, fuel-air ratios, and values of $p_eA/M_e\sqrt{R_eT_e}$. Curves for engine speeds of 2000, 2400, and 3000 rpm are presented.

Each of the individually faired curves are for a substantially constant value of the dimensionless parameter $p_eA/M_e\sqrt{R_eT_e}$, as indicated on the figure. They are parabolic in form and of the same general shape as those of mean turbine efficiency against blade-to-jet speed ratio shown in reference 1. The slight irregularities in the succession of the parameter $p_eA/M_e\sqrt{R_eT_e}$ are attributed to experimental error.

Turbine-power correlation. - Peak turbine power is correlated in figure 5(a) where the maximum faired values of the parameter $550\ P_t/M_eR_eT_e$ from each curve of constant $p_eA/M_e\sqrt{R_eT_e}$ of figure 4 are plotted against the corresponding values of $p_eA/M_e\sqrt{R_eT_e}$. Similar data from reference 1 are included for comparison.

The value of the power parameter decreases at a decreasing rate as the value of the parameter $p_eA/M_e\sqrt{R_eT_e}$ increases. These curves are independent of fuel-air ratio and engine inlet-manifold pressure. An engine-speed effect is in evidence, however, indicating the importance of additional variables to those considered in the correlation parameter.

The blowdown turbine of reference 1 produces higher values of the power parameter for a given value of $p_eA/M_e\sqrt{R_eT_e}$. This result was expected inasmuch as data obtained from tests of the two turbine wheels, each operating at steady-flow conditions, indicate that the wheel of reference 1 is the more efficient one.

Effect of blade-to-jet speed ratio on turbine power. - The effect of blade-to-jet speed ratio on turbine power is presented in figure 5(b) in which all data obtained in the investigation are correlated.

The correlation was obtained by dividing the value of the turbine-power parameter for each data point by the maximum faired value of the power parameter for each curve of constant $p_eA/M_e\sqrt{R_eT_e}$ (fig. 4) and plotting against the corresponding blade-to-jet speed ratio $u/\bar{V}_e$.

The curve is independent of engine speed, engine inlet-manifold pressure, fuel-air ratio, and turbine-exhaust pressure. Maximum turbine power occurs at a value of blade-to-jet speed ratio of about 0.4.

The use of values of $\bar{V}_e$ from figure 10 of reference 5 is considered satisfactory here because any discrepancy that might exist between the actual values of $\bar{V}_e$ and those of reference 5 enter figure 5(b) to the first power only and are then minimized because the correlation curve is fairly flat in the vicinity of the peak. The error introduced by the assumption appears to be negligible because the correlation obtained is good and the shape of the curve and location of the optimum blade-to-jet speed ratio obtained is characteristic of the impulse-type wheel investigated.

Correlation of pressure drop through engine-exhaust system and turbine. - The pressure drop through the engine-exhaust system and turbine is correlated in figure 6.

The correlation was effected by dividing the pressure drop as obtained from the static taps in the six turbine-inlet pipes and the static taps in the turbine-exhaust hood by the engine inlet-manifold pressure and plotting against the ratio of turbine-exhaust pressure to engine inlet-manifold pressure. Data were not obtained at all conditions of operation because of occasional mechanical failure of one of the exhaust-pressure measuring systems.

At constant engine speed, the pressure drop decreases with increasing blowdown-turbine exhaust pressure and the curve level rises with increasing engine speed (fig. 6). The pressure drop indicated in the correlation includes losses due to a large part of the exhaust piping with several sharp bends between the engine and the turbine. Although the validity of the absolute values of the upstream pressure measurements may be doubtful because of the cyclic nature of the flow in the tubes, it is believed that the values of the pressure are useful in showing the trend of the pressure drop due to the exhaust restriction for a range of operating conditions.

Effect of presence of turbine on engine power and volumetric efficiency. - The effect of the presence of the turbine on engine power and volumetric efficiency is shown in figure 7. The curves of this figure are for engine speeds of 2000, 2400, and 3000 rpm, engine inlet-manifold pressure of 40 inches mercury absolute, a fuel-air ratio of 0.085, and a carburetor-air temperature of $90^{\circ} \pm 5^{\circ}$ F.

The variation of engine brake horsepower with p_e/p_m is shown in figure 7(a). The pressure p_e refers to the turbine exhaust when the turbine was in place and to the engine exhaust when the turbine was not in the system. The data for the case of the engine operating alone were obtained from reference 3 wherein the engine exhausted to a modified P-38 exhaust collector.

The difference in engine power with and without the turbine increases with increasing engine speed and decreasing p_e/p_m (from a value of about 1.0). At a value of p_e/p_m equal to 0.36 and an engine speed of 2000 rpm, the engine developed 927 horsepower when the turbine was not in the system and 890 horsepower when the turbine was in the system. This engine-power loss is equivalent to about 28 percent of the turbine power obtained at optimum blade-to-jet speed ratio and the aforementioned conditions.

This loss in power is greater than was anticipated from the turbine design and is attributed to the combined effects of the large flow resistance of the exhaust pipes connecting the engine and the turbine and the fact that the data from reference 5, which were used in the turbine design, are not directly applicable quantitatively to the engine of this investigation. Undoubtedly, the engine power loss can be reduced at the design condition by utilizing a somewhat larger blowdown-turbine-nozzle area. The turbine-power correlation (fig. 5) would not be materially affected by a change in nozzle area (provided the geometry of the turbine-nozzle diaphragms is similar) because the parameters thereof properly account for such change.

The variation of volumetric efficiency η_v with p_e/p_m is shown in figure 7(b). Data obtained with the turbine in place match the faired curves from reference 3 (engine exhausting to modified P-38 exhaust collector) fairly well at low engine speeds and values of p_e/p_m throughout the range investigated. As speed is increased, however, volumetric efficiency eventually decreases. As in reference 5, exhaust restriction affects power before volumetric efficiency.

Performance of Complete Engine Systems

Variation of net thrust horsepower and specific fuel consumption of five engine systems with altitude. - The calculated performance of five propulsion systems each incorporating a 1710-cubic-inch displacement engine is presented in figure 8 for an airplane velocity of 400 miles per hour over a range of altitudes from sea level to 45,000 feet.

As has been shown in reference 6, a compound engine incorporating a steady-flow turbine can be operated at a ratio of engine exhaust to engine-inlet-manifold pressure such that the power is a maximum or the specific fuel consumption is a minimum for a given altitude and set of engine conditions. In figures 8(a) and 8(b), the variation of net thrust horsepower and specific fuel consumption with altitude is shown for the conditions corresponding to best-power and best-economy operations, respectively. Inasmuch as the blowdown-turbine compound system A, the turbosupercharged system D, and the all-geared supercharging system E all operate at fixed values of exhaust pressure for a given altitude, the curves representing these three systems do not change in going from best-power (fig. 8(a)) to best-economy operation (fig. 8(b)).

It is shown that for best-power conditions the two-turbine system A has the highest power and lowest specific fuel consumption of all five systems throughout the altitude range from essentially sea level to 45,000 feet. Its power is 23 percent higher with a corresponding fuel consumption 20 percent lower than that of the turbosupercharged engine D at an altitude of 45,000 feet for the given conditions.

The blowdown-turbine system C produces more power than the steady-flow turbine system B up to an altitude of 31,000 feet. The specific-fuel-consumption curves cross at an altitude of about 9000 feet, above which altitude the steady-flow-turbine system B has lower specific fuel consumption. At low altitudes, system C produces about the same power and specific fuel consumption as system A.

The following table summarizes the relative power and fuel consumption of the five systems at four altitudes based on the performance of the turbosupercharged engine (best-power p_e/p_m):

Altitude (ft)	Geared blowdown and steady-flow turbines (A)	Geared steady-flow turbine (B)	Geared blowdown turbine (C)	Turbosupercharged engine (D)	All-geared supercharging with individual jet stacks (E)
Relative net thrust horsepower					
0	108	100	108	100	105
15,000	113	106	111	100	102
30,000	118	107	107	100	95
45,000	123	109	102	100	87
Relative net thrust specific fuel consumption					
0	92	98	93	100	98
15,000	88	91	93	100	103
30,000	84	90	95	100	109
45,000	80	89	100	100	119

The performance curves for best-economy conditions (fig. 8(b)) are similar to those of figure 8(a) and show that the two-turbine system A again has lower fuel consumption than the other four systems throughout the altitude range. The blowdown-turbine system C has a higher specific fuel consumption than the steady-flow turbine system B above an altitude of about 2000 feet but it produces higher power than the steady-flow-turbine system up to an altitude of about 39,000 feet. The improvement in specific fuel consumption for systems A and B in going from best-power to best-economy operation is obtained at the expense of a power loss.

SUMMARY OF RESULTS

Investigation of the performance of a blowdown turbine installed in the exhaust system of a 12-cylinder, liquid-cooled engine of 1710-cubic-inch displacement gave the following results:

1. The power of the blowdown turbine at optimum blade-to-jet speed ratio was correlated on a nondimensional basis such that the resultant curve was independent of fuel-air ratio and engine inlet-manifold pressure.

2. Turbine power at all values of blade-to-jet speed ratio was correlated by plotting the ratio of turbine power at any value of turbine speed to the maximum faired value of turbine power against the corresponding blade-to-jet speed ratio. Maximum turbine power for the turbine investigated occurred at a value of blade speed equal to about 0.4 of the mean jet velocity at the turbine-nozzle exit. The correlation is independent of engine speed, engine inlet-manifold pressure, fuel-air ratio, and turbine-exhaust pressure.

3. The blowdown turbine investigated developed 134 horsepower (approximately maximum for the range of the investigation) at an average exhaust pressure of 14.4 inches mercury absolute when the engine was operated at a speed of 2000 rpm, an engine inlet-manifold pressure of 40 inches mercury absolute, and a fuel-air ratio of 0.085. The corresponding engine brake horsepower (from faired data) was 890. Previously obtained data indicated that at an engine-exhaust pressure of 14.4 inches mercury absolute and the same engine operating conditions, the engine would develop 927 horsepower if the turbine were not in the system.

From calculations of the performance of five engine systems, the following results were obtained:

4. At an altitude of 45,000 feet, the assumed compound engine incorporating a blowdown turbine and a steady-flow turbine in series in the engine exhaust and geared to the engine crankshaft produced 23 percent more power than did a turbosupercharged engine operating at the same conditions.

5. The blowdown-turbine compound engine produced more power than the steady-flow turbine compound engine for the altitude range from sea level to about 31,000 feet and lower specific fuel consumption for altitudes up to 9000 feet.

6. For low-altitude operation, the geared blowdown-turbine system gave approximately the same power and economy as the system incorporating a blowdown turbine and a steady-flow turbine in series designed for the best-power operation.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, July 16, 1948.

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APPENDIX - TURBINE-NOZZLE AREA AND EXHAUST RESTRICTION

As is indicated in references 3 and 7 and other reports in which the effect of exhaust pressure on engine performance is shown, engine power decreases with increasing exhaust pressure (decreasing exhaust-nozzle area). On the other hand, it is generally expected that the energy recovery from the exhaust gas will increase with a decrease in exhaust-nozzle area. The design nozzle area of devices for utilization of energy in engine exhaust gas, such as turbines and jet stacks, may therefore be quite critical if the sum of the powers of the reciprocating engine and the exhaust-energy-recovery device is to be maximum.

A discussion of nozzle area applicable to the present problem is contained in reference 5, in which it is seen that the change in indicated power at fixed engine conditions, the criterion for choice of nozzle area, is a function of the ratio p_e/p_m and the quantity v_dn/A. Reference 5 further shows that for the condition of no engine power loss, the critical or proper values of v_dn/A increase with increasing p_e/p_m. In view of this trend, optimum nozzle area for a compound system incorporating a reciprocating engine and a blowdown turbine will obviously increase with altitude. If a blowdown turbine is to be interposed in the gas stream between a reciprocating engine and a steady-flow turbine and the engine is to be operated at a constant value of p_e/p_m, a single blowdown-turbine-nozzle area will be satisfactory for all altitudes.

The turbine-nozzle area for this investigation was designed for no engine power loss at an engine speed of 3000 rpm and a ratio of exhaust to engine inlet-manifold pressure equal to 0.7. The variation of v_dn/A with p_e/p_m for the 1820-cubic-inch displacement engine (reference 5) was used for the nozzle design because similar data for the present engine were unavailable. At a value of p_e/p_m of 0.7 and no engine power loss, a value of v_dn/A equal to 210 is indicated. By substituting the engine displacement and design speed in the relation $v_dn/A = 210$, the required effective nozzle area for the 12 engine cylinders is 0.236 square foot. If this annular area normal to the direction of the exhaust-gas flow were to be included in the blowdown turbine, however, the turbine would be unduly large and heavy. Inasmuch as pairs of engine cylinders may be selected such that they have nonoverlapping exhaust periods, one nozzle segment with an area of 2.83 square inches (one-twelfth of the required effective nozzle area) can serve two cylinders. In this way, the actual area was reduced to one-half of the effective nozzle area and thus the weight and diameter were reduced.

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2. Pinkel, Benjamin, and Turner, L. Richard: Thermodynamic Data for the Computation of the Performance of Exhaust-Gas Turbines. NACA ARR No. 4B25, 1944.

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5. Pinkel, Benjamin, Turner, L. Richard, Voss, Fred, and Humble, Leroy V.: Exhaust-Stack Nozzle Area and Shape for Individual Cylinder Exhaust-Gas Jet-Propulsion System. NACA Rep. No. 765, 1943.

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7. Pinkel, Benjamin: Utilization of Exhaust Gas of Aircraft Engines. SAE Trans., vol. 54, 1946, pp. 714-734; discussion, p. 735.

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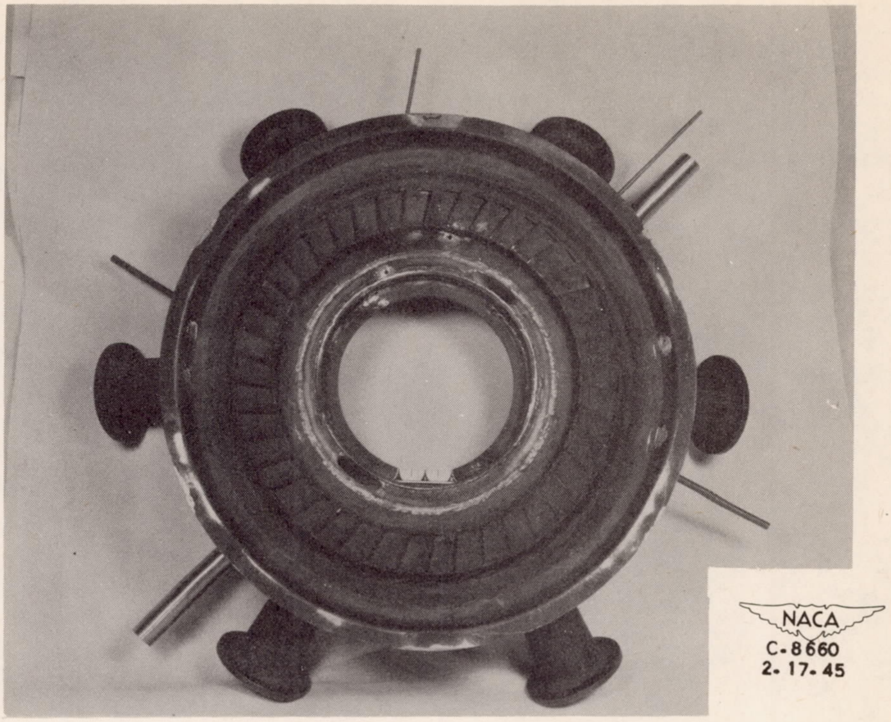
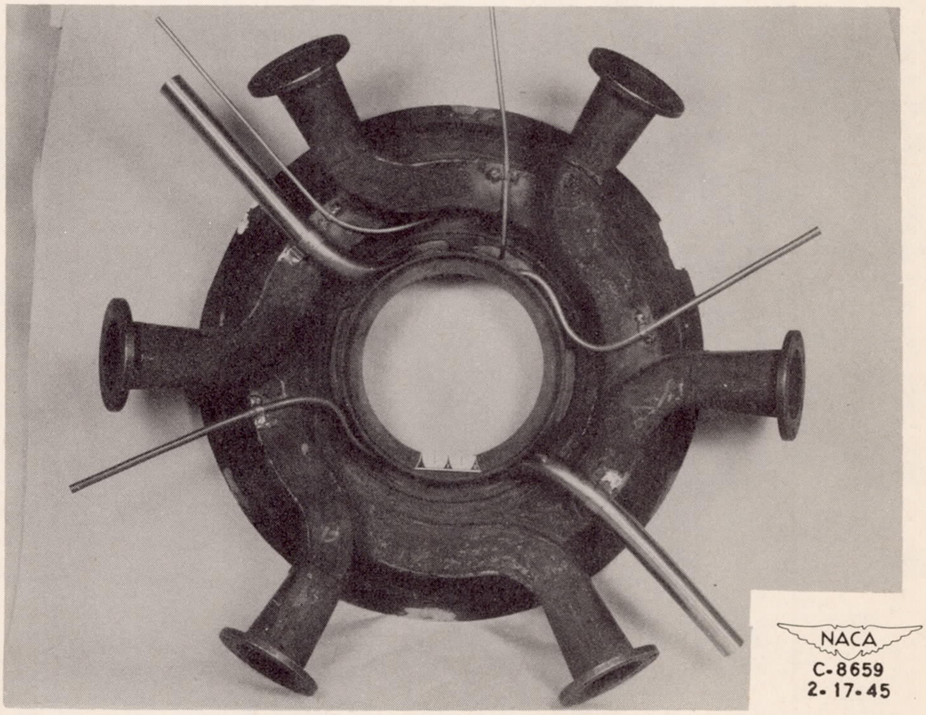


(a) Front view.



(b) Rear view.

Figure 1. - Blowdown-turbine nozzle assembly.

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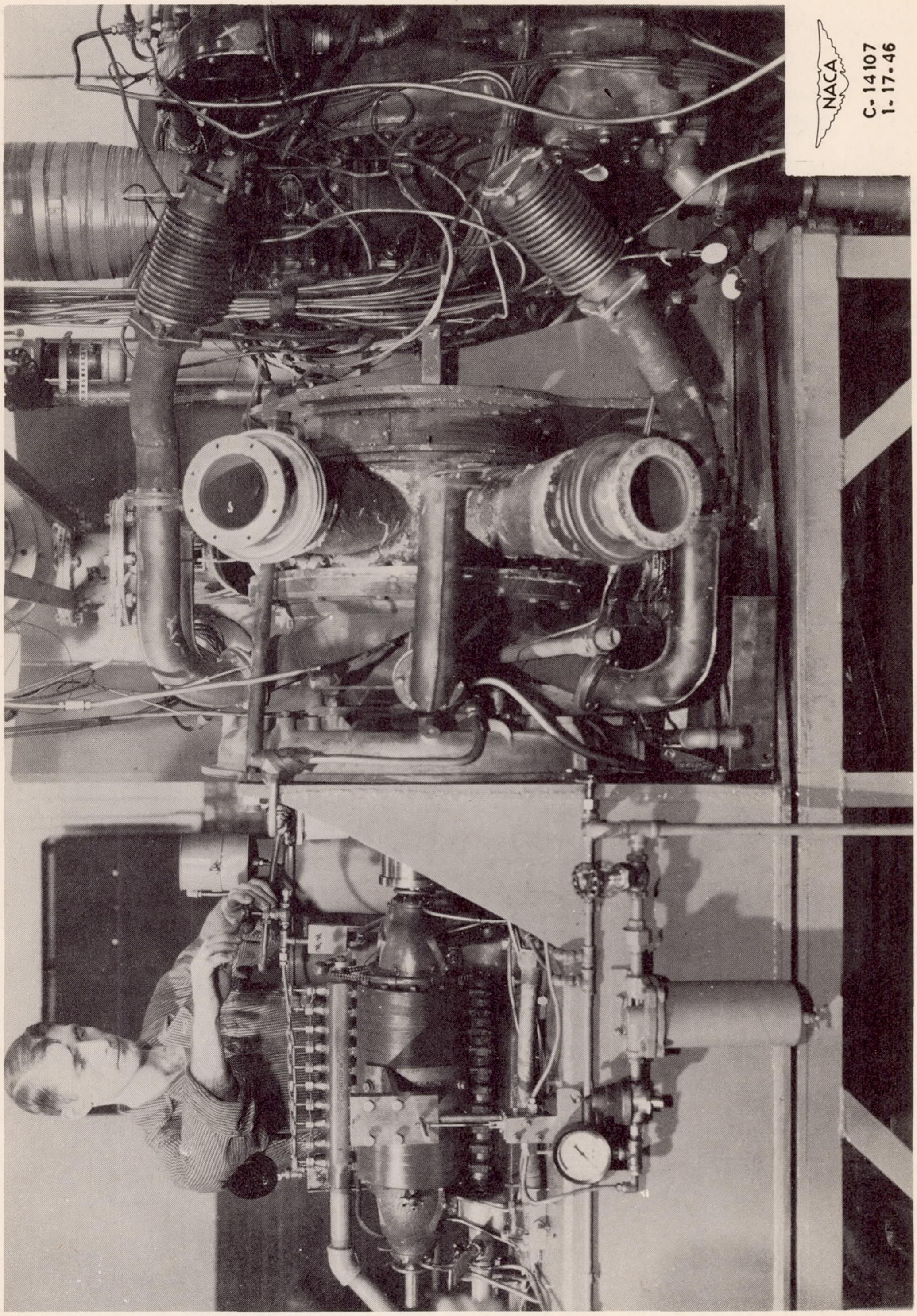

Figure 2. - Blowdown-turbine installation.

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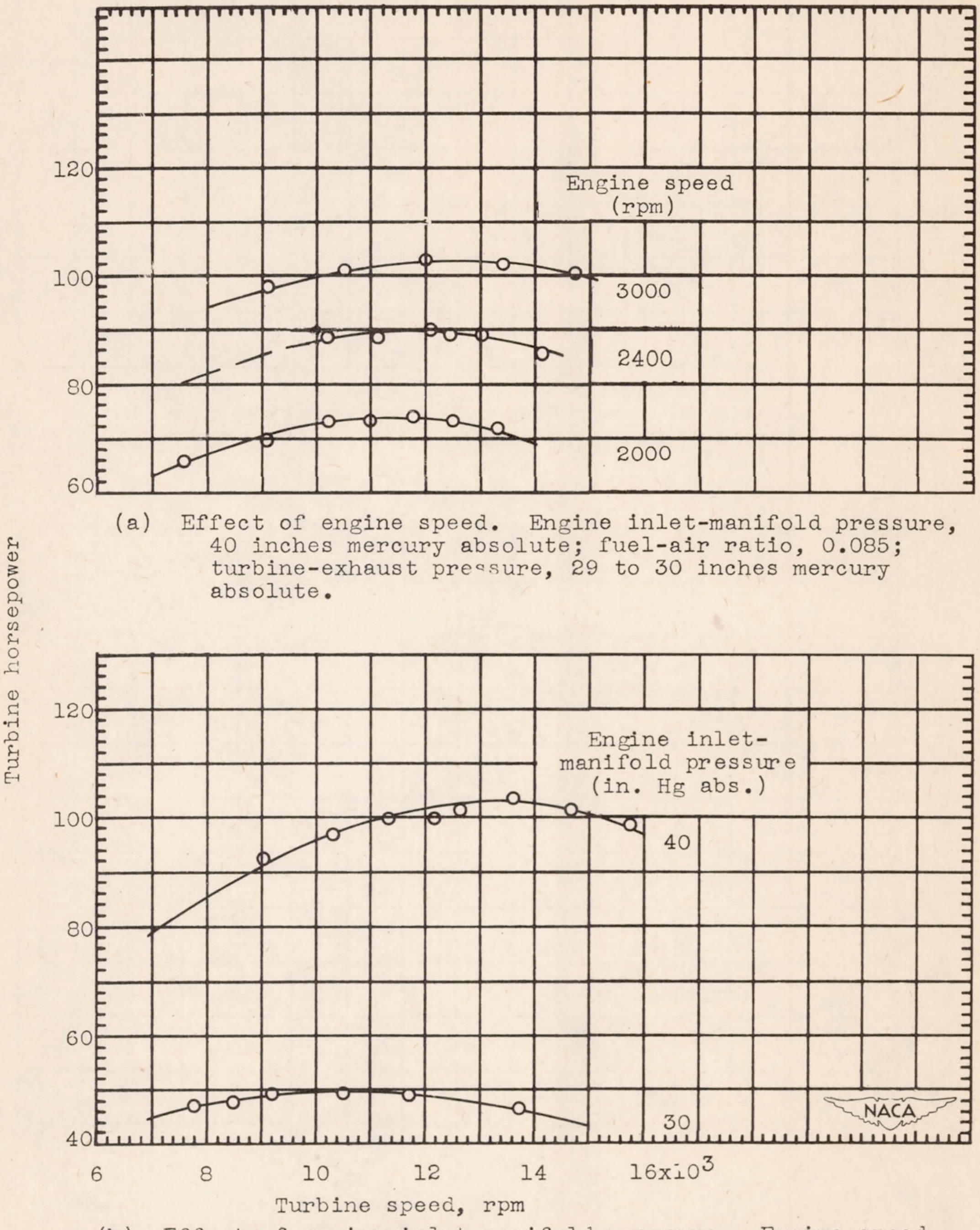

(a) Effect of engine speed. Engine inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.085; turbine-exhaust pressure, 29 to 30 inches mercury absolute.

(b) Effect of engine inlet-manifold pressure. Engine speed, 2000 rpm; fuel-air ratio, 0.085; turbine-exhaust pressure, 21 to 22 inches mercury absolute.

Figure 3. - Representative blowdown-turbine power data.

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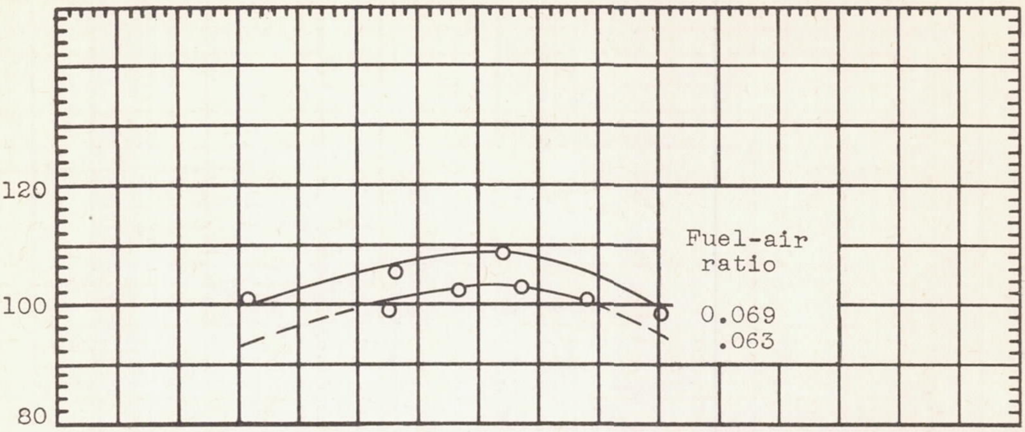
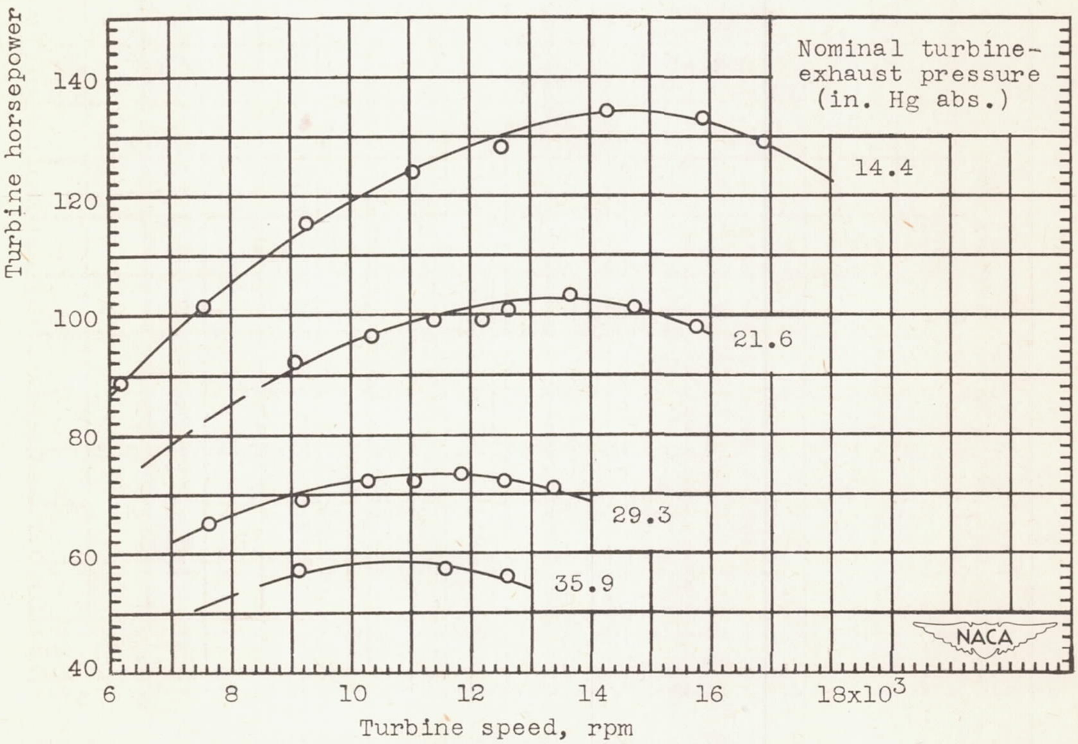
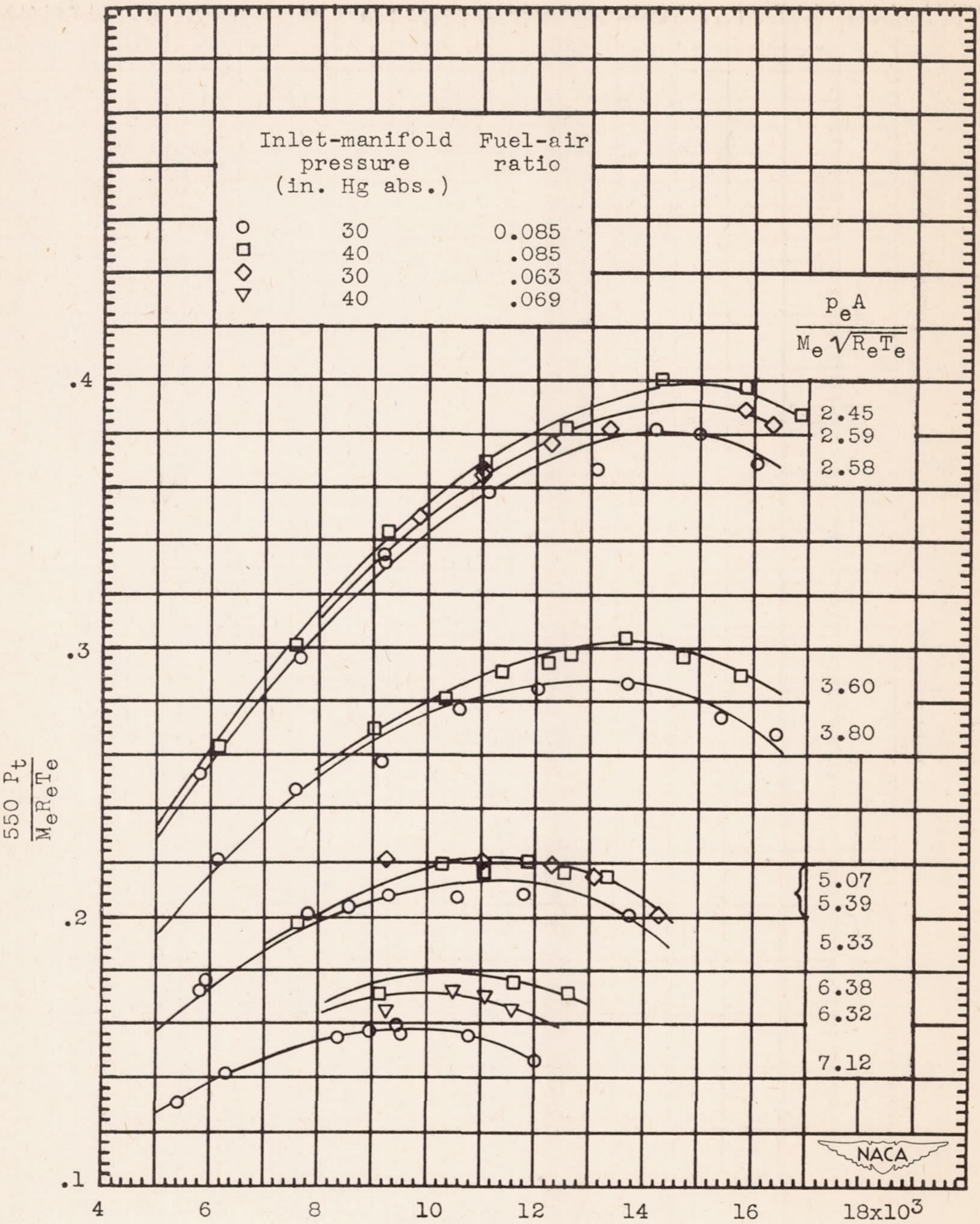


(c) Effect of fuel-air ratio. Engine speed, 2400 rpm; engine inlet-manifold pressure, 40 inches mercury absolute; turbine-exhaust pressure, 25 to 26 inches mercury absolute.



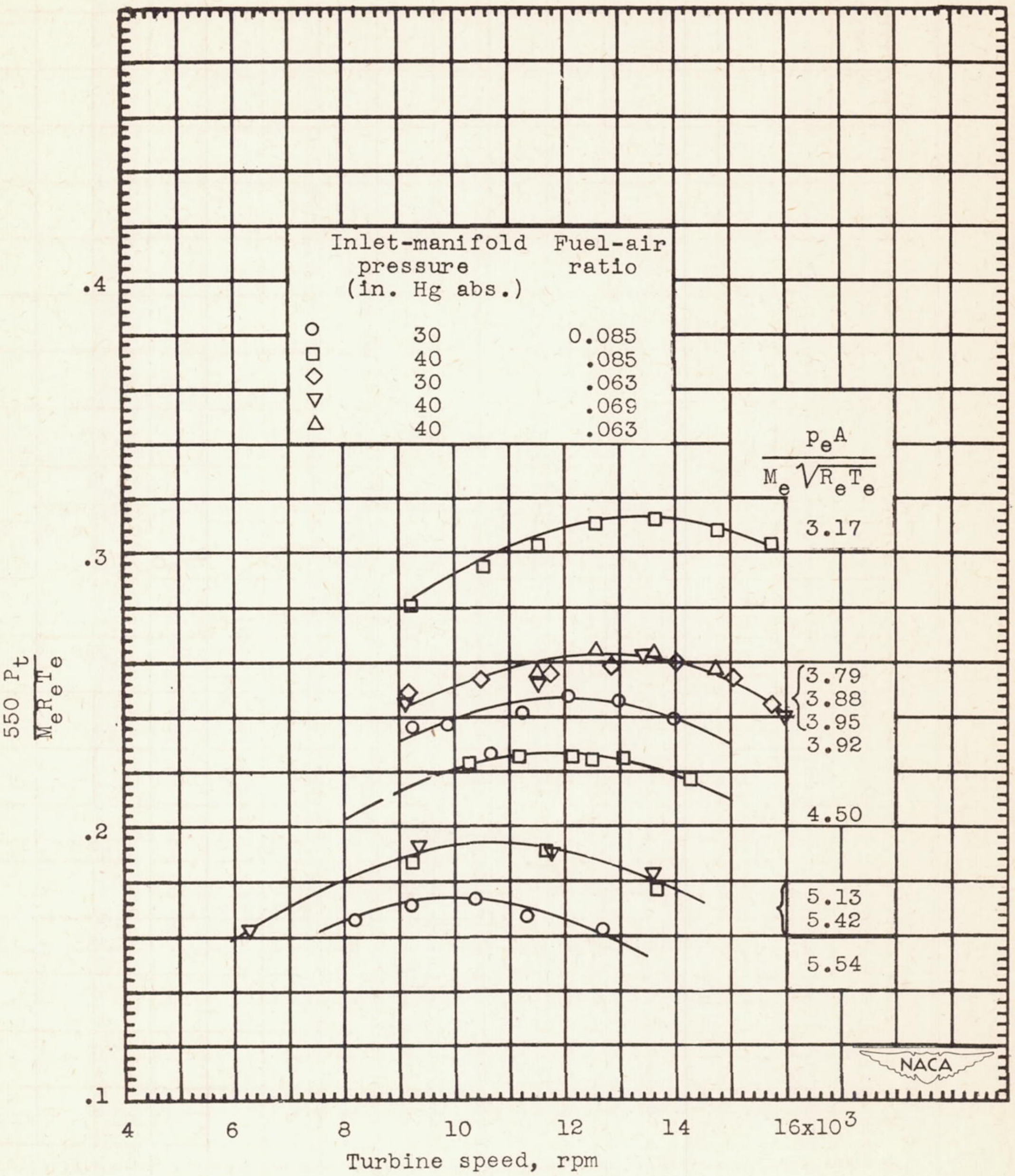
(d) Effect of turbine-exhaust pressure. Engine speed, 2000 rpm; engine inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.085.

Figure 3. - Concluded. Representative blowdown-turbine power data.



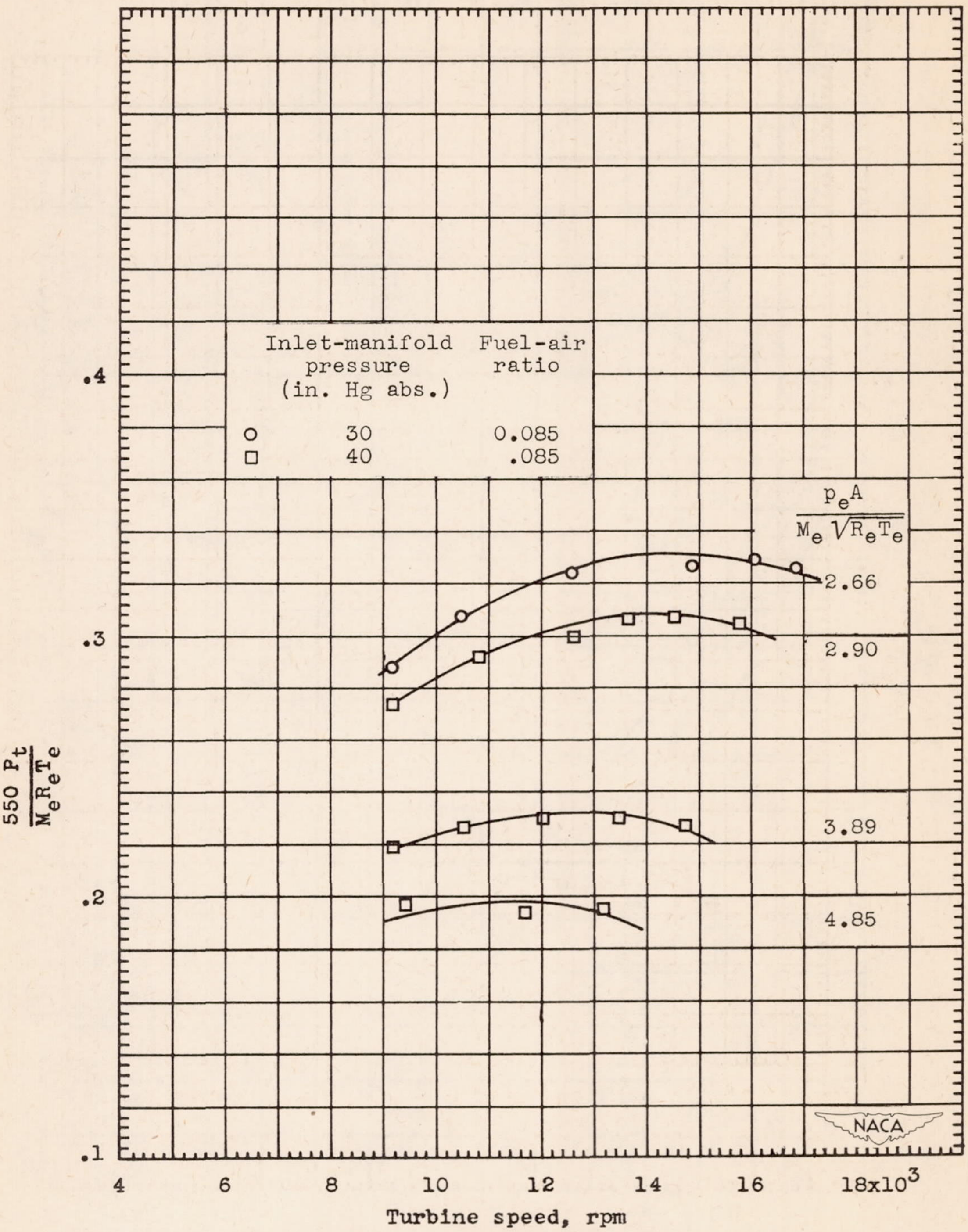
(a) Engine speed, 2000 rpm.

Figure 4. - Variation of blowdown-turbine power with turbine speed.



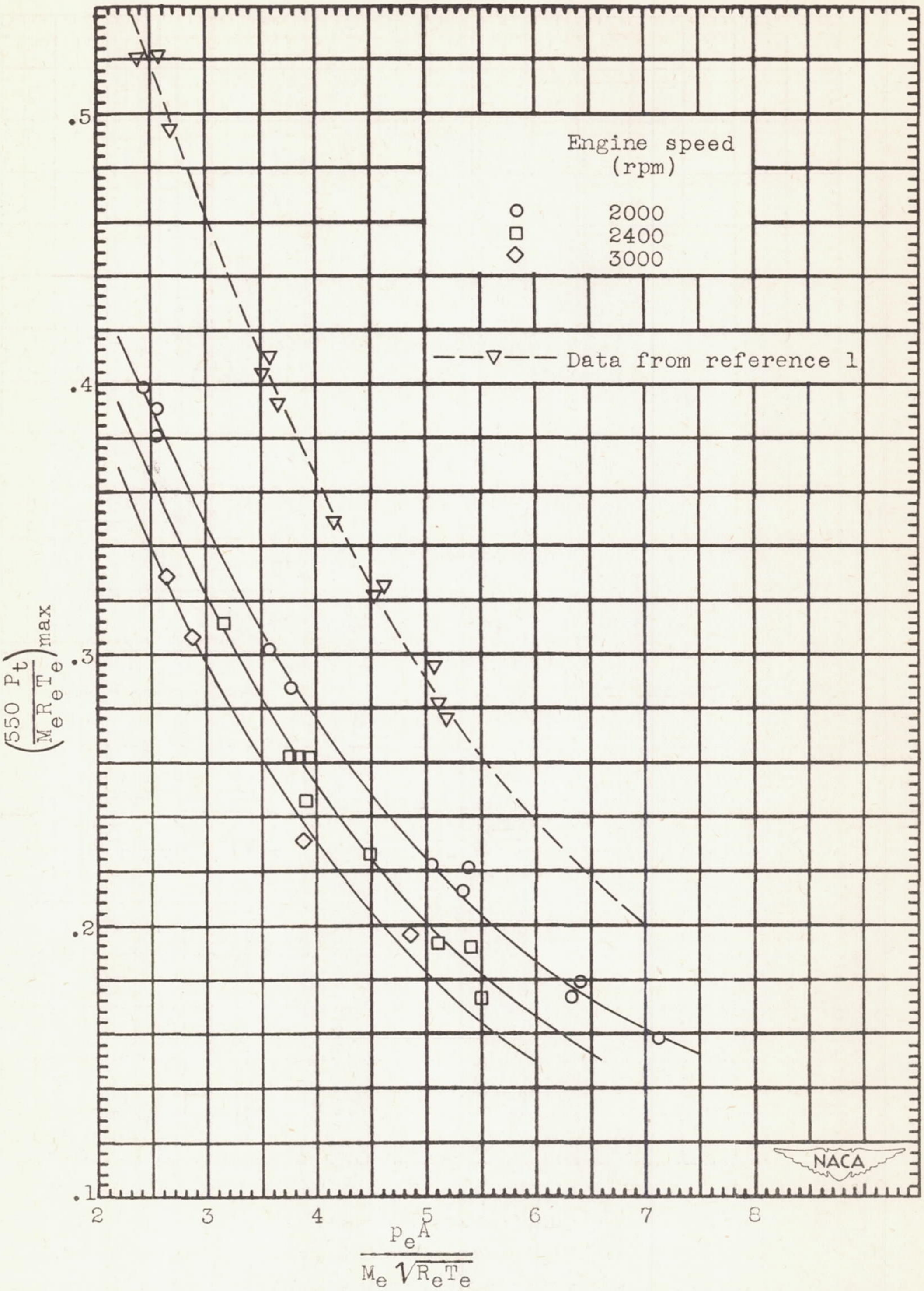
(b) Engine speed, 2400 rpm.

Figure 4. - Continued. Variation of blowdown-turbine power with turbine speed.



(c) Engine speed, 3000 rpm.

Figure 4. - Concluded. Variation of blowdown-turbine power with turbine speed.



(a) Correlation of turbine power data at optimum blade-to-jet speed ratio.

Figure 5. - Correlation of blowdown-turbine performance.

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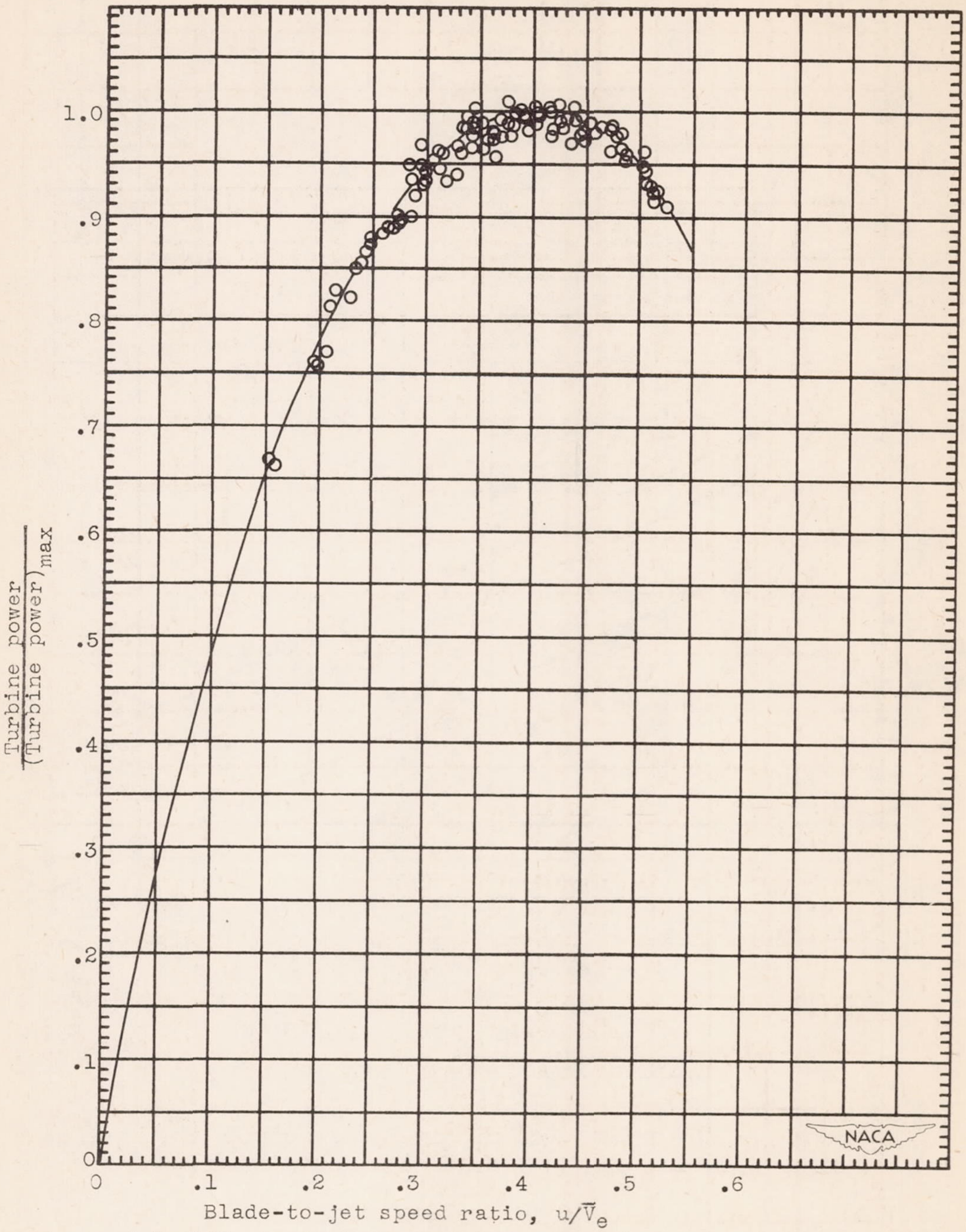

(b) Effect of blade-to-jet speed ratio on turbine power.

Figure 5. - Concluded. Correlation of blowdown-turbine performance.

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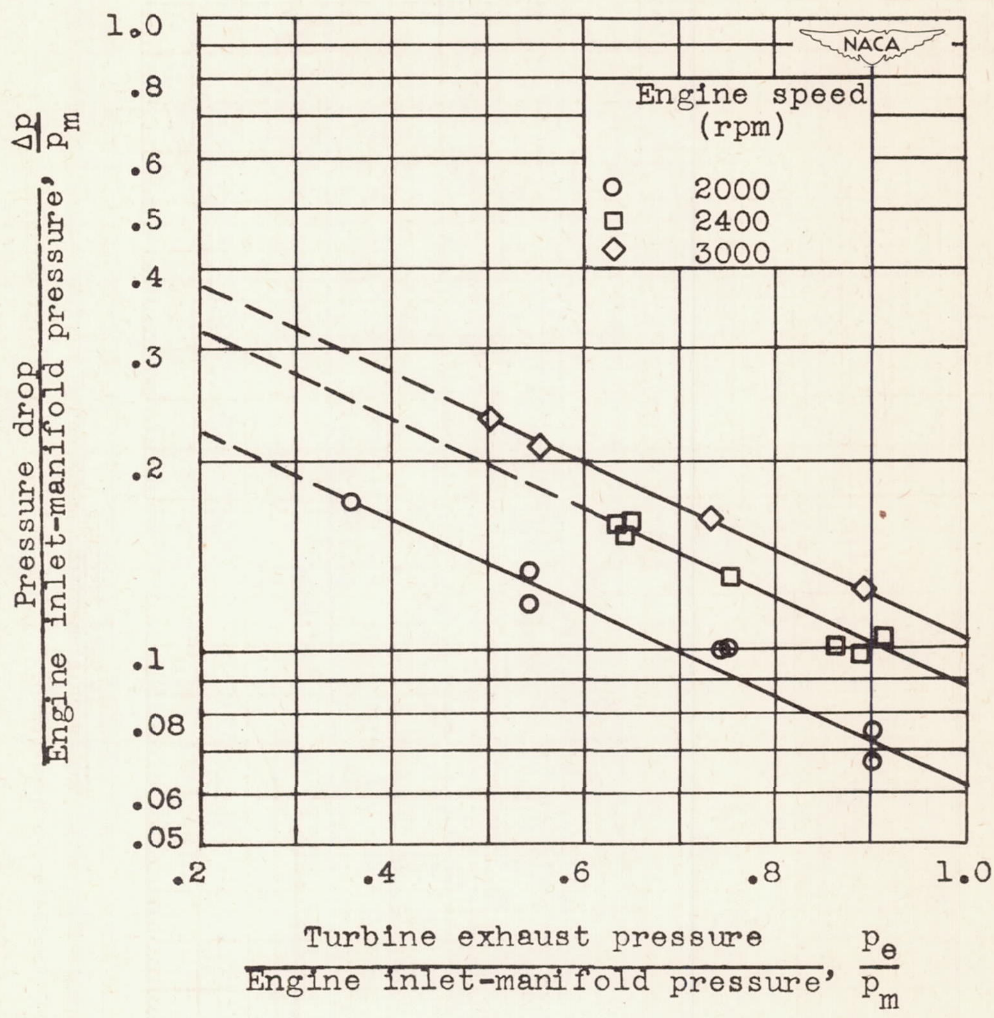
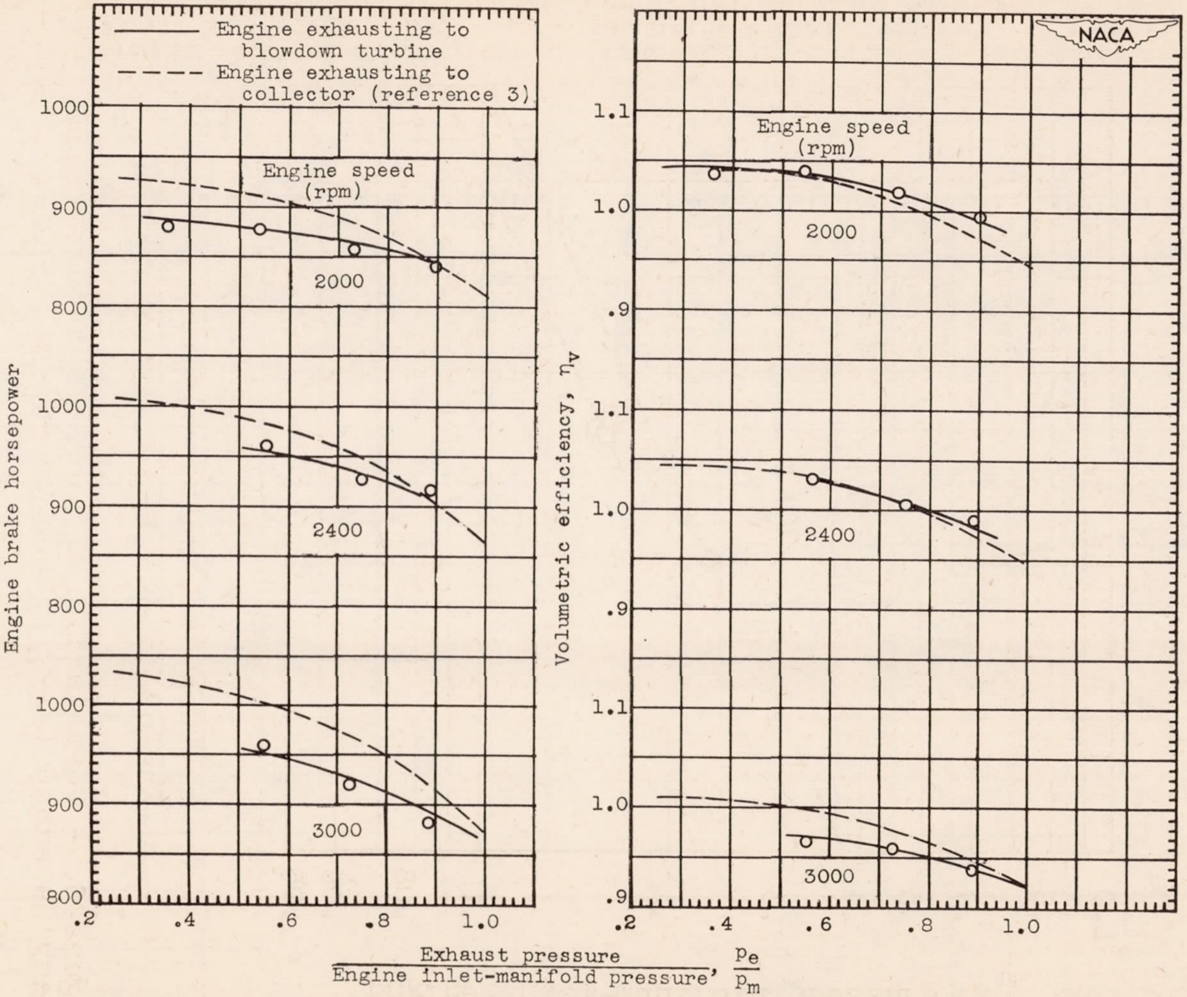


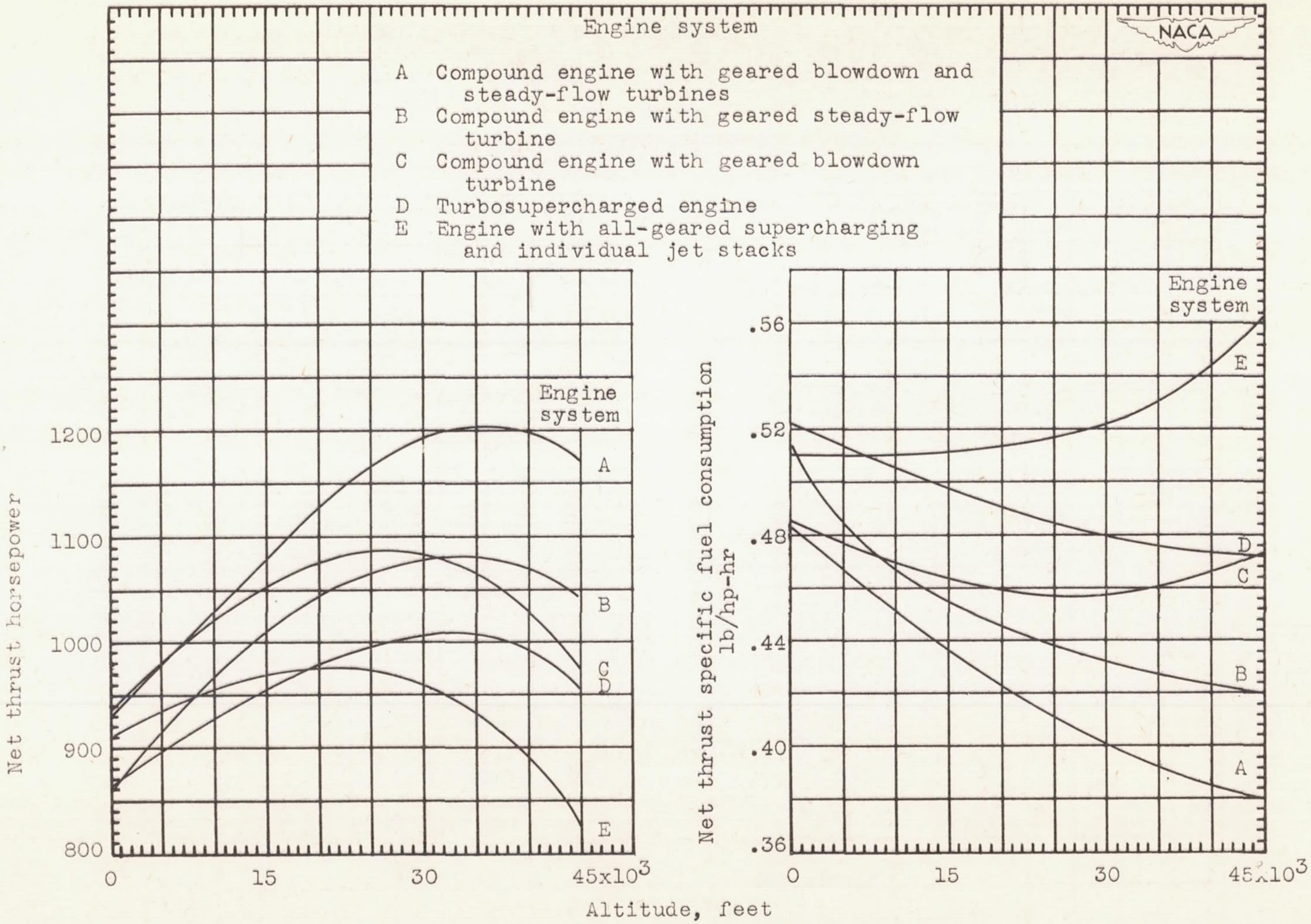
Figure 6. - Correlation of pressure drop through engine exhaust system and blowdown-turbine.



(a) Engine brake horsepower.

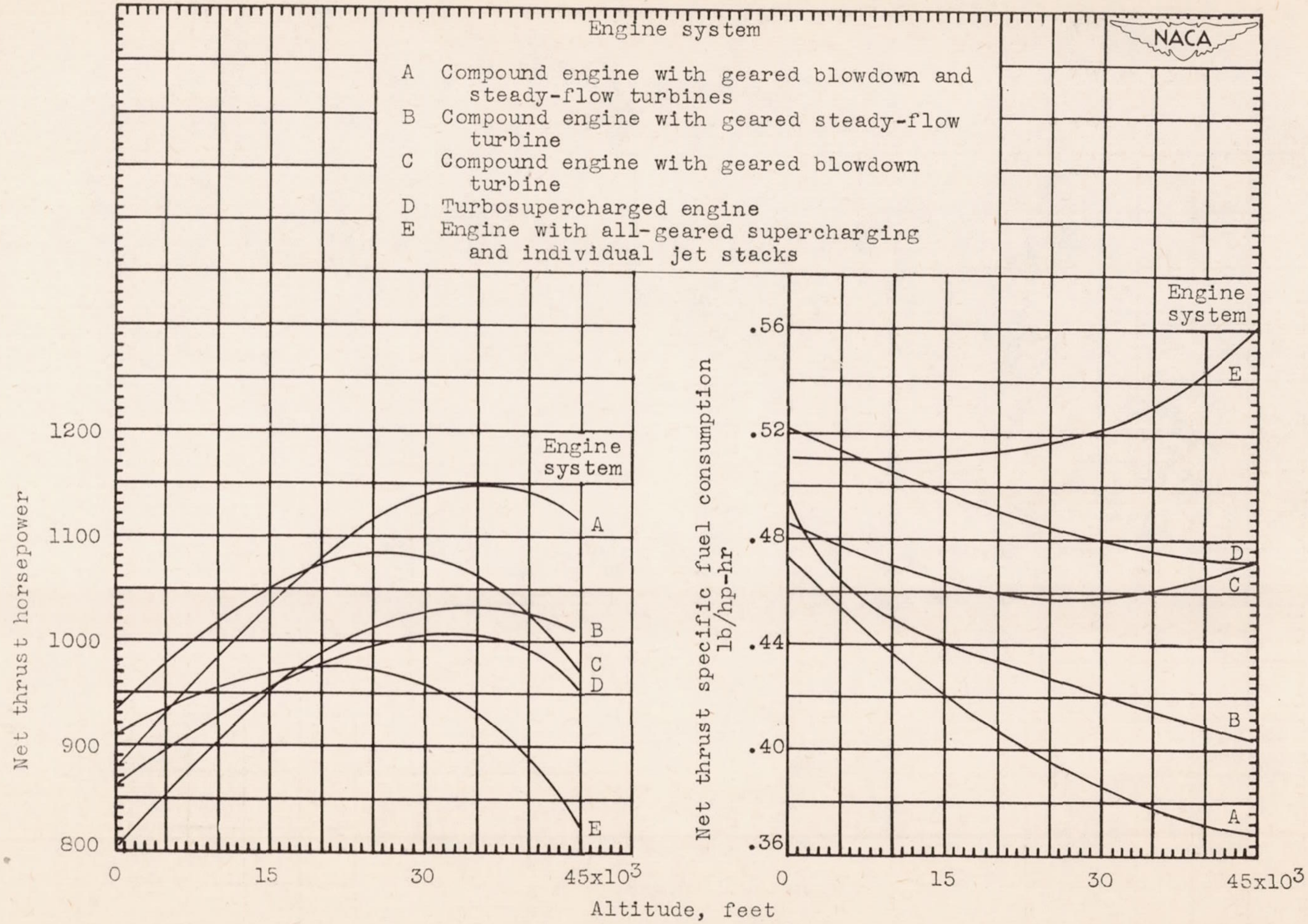
(b) Volumetric efficiency.

Figure 7. - Effect of presence of blowdown turbine on engine brake horsepower and volumetric efficiency. Engine inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.085; carburetor-air temperature, 90° ± 5° F.



(a) Best power p_e/p_m.

Figure 8. - Variation of net thrust horsepower and specific fuel consumption with altitude for five engine systems. Engine speed, 2600 rpm; engine inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.069; airplane velocity, 400 miles per hour.



(b) Best economy p_e/p_m.

Figure 8. - Concluded. Variation of net thrust horsepower and specific fuel consumption with altitude for five engine systems. Engine speed, 2600 rpm; engine inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.069; airplane velocity, 400 miles per hour.