NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
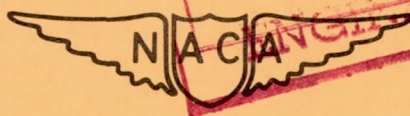
TECHNICAL NOTE

No. 1735

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

By Leland G. Desmon and Eldon W. Sams

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Washington
November 1948

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE No. 1735

PERFORMANCE OF EXHAUST-GAS BLOWDOWN TURBINE

AND VARIOUS ENGINE SYSTEMS USING A
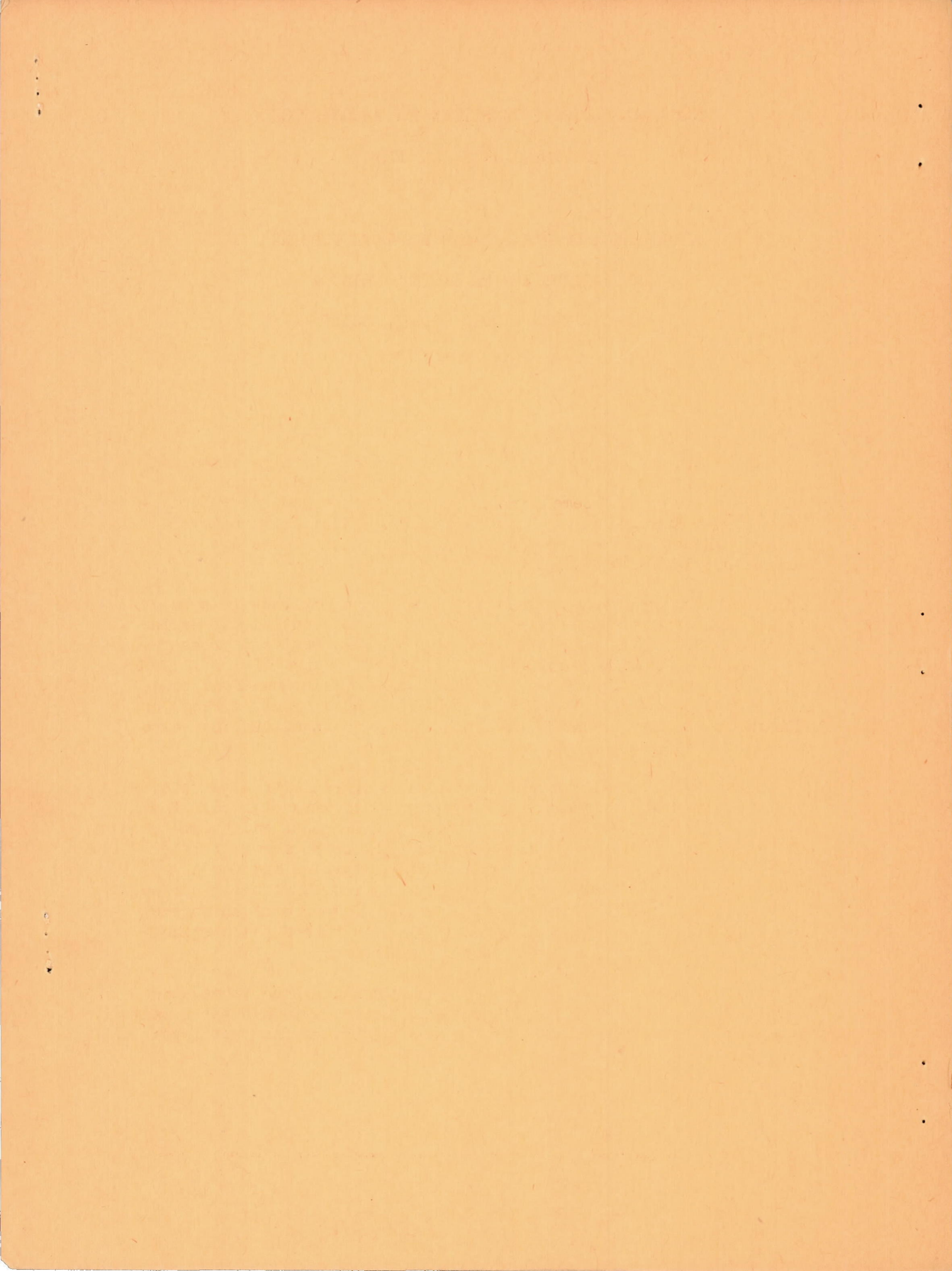
12-CYLINDER LIQUID-COOLED ENGINE

By Leland G. Desmon and Eldon W. Sams

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 nonover-
lapping 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 pres-
sure 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 horse-
power 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 pre-
sented 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 appre-
ciable engine power loss.

Inasmuch as the investigation of reference 1 was conducted
over a limited range of conditions with a comparatively small tur-
bine 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 pre-
sented 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 cal-
culated performance of an engine system with all-geared super-
charging, 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 per-
manently fixed to the individual blades. The wheel and the shaft,
the bearing housing, and the oil system were obtained from a com-
mercially manufactured turbosupercharger.

A labyrinth-type seal was placed between the nozzle diaphragm
and the bearing housing to prevent leakage into or out of the tur-
bine gas system, and compressed air was used to balance the seal
pressures and cool the enclosed part of the bearing housing. Pro-
vision 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
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 butter-
fly 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° ±15° F, the engine oil-inlet temperature was maintained at 150° ± 5° F by automatic control, and the coolant-outlet temperature was held constant at 220° ±5° 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

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

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

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

$$\Delta T_e = \frac{550\, \dot{P_t}}{M_e R_e}\left(\frac{\gamma_e - 1}{\gamma_e}\right) \tag{6}$$

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 $550\, P_t/M_e R_e T_e$ 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.

976

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

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

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

Net thrust specific fuel consumption ntsfc is

$$ntsfc = \frac{3600 \ fgM_a}{nthp} \qquad (8)$$

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 $550\ P_t/M_e R_e T_e$ with turbine speed is shown for various engine inlet-manifold pressures, fuel-air ratios, and values of $p_e A/M_e \sqrt{R_e T_e}$. 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 $p_e A/M_e \sqrt{R_e T_e}$, 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 $p_e A/M_e \sqrt{R_e T_e}$ 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 $550\ P_t/M_e R_e T_e$ from each curve of constant $p_e A/M_e \sqrt{R_e T_e}$ of figure 4 are plotted against the corresponding values of $p_e A/M_e \sqrt{R_e T_e}$. 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 $p_e A/M_e \sqrt{R_e T_e}$ 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 $p_e A/M_e \sqrt{R_e T_e}$. 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 $p_e A/M_e \sqrt{R_e T_e}$ (fig. 4) and plotting against the corresponding blade-to-jet speed ratio $u/\overline{V}_e$.

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 $\overline{V}_e$ from figure 10 of reference 5 is considered satisfactory here because any discrepancy that might exist between the actual values of $\overline{V}_e$ 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° ±5° 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 horse-
power 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)	Turbo-supercharged 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.

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 $v_d n/A$. Reference 5 further shows that for the condition of no engine power loss, the critical or proper values of $v_d n/A$ 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 $v_d n/A$ 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 $v_d n/A$ equal to 210 is indicated. By substituting the engine displacement and design speed in the relation $v_d n/A = 210$, 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.

REFERENCES

1. Turner, L. Richard, and Desmon, Leland G.: Performance of Blow-
   down Turbine Driven by Exhaust Gas of Nine-Cylinder Radial
   Engine. NACA Rep. No. 786, 1944.

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

3. Desmon, Leland G., and Doyle, Ronald B.: Effect of Exhaust Pres-
   sure on the Performance of a 12-Cylinder Liquid-Cooled Engine.
   NACA TN No. 1367, 1947.

4. Turner, L. Richard, and Noyes, Robert N.: The Performance of a
   Composite Engine Consisting of a Reciprocating Spark-Ignition
   Engine, a Blowdown Turbine, and a Steady-Flow Turbine. NACA
   TN No. 1447, 1947.

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.

6. Desmon, Leland G., and Doyle, Ronald B.: Calculated Performance
   of 12-Cylinder Liquid-Cooled Engine with Exhaust-Gas Turbine
   Geared to Crankshaft. NACA TN No. 1602, 1948.

7. Pinkel, Benjamin: Utilization of Exhaust Gas of Aircraft Engines.
   SAE Trans., vol. 54, 1946, pp. 714-734; discussion, p. 735.
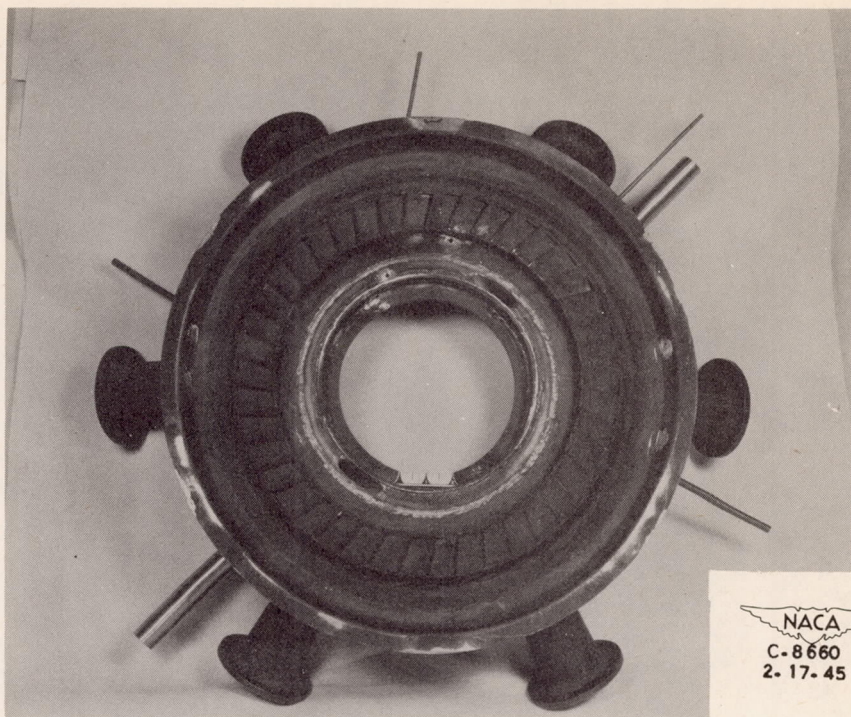
(a) Front view.
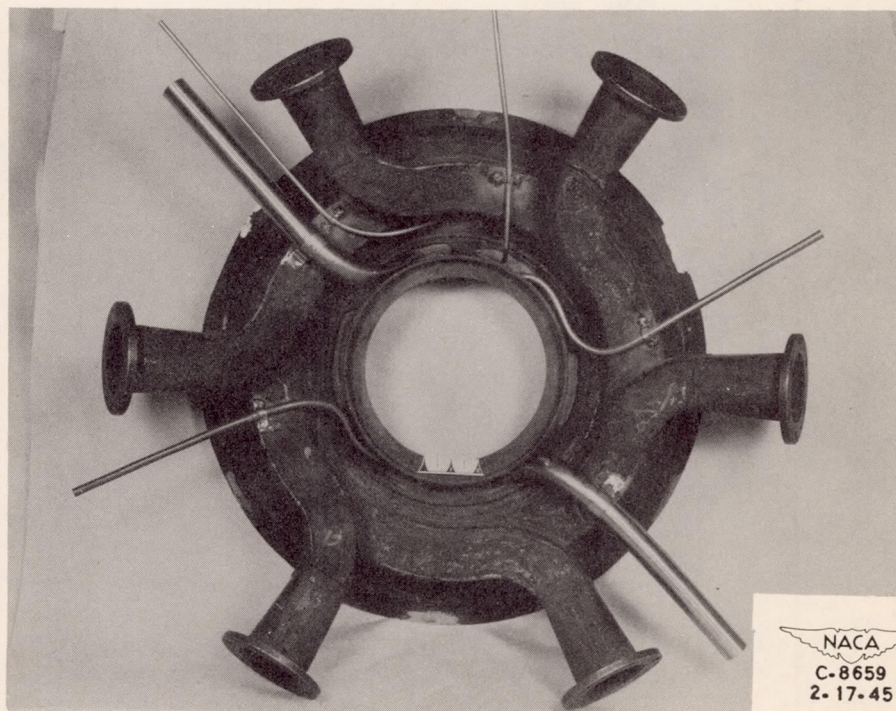
(b) Rear view.

Figure 1. - Blowdown-turbine nozzle assembly.

C-14107
1-17-46
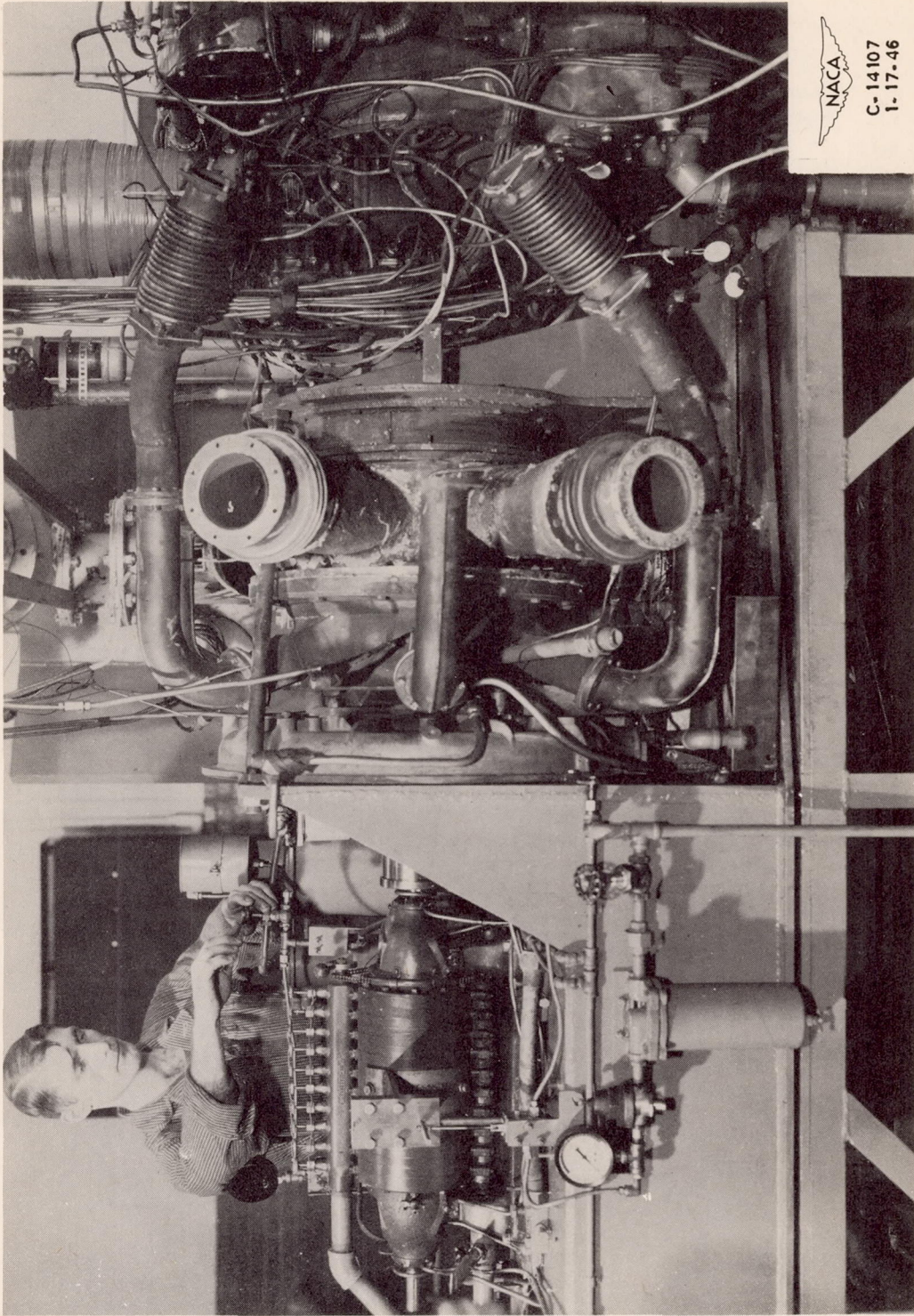
Figure 2. - Blowdown-turbine installation.
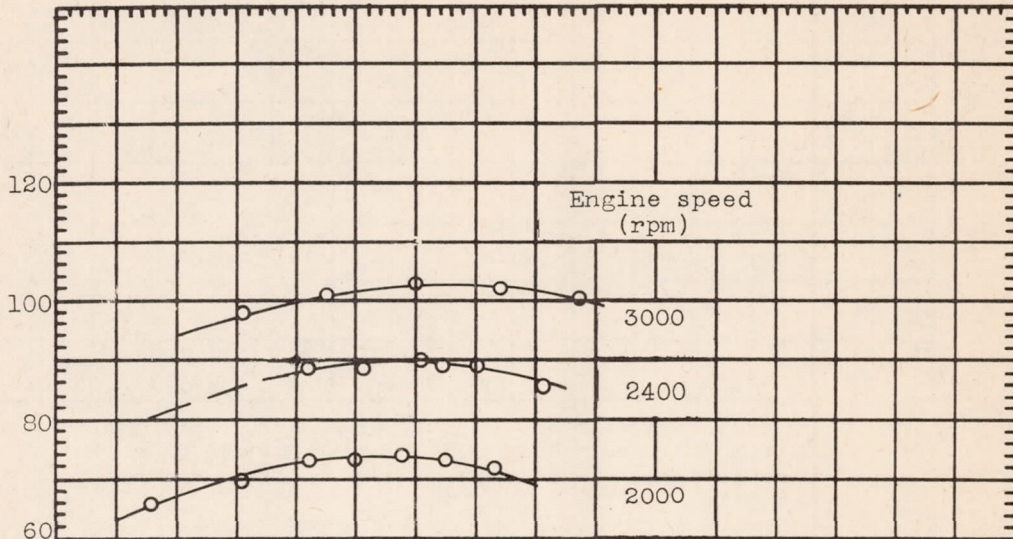
(a) Effect of engine speed. Engine inlet-manifold pressure,
40 inches mercury absolute; fuel-air ratio, 0.085;
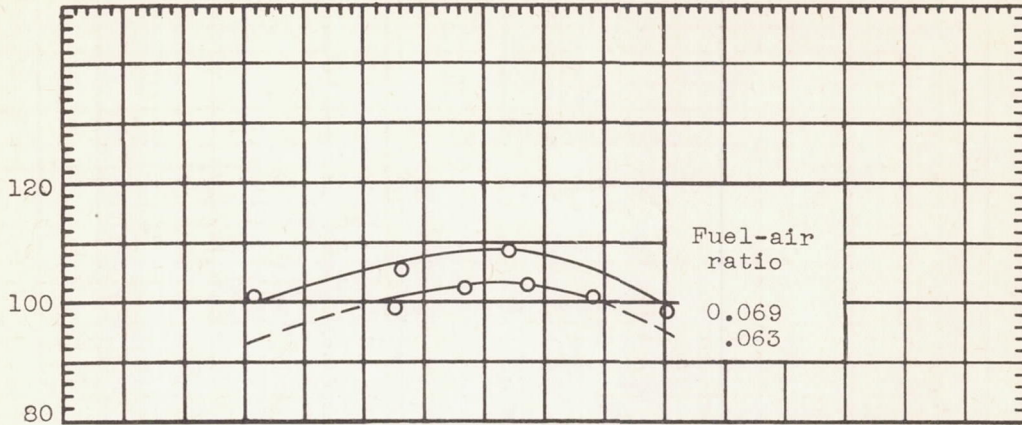turbine-exhaust pressure, 29 to 30 inches mercury
absolute.

(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.
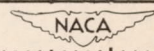
(c) Effect of fuel-air ratio. Engine speed, 2400 rpm; engine
inlet-manifold pressure, 40 inches mercury absolute;
turbine-exhaust pressure, 25 to 26 inches mercury
absolute.
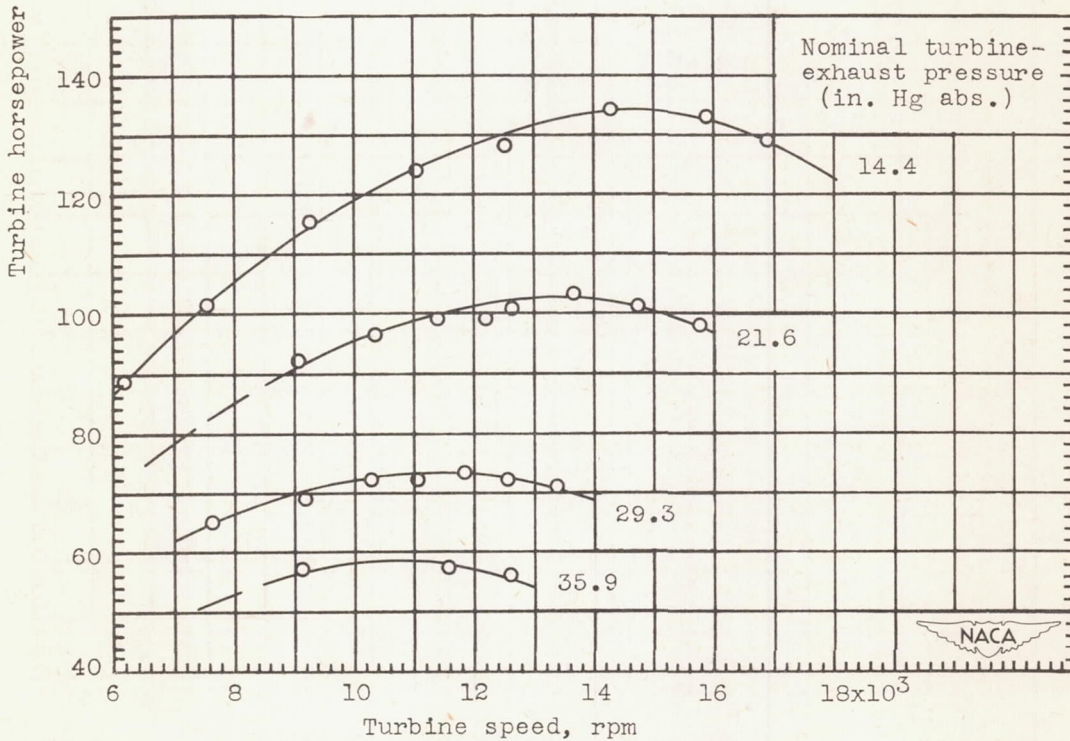
(d) Effect of turbine-exhaust pressure. Engine speed, 2000 rpm;
engine inlet-manifold pressure, 40 inches mercury
absolute; fuel-air ratio, 0.085.
Figure 3. - Concluded. Representative blowdown-turbine power data.
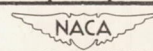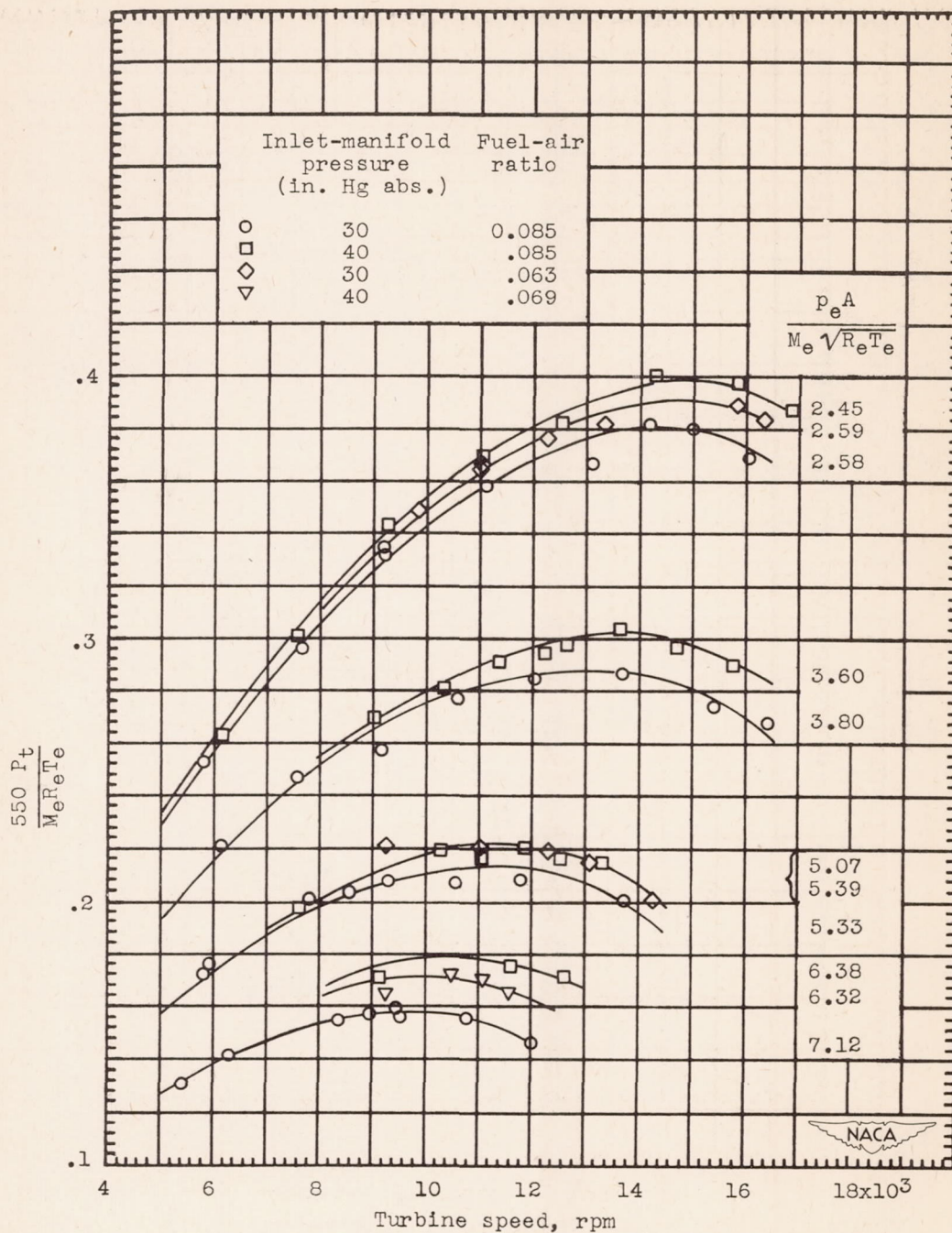
(a) Engine speed, 2000 rpm.
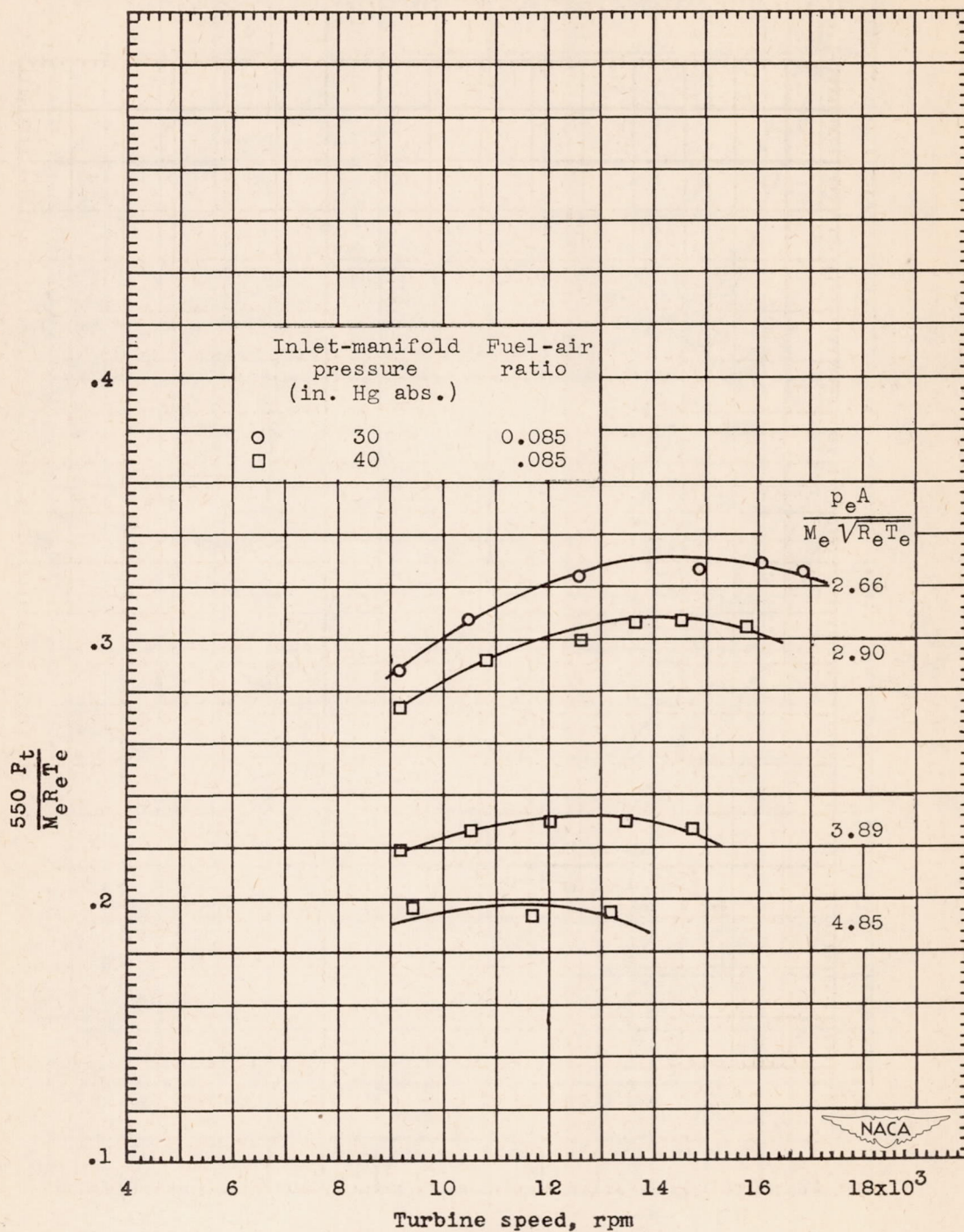
Figure 4. - Variation of blowdown-turbine power with turbine speed.
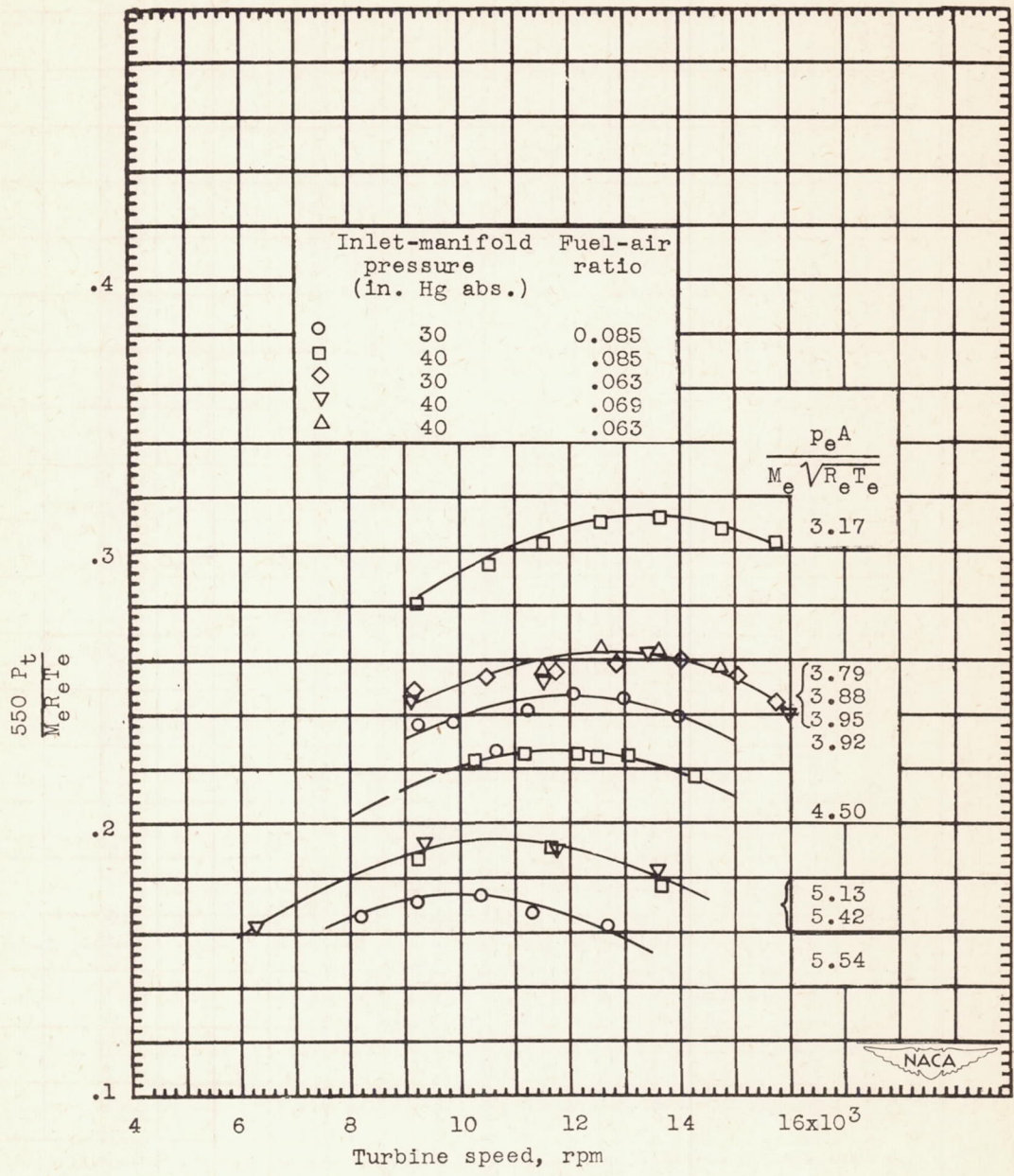
(b) Engine speed, 2400 rpm.

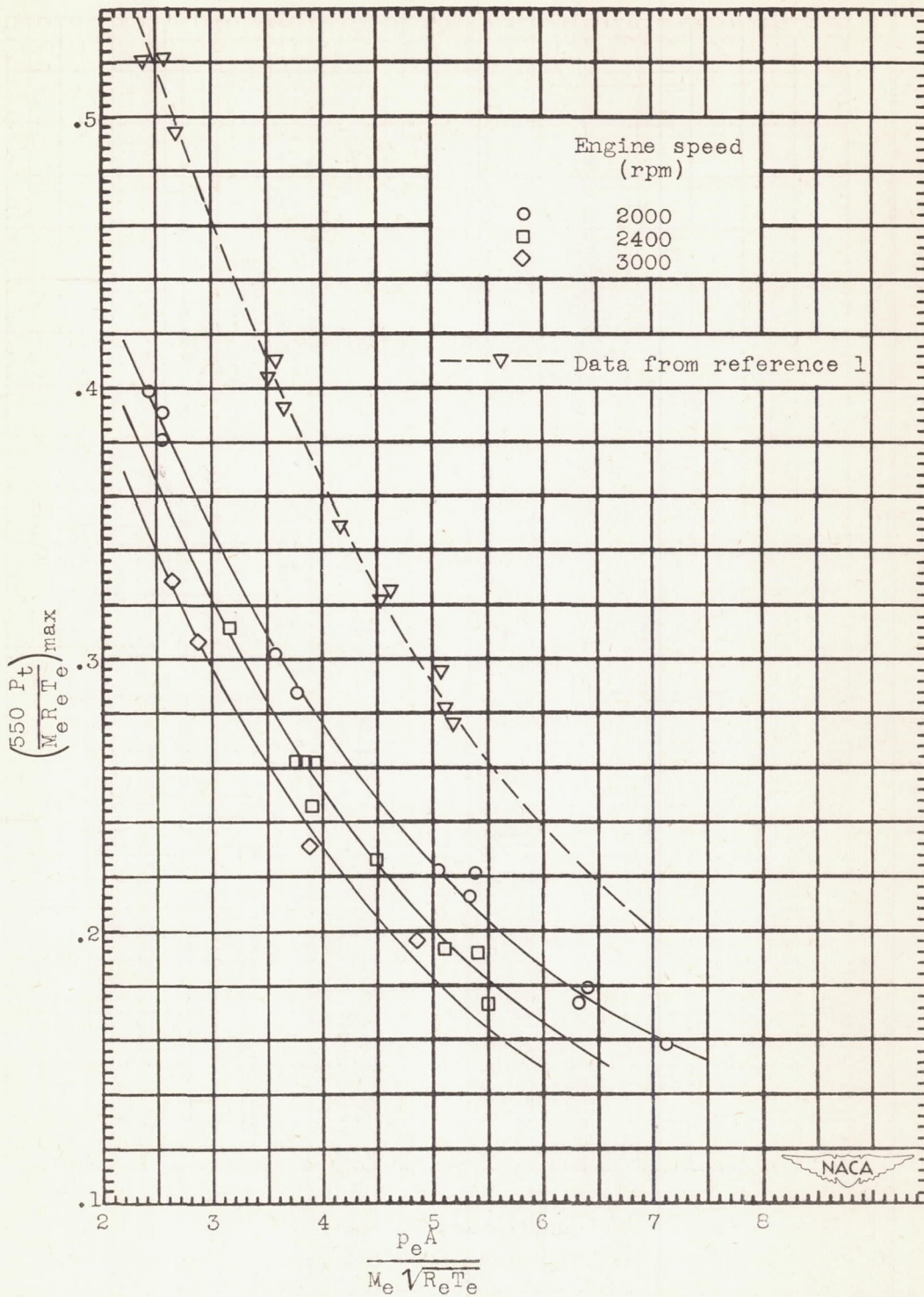Figure 4. - Continued. Variation of blowdown-turbine power with turbine speed.

(c) Engine speed, 3000 rpm.

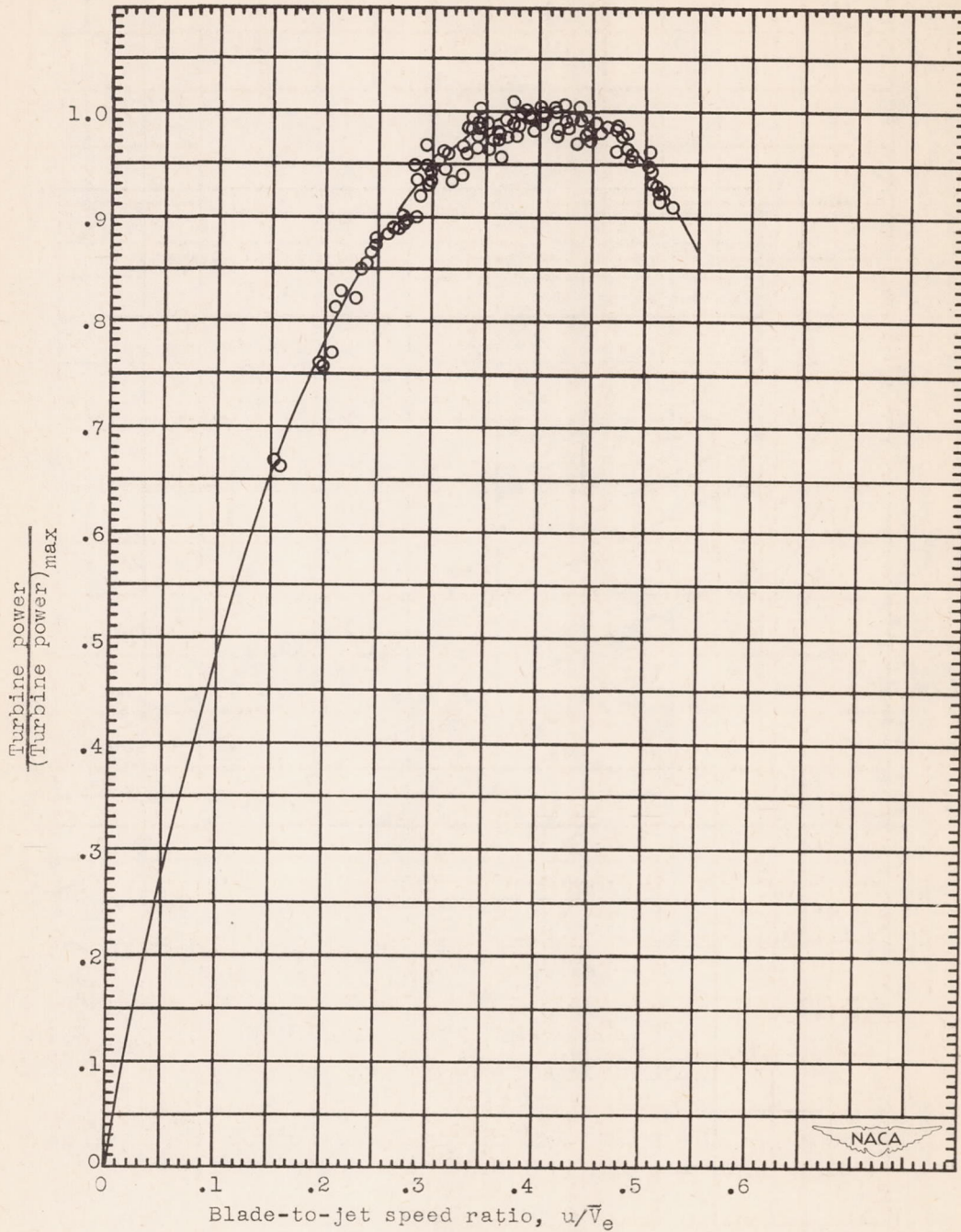Figure 4. - Concluded. Variation of blowdown-turbine power with turbine speed.

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

Figure 5. - Correlation of blowdown-turbine performance.

976

Turbine power / (Turbine power)$_{max}$

Blade-to-jet speed ratio, $u/\overline{V}_e$

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

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

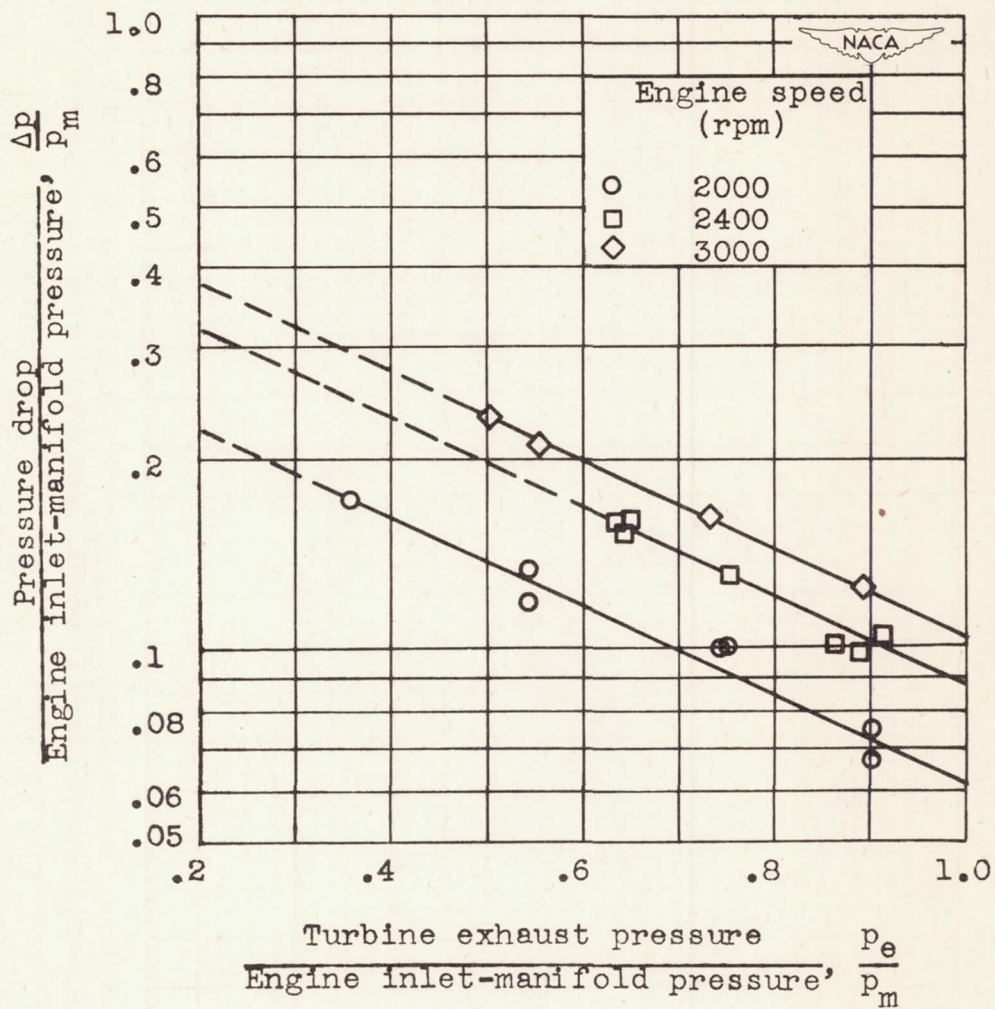Figure 6. - Correlation of pressure drop through
engine exhaust system and blowdown-turbine.

(a) Engine brake horsepower.
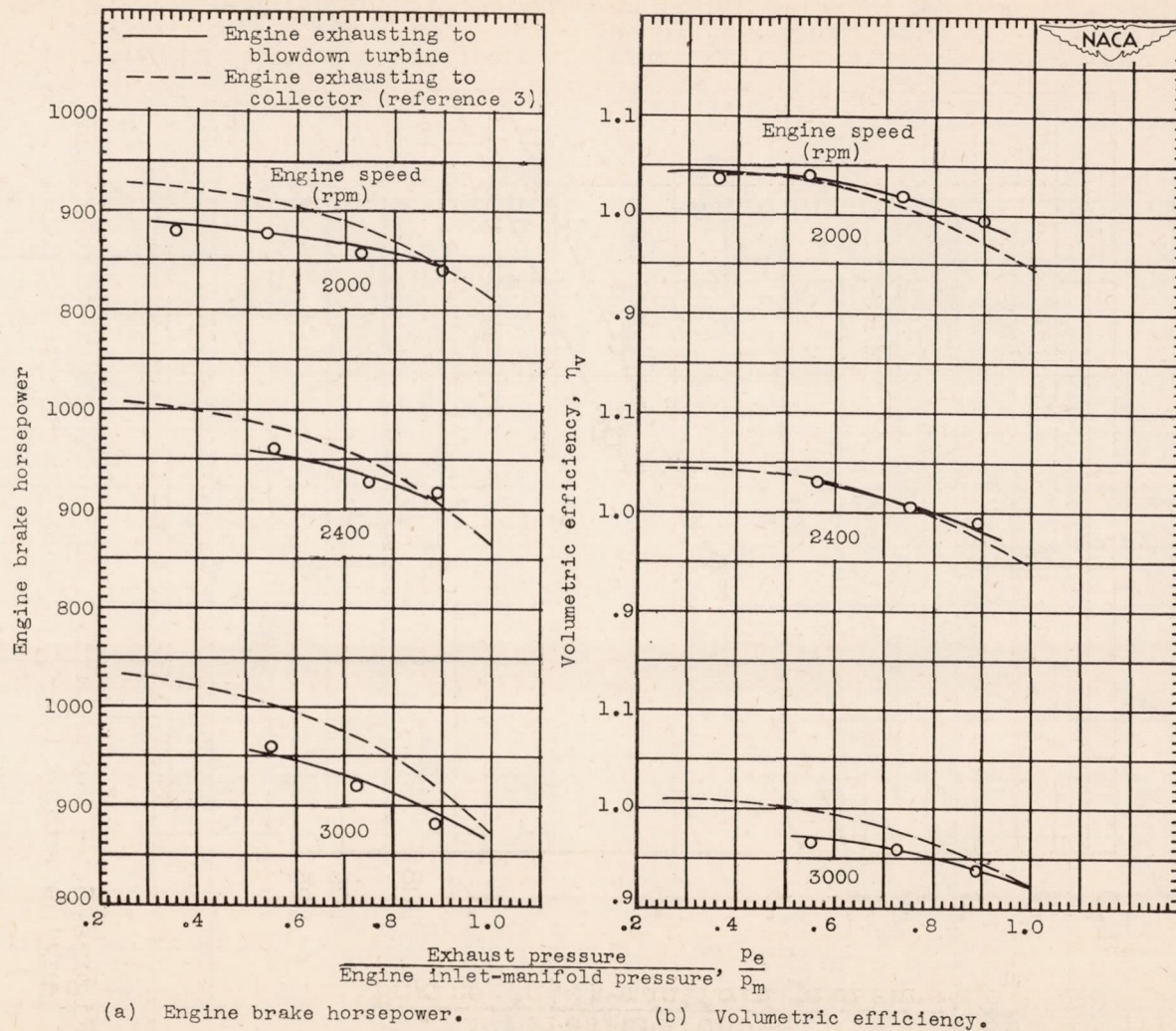
(b) Volumetric efficiency.

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.
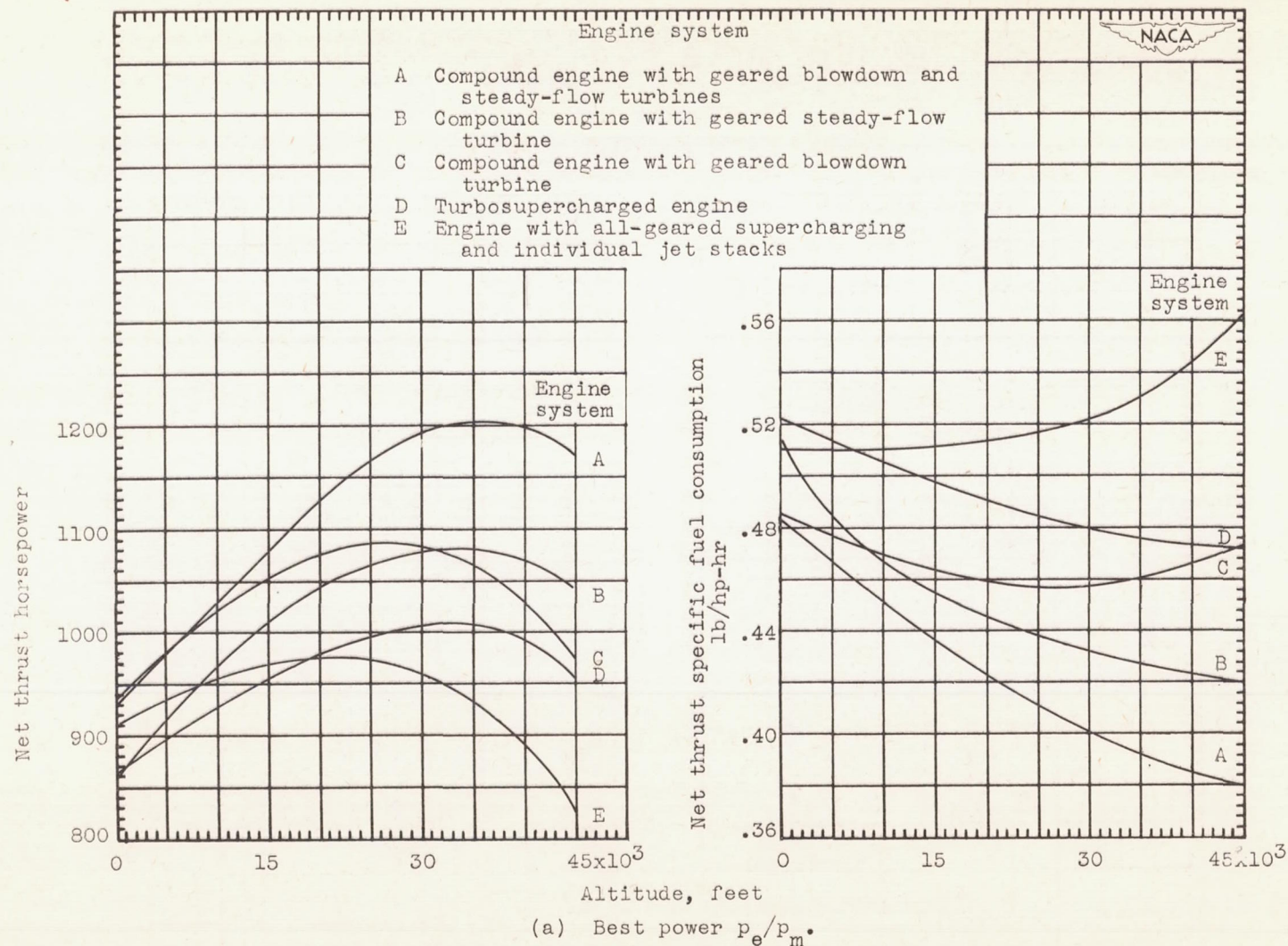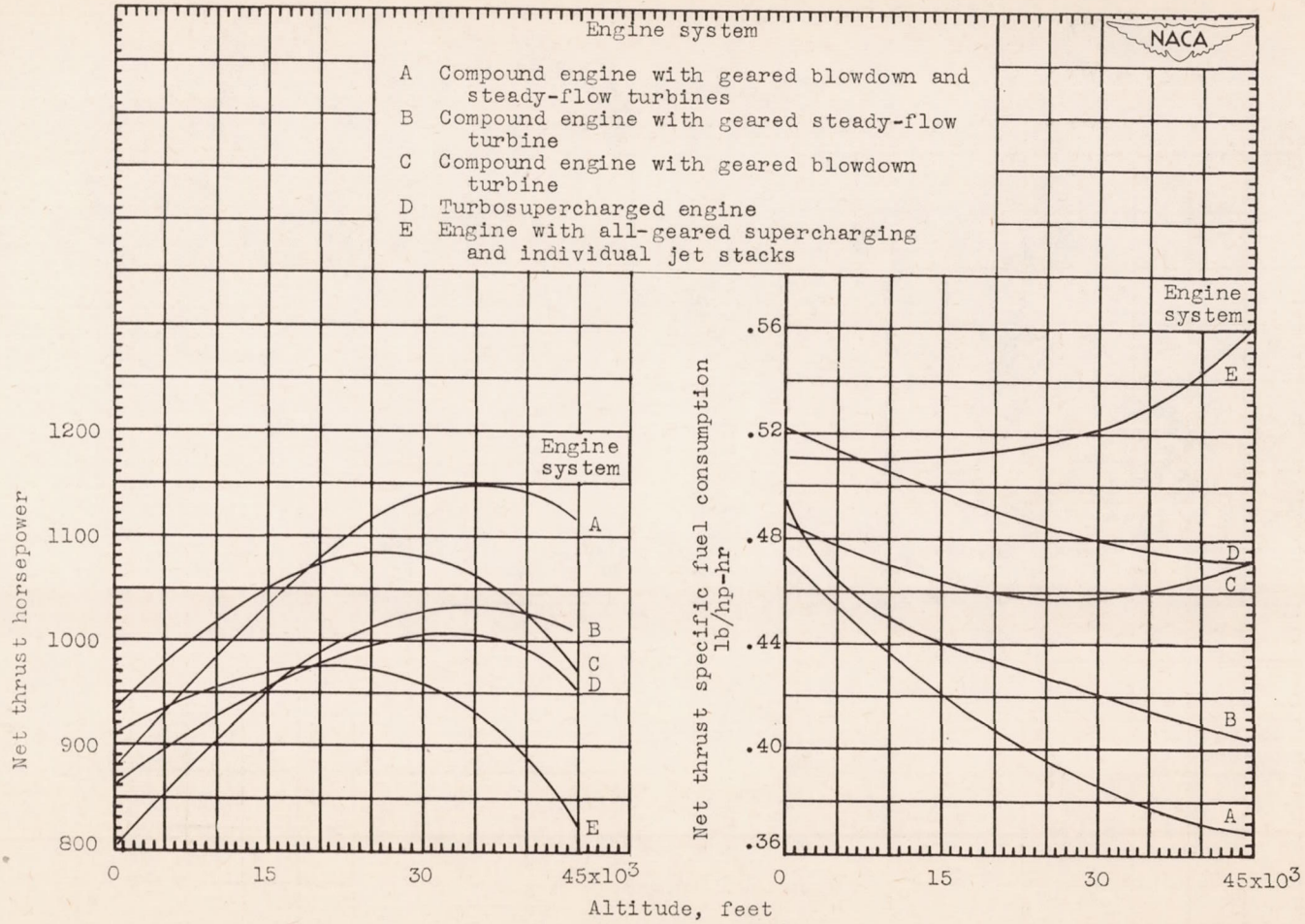
(a) Best power p_e/p_m.

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.

Engine system

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

Altitude, feet

(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.