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THE PERFORMANCE OF A COMPOSITE ENGINE CONSISTING OF

A RECIPROCATING SPARK-IGNITION ENGINE, A BLOWDOWN

TURBINE, AND A STEADY-FLOW TURBINE

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SUMMARY

An analysis is presented of the performance of a composite engine consisting of a reciprocating spark-ignition engine, two superchargers, a blowdown turbine, and a steady-flow turbine. The performance of composite engines with geared-in turbines and of composite engines using auxiliary propellers to absorb the excess power of the steady-flow turbines was analyzed in order to determine the suitability and cost of design compromises when the size of turbines and superchargers and all gear ratios are assumed fixed.

The analysis indicated the possibility of attaining at an altitude of 30,000 feet the minimum brake specific fuel consumption of the order of 0.336 pound per horsepower-hour with turbines and superchargers operating at an assumed maximum efficiency of 70 percent.

INTRODUCTION

The composite engine, consisting of a reciprocating engine as the primary stage with one or more gas turbines to act as additional stages of expansion, is currently being considered for use in the propulsion of long-range aircraft. Several analyses have been made of composite-engine systems using a single steady-flow turbine. (See, for example, references 1 and 2.)

The blowdown turbine, which uses exhaust gas discharged intermittently from separate cylinders of the primary engine (described in reference 3), can remove energy from the exhaust gas without imposing any additional back pressure on the engine. In addition, the blowdown turbine recovers power from the kinetic energy of the gas in the exhaust ports and stacks that is ordinarily wasted in the exhaust collector when the exhaust gases are used to drive a steady-flow turbine. The output of a blowdown turbine increases less

rapidly, however, than that of a steady-flow turbine as the turbine-discharge pressure is decreased. For most cases, more power may be recovered from the exhaust gas by using a blowdown turbine and a steady-flow turbine in series than by using either turbine separately.

This analysis presents the calculated performance for various flight conditions of the following three composite-engine systems, each of which includes a spark-ignition engine, a blowdown turbine, a steady-flow turbine, two superchargers, and a 50-percent effective intercooler.

(a) Variable-component system: For every point of the calculation, the size and rotative speed of the components are assumed to be correct for operation at maximum efficiency at that point. Each turbine directly drives a supercharger and any excess power from the turbines is delivered to the engine through gear trains, and conversely, any deficiency in turbine power required by the superchargers is provided by the engine.

(b) Fixed-component system: Turbines and superchargers of fixed size are connected to the engine with fixed gears. In such a system the speed of the components will necessarily depend on engine speed, and losses in the efficiency of the turbines and losses due to throttling the auxiliary supercharger will occur.

(c) Auxiliary-propeller system: This system is the same as the fixed-component system except that steady-flow-turbine power in excess of that required by the auxiliary supercharger is absorbed by an auxiliary propeller. In such a system, it is unnecessary to throttle the auxiliary supercharger.

The variable-component system represents the best performance attainable with the assumed component efficiencies and therefore serves as a basis of evaluating the performance of the more realistic fixed-component and auxiliary-propeller systems.

The performance of the variable-component system is compared with the performance of systems composed of the same reciprocating engine using only a geared steady-flow turbine and the same engine with individual cylinder jet stacks used for jet propulsion. In evaluating performance, no consideration was given to the difference in weight of the various systems being compared.

PROCEDURE

In this analysis, the net power of a composite-engine system is defined as the sum of the indicated engine power and the power

developed by the turbines and jet propulsion less the power consumed by engine friction, supercharging, and drag of picking up the inlet charge air.

The indicated engine power as determined from an engine calibration is here defined as the sum of the brake power, the power absorbed by the supercharger, and the engine friction power measured or calculated for equal intake and exhaust pressure. The engine friction power is therefore a function of engine speed.

The specific air consumption was calculated from test volumetric efficiencies of a reciprocating engine and the calculated net power of the composite engine. The specific fuel consumption is the product of the specific air consumption and the fuel-air ratio. The computation of specific fuel consumption was made for a fuel-air ratio of 0.067 for all conditions. In the interpretation of the results of the analysis, it must be remembered that the specific fuel consumption will be increased in proportion to the fuel-air ratio for those conditions that require enriching because of knock limitations of the fuel.

When the computations for the analysis were started, the only available engine data applicable to the analysis were from tests of a single cylinder of a current high-performance nine-cylinder aircraft engine having a displacement of 1820 cubic inches and a nominal valve overlap of 40°. These test data were for an engine speed of 1700 rpm and a fuel-air ratio of 0.10. Calculation of the performance of the composite engine was made using this engine data, assuming that the power and air flow of an engine for a fuel-air ratio of 0.10 was equal to that obtained for a fuel-air ratio of 0.067.

Subsequently, suitable multicylinder-engine data became available as a result of tests of a current 18-cylinder aircraft engine having a displacement of 2800 cubic inches and a nominal valve overlap of 40°. These data were taken at an engine speed of 2000 rpm, an intake-manifold pressure of 30 inches of mercury absolute, and a fuel-air ratio of 0.069. As a check on the validity of the use of the single-cylinder data to compute the performance of full-scale composite engines, the performance of the composite engine was calculated for an engine speed of 2100 rpm and an intake-manifold pressure of 35 inches of mercury absolute by extrapolating the available multicylinder-engine data.

The details of calculating the performance of the composite engine are given in appendix A.

DISCUSSION

Variable-Component System

The variable-component system consists of the following components: a conventional four-stroke-cycle spark-ignition engine, blowdown and steady-flow turbines, a tail pipe designed for jet propulsion, and two independent stages of supercharging. A diagram of this arrangement is shown in figure 1. The auxiliary-stage supercharger is connected to the shaft of the steady-flow turbine and the engine-stage supercharger is connected to the shaft of the blowdown turbine. Each combination of turbine and supercharger is so geared to the engine through separate gear trains that any excess or deficit in power may be delivered to or made up by the engine. The exhaust gas flows from the individual engine cylinders to the blowdown turbine, then through the steady-flow turbine, and is discharged through the jet-propulsion nozzle.

The basic reciprocating engine of the composite engines discussed is assumed to be an 18-cylinder engine having a bore of $5\frac{3}{4}$ inches and a stroke of 6 inches. The displacement volume of such an engine would be approximately 2800 cubic inches.

Nozzle area for blowdown turbine. - In the calculation of the performance of the blowdown turbine, the kinetic energy associated with the exit velocity from the blowdown turbine was assumed to be dissipated and not conserved for use by the steady-flow turbine; the total pressure at the inlet to the steady-flow turbine was assumed to be equal to the static pressure at the outlet of the blowdown turbine.

The best area for the nozzles of the blowdown turbine can be chosen for any ratio of blowdown-turbine static discharge pressure to intake-manifold pressure without determining the performance of the entire composite engine. As the area of a nozzle at the end of an individual exhaust stack is reduced, the mean exhaust-gas jet velocity $\overline{V}_e$ developed at the nozzles of the blowdown turbine increases. The engine power at first remains constant and then decreases with no change in air weight flow. Finally the air weight flow decreases. The ratio $v_d n/A$ has been shown by reference 4 to be the controlling parameter in this process, where v_d is the displacement volume of the engine, n is the engine speed, and A is the exhaust-stack-nozzle area.

The change in net power of the engine and blowdown turbine ΔP is given by the equation

$$\Delta P = (\eta_{V,o} + \Delta\eta_V)(1 + f)\left(\frac{p_m\, v_d\, n}{2g\, R\, T_s'}\right)\sqrt{\frac{T_s'}{T_m'}}\left(\frac{\overline{V}_e^{\,2}}{2}\,\overline{\eta}_b\right) + \left(\frac{p_m\, v_d\, n}{2}\right)\Delta\phi \quad (1)$$

where

η_V volumetric efficiency of engine

$\eta_{V,o}$ volumetric efficiency of engine with stub stacks having no restriction

$\Delta\eta_V$ change in η_V due to stack restriction (assumed zero)

f fuel-air ratio

p_m intake-manifold absolute static pressure, (lb/sq ft)

g acceleration of gravity, 32.2 (ft)/(sec^2)

R gas constant for air, 53.35 (ft-lb)/(lb)(^{O}F)

T_s' standard total intake-manifold temperature, 540 (^{O}R)

T_m' total intake-manifold temperature, (^{O}R)

$\overline{\eta}_b$ mean blowdown-turbine efficiency

$\Delta\phi$ change, due to stack restriction, in the ratio of indicated mean effective pressure of engine to intake-manifold pressure

All the symbols used are defined where first used and, for convenience, are also recapitulated in appendix B.

Equation (1) may be simplified by expressing the change in power in the nondimensional form

$$\Delta\Phi = (\eta_{V,o} + \Delta\eta_V)\sqrt{\frac{T_s'}{T_m'}}\left[\frac{(1 + f)\,\overline{V}_e^{\,2}\,\overline{\eta}_b}{2g\, R\, T_s'}\right] + \Delta\phi \quad (2)$$

where

$$\Delta\Phi = \frac{\Delta P}{\dfrac{P_m \; v_d \; n}{2}}$$

Figure 2 shows $\Delta\Phi$ as a function of the ratio $v_d n/A_b$ for various values of the ratio of blowdown-turbine static discharge pressure to intake-manifold pressure, where A_b is the blowdown-turbine nozzle area. The variation of the intake-manifold temperature T_m' with engine speed was neglected and T_m' was assumed equal to the standard temperature T_s'.

In an installation of fixed nozzle area, the ratio $v_d n/A_b$ increases in proportion to engine speed. If it is tentatively assumed that desirable operation of the composite engine will be obtained in the range of ratios of blowdown-turbine static discharge pressure to intake-manifold pressure between 0.6 and 1.0, operation at nearly maximum $\Delta\Phi$ will be obtained if a value for $v_d n/A_b$ of 200 feet per second is chosen for a cruising engine speed of 2100 rpm. For current air-cooled engines, rated-power and emergency speeds are about 15 and 30 percent higher, respectively, than cruising speed; that is, 2415 and 2730 rpm. On this basis, the values of $v_d n/A_b$ for rated and emergency speeds become 230 and 260 feet per second, respectively. Over the range of $v_d n/A_b$ from 200 to 260 feet per second, figure 2 indicates that at any ratio of blowdown-turbine static discharge pressure to intake-manifold pressure between 0.6 and 1.0, the value of $\Delta\Phi$ is nearly constant at its maximum value. For this particular case, the effective blowdown-turbine nozzle area A_b is 40.8 square inches. This effective area is equal to the physical area only when each engine cylinder discharges through a separate group of nozzles in the nozzle diaphragm.

The effect of exhaust-stack restriction on cylinder-head temperature for constant cooling conditions is shown in figure 3. These results, which are similar to results obtained at other engine operating conditions, were obtained from the single-cylinder data. For a value of $v_d n/A$ of 260 feet per second, which corresponds to the assumed emergency engine speed, cylinder-head temperatures are approximately 10° F higher than with no stack restriction where $v_d n/A$ values range from approximately 100 to 120 feet per second for the same engine speed. These results indicate that the reduction of exhaust-stack-nozzle area will cause only a small increase in cylinder-head temperature.

Performance of variable-component system. - The results of the analysis for the variable-component system based on single-cylinder data are presented for the following four altitudes: sea level, 15,000, 30,000, and 45,000 feet. Computations were made for engine speeds of 2100, 2415, and 2730 rpm and for three or four intake-manifold pressures. The net brake mean effective pressure and net brake specific fuel consumption are plotted in figure 4 against the ratio of total pressure at inlet of steady-flow turbine to intake-manifold pressure p'_0/p_m. These results were obtained using turbine and supercharger efficiencies of 70 percent and gear efficiencies of 85 percent. The results obtained by using multicylinder-engine data and the same values of turbine, supercharger, and gear efficiencies are also shown in figure 4 for an engine speed of 2100 rpm and an intake-manifold pressure of 35 inches of mercury absolute. These results are for a fuel-air ratio of 0.067, which is a representative fuel-air ratio for an engine running at cruise conditions. For higher power output, the plotted specific fuel consumptions would be increased in proportion to any increase in the fuel-air ratio.

Some significant features of the performance of the variable-component system based on single-cylinder data in the computation of the performance of the reciprocating engine with turbine and supercharger efficiencies of 70 percent, gear efficiencies of 85 percent, a fuel-air ratio of 0.067, and an altitude of 30,000 feet are shown in the following table:

Intake-manifold pressure p_m (in. Hg absolute)	Engine speed N (rpm)	$(bsfc)_{min}$ (lb/hp-hr)	$(p'_b/p_m)_0$ (1)	$(bmep)_0$ (lb/sq in.) (2)
35	2100	0.348	0.93	199
	2730	.363	.90	188
50	2100	0.336	0.94	283
	2730	.346	.92	271

[1]The ratio $(p'_b/p_m)_0$ denotes the ratio of blowdown-turbine exhaust pressure to intake-manifold pressure for which the brake specific fuel consumption is a minimum.

[2]The expression $(bmep)_0$ denotes the brake mean effective pressure that corresponds to minimum brake specific fuel consumption.

For low p_b'/p_m ratios, the specific fuel consumption, as cal-culated from the multicylinder data, is slightly higher and the power slightly lower than that obtained when calculated from the single-cylinder data. For high ratios of p_b'/p_m, the opposite is true. For a ratio of p_b'/p_m near unity, the results obtained from either multicylinder data or single-cylinder data are in close agreement.

The values of net brake mean effective pressure and net brake specific fuel consumption for the variable-component system computed using single-cylinder data, a blowdown-turbine efficiency of 70 per-cent, steady-flow turbine and supercharger efficiencies of 85 per-cent, and gear efficiencies of 95 percent are shown in figure 5. For these efficiencies, the analysis indicated that a minimum brake specific fuel consumption of 0.303 pound per horsepower-hour could be obtained at an altitude of 30,000 feet, an engine speed of 2100 rpm, an intake-manifold pressure of 50 inches of mercury absolute, and a fuel-air ratio of 0.067 (fig. 5(c)). A comparison of figure 5 with figure 4 shows that the regions in which maximum power and minimum fuel consumption occur are located at slightly higher values of p_b'/p_m for the higher steady-flow turbine, supercharger, and gear efficiencies in figure 5. Regardless of which set of component efficiencies are used for the computation, maximum power and min-imum fuel consumption occur approximately in the p_b'/p_m range from 0.5 to 0.7 and 0.85 to 1.1, respectively.

The distribution of power between the various auxiliary units that make up the variable-component system is shown in figure 6. These powers were evaluated at a p_b'/p_m ratio of 1.0 for turbine and supercharger efficiencies of 70 percent. The engine conditions for this distribution are an intake-manifold pressure of 35 inches of mercury absolute and an engine speed of 2100 rpm. Single-cylinder data were used for computing the air flow and the power of the recip-rocating engine. The corresponding net brake mean effective pres-sure for the variable-component system can be obtained from figure 4. The results obtained for other engine conditions are similar to those shown. For ratios of p_b'/p_m near unity, the powers of the blowdown turbine and the steady-flow turbine always exceed those required for the engine-stage and auxiliary-stage superchargers, respectively.

Comparison of variable-component system with other types of composite engine. - For comparison with the variable-component system, the performance of a supercharged engine with a geared-in steady-flow turbine and a jet-propulsion nozzle and of a super-charged engine with individual cylinder jet stacks having optimum stack discharge area to be used for jet propulsion was computed.

The results of analysis of these two systems were calculated using
single-cylinder data, turbine and supercharger efficiencies of
70 percent, gear efficiencies of 85 percent, an intake-manifold
pressure of 35 inches of mercury absolute, andengine speed of
2100 rpm, a fuel-air ratio of 0.067, an altitude of 30,000 feet,
and an airplane velocity of 375 miles per hour. The results are
presented in the following table:

	$(bsfc)_{min}$ (lb/hp-hr)	$(p_b'/p_m)_o$	$(bmep)_o$ (lb/sq in.)
Geared-in steady-flow turbine	0.382	1.01	175
Individual cylinder jet stacks	0.429	--------	182
Variable-component system including blowdown and steady-flow turbines	0.348	0.93	199

The variable-component system not only has the lowest net specific
fuel consumption but also has the greatest power output.

For direct comparison with the system described in reference 2,
which consists of an engine and a steady-flow turbine (similar to
the geared-in steady-flow turbine system used in the preceeding com-
parison), the variable-component system with blowdown and steady-flow-
turbines was analyzed for an engine speed of 2000 rpm, an intake-
manifold pressure of 40 inches of mercury absolute, and a fuel-air
ratio of 0.063; the multicylinder-engine data for this analysis were
obtained from table II of reference 2. The net brake specific fuel
consumptions for these two systems are shown in figure 7 as a func-
tion of p_b'/p_m for various altitudes. A blowdown-turbine efficiency
of 70 percent, steady-flow-turbine and supercharger efficiencies of
85 percent, and gear efficiencies of 95 percent were used in the cal-
culations. For the engine conditions shown, the fuel consumption of
the variable-component system was from 0.01 to 0.02 pound per
horsepower-hour lower than that obtained with the system described
in reference 2.

Choice of fixed nozzle areas for steady-flow turbine. - The
variation of steady-flow-turbine nozzle area with the ratio p_b'/p_m
for the chosen blowdown-turbine nozzle area (40.8 sq in.) is shown

in figure 8. Reference to figures 4 and 5 shows that the mean p_b'/p_m value for maximum power output varies from approximately 0.7 at sea level to 0.6 at an altitude of 45,000 feet. If operation at low intake-manifold pressures at sea level is excluded from consideration, it may be seen from figure 8 that with a steady-flow-turbine nozzle area approximately equal to 21 square inches, the engine will operate in the neighborhood of p_b'/p_m values for maximum power output.

Similarly from figures 4 and 5, the mean p_b'/p_m value for minimum fuel consumption varies from approximately 1.05 at sea level to 0.95 at an altitude of 45,000 feet. Again excluding operation at low intake-manifold pressures at sea level, it may be seen from figure 8 that with a steady-flow-turbine nozzle area of approximately 14 square inches, the engine will operate in that range of p_b'/p_m values for minimum specific fuel consumption.

Thus, if operation of the composite engine in the region of maximum power output is desired, a fixed steady-flow-turbine nozzle area of 21 square inches should be used. If, on the other hand, minimum specific fuel consumption is the more important consideration, a fixed steady-flow-turbine nozzle area of 14 square inches should be used.

Turbine speeds. - The variation of the ratio of pitch-line velocity of the steady-flow-turbine wheel to engine speed for maximum turbine efficiency with the ratio p_b'/p_m is also shown in figure 8. For convenience, a pair of dotted lines showing the variation of the ratio p_b'/p_m with engine operating conditions for the steady-flow-turbine nozzle areas of 21 and 14 square inches are superimposed upon the lines of steady-flow-turbine speed variation. Thus, for a steady-flow-turbine nozzle area of 21 square inches, the ratio of pitch-line velocity of the steady-flow turbine to engine speed for maximum turbine efficiency varies from $7\frac{1}{2}$ feet per engine revolution at sea level for an engine speed of 2100 rpm and an intake-manifold pressure of 35 inches of mercury absolute to $32\frac{1}{2}$ feet per engine revolution at 45,000 feet for the same engine operating conditions. Because of the wide variation of the ratio of pitch-line velocity to engine speed for maximum turbine efficiency with altitude, it is impossible to gear the steady-flow turbine to the engine with a fixed gear ratio and have the turbine operate at nearly peak efficiency at all altitudes from sea level to 45,000 feet for all of the assumed engine operating conditions.

If the steady-flow turbine is geared to the engine with a single gear ratio and required to operate at all altitudes between sea level and 45,000 feet, the magnitude of the loss in turbine efficiency that will occur can be illustrated by the following example:

Assume that it is desired to operate the composite engine, having a
steady-flow-turbine nozzle area of 21 square inches, at sea level
and at an altitude of 45,000 feet, an engine speed of 2100 rpm, and
an intake-manifold pressure of 50 inches of mercury absolute. If
the gear ratio between the turbine and the engine is so chosen that
the turbine efficiency is the same at both altitudes, the value of
this efficiency, assuming that turbine efficiency varies parabol-
ically with blade-to-jet-speed ratio, will be only 0.728 times the
peak efficiency of the turbine. Thus if the peak turbine efficiency
is 70 percent, the efficiency at sea level and 45,000 feet will be
approximately 50 percent.

The ratio of the pitch-line velocity of the blowdown-turbine
wheel to engine speed required for maximum turbine efficiency is
shown in figure 9. This ratio is a function only of p_b'/p_m, engine
speed, and altitude. A small variation of this speed ratio occurs
with altitude because of the variation with altitude of the intake-
manifold temperature. The variation of the ratio p_b'/p_m with
intake-manifold pressure at each engine speed for steady-flow-turbine
nozzle areas of 21 and 14 square inches is shown by broken lines
that correspond to those in figure 8. For either of these steady-
flow-turbine nozzle areas, the variation of the ratio of blowdown-
turbine-wheel pitch-line velocity to engine speed with engine
operating conditions is sufficiently restricted so that a fixed
value of gear ratio may be used between the blowdown turbine and the
engine. For example, if gears are so chosen that the ratio of the
pitch-line velocity of the blowdown-turbine wheel to engine speed
is 20 and 17 feet per engine revolution for steady-flow-turbine nozzle
areas of 21 and 14 square inches, respectively, it was found that the
blowdown-turbine power output was always between 92 and 100 percent
of the power output corresponding to maximum efficiency for all con-
ditions of engine operation.

Effect of blowdown turbine on stresses in steady-flow turbine. -
For an engine speed of 2730 rpm, which is the assumed emergency-
speed rating, the pitch-line velocity of the blowdown-turbine wheel
for a speed ratio of 17 feet per engine revolution is only 775 feet
per second. Because of this low pitch-line velocity, a reasonably
sized blowdown turbine may be designed that can operate at high
exhaust-gas temperatures without being overstressed.

The optimum wheel speeds of the steady-flow turbine are much
greater under some conditions than those of the blowdown turbine.
(See fig. 8.) For this reason the steady-flow turbine cannot oper-
ate at its optimum speed with high inlet exhaust-gas temperatures
without being overstressed. Removal of energy from the exhaust gas

by the blowdown turbine reduces the gas temperature an average of
about 150° F before the gas reaches the steady-flow turbine. This
reduction in temperature increases the allowable centrifugal stresses
that the turbine wheel and buckets can withstand.

Fixed-Component System

In the preceding discussion on turbine speeds, it was shown
that the steady-flow turbine with a fixed nozzle area could not be
geared to the engine with a fixed gear ratio and always operate near
peak efficiency at all altitudes between sea level and 45,000 feet.
If flight is restricted to a maximum altitude of 30,000 feet, the
steady-flow turbine of fixed nozzle area can be geared to the engine
with a single gear ratio and operate with an efficiency that is greater
than 0.8 of its peak efficiency for cruise and rated-power operation
of the engine at altitude. If the turbine efficiency is to be greater
than 0.8 of its peak efficiency for sea-level operation, intake-
manifold pressures must be greater than 50 inches of mercury absolute.
In a system having fixed-sized components and fixed gear ratios,
additional losses occur at many points of operation because, except
at a few points, a stage of supercharging must be throttled.

As an example of the performance that may be obtained by gearing
the steady-flow turbine of fixed nozzle area to the engine with a
single-gear ratio, the fixed-component system incorporating a blowdown
turbine, a steady-flow turbine, and two stages of supercharger, all
of which are geared to the engine, is discussed: The steady-flow
turbine is connected to an assumed two-speed-and-disengaged super-
charger by means of an idler shaft. The turbine power is transmitted
to the idler shaft through gears of 90-percent efficiency. The super-
charger power is taken from the idler shaft through a second set of
gears also operating at 90-percent efficiency. Excess power is
transmitted to the engine from the idler shaft through gears of
95-percent efficiency. (See fig. 10.) In order to determine the
sources of the power losses in the fixed-component system, the loss
in power caused by the decrease in turbine efficiency and the increased
loss in power occurring because the auxiliary-supercharger power
was transmitted from the steady-flow turbine through a gear train (as
contrasted to the direct transmission of this power in the variable-
component system) were separtely evaluated. The remainder of the
difference between the power of the variable-component system and
the fixed-component system was interpreted as a loss due to throttling
of the auxiliary supercharger.

Choice of gear ratios between components. - The system was
analyzed for a steady-flow-turbine nozzle area of 21 square inches,

which corresponds to operation of the composite engine in the region
near maximum power. For this nozzle area, the blowdown turbine was
assumed to be geared to the engine as shown in figure 11 so that the
ratio of pitch-line velocity of the blowdown-turbine wheel to engine
speed would be 20 feet per engine revolution. The variation of com-
posite-engine power for high powers at sea level and cruise power at
an altitude of 30,000 feet is shown in figure 12 as a function of
steady-flow-turbine speed. The best power output is obtained at
different ratios of turbine speed to engine speed at different
altitudes. A compromise gear ratio may be chosen for an actual
engine to favor the more important operating condition., For the sub-
sequent analysis of the fixed-component system, a gear ratio was
chosen that produces a ratio of the pitch-line velocity of the steady-
flow-turbine wheel to engine speed of 18 feet per engine revolution;
this gear ratio causes approximately equal losses in engine power
for an intake-manifold pressure of 65 inches of mercury absolute at
sea level and the cruise condition at an altitude of 30,000 feet.
Gear ratios between the two-speed-and-disengaged auxiliary super-
charger and the steady-flow turbine were assumed that would give
ratios of supercharger impeller tip speed to turbine-wheel pitch-
line velocity of 1.6 and 1.0. The speed ratio of 1.6 was chosen to
allow nearly full-throttle operation of the auxiliary supercharger
at cruise and rated power operation of the composite engine at an
altitude of 30,000 feet. The speed ratio of 1.0 was chosen to allow
nearly full-throttle operation for rated power climb at an altitude
of 15,000 feet.

Performance of fixed-component system. - The computed values of
brake specific fuel consumption, brake mean effective pressure, and
the individual losses in composite engine power caused by the use of
fixed gearing between the turbines and the engine and between the
auxiliary supercharger and the steady-flow turbine are shown in
table I for various conditions of engine operation. These losses
are: (a) loss due to decreased turbine efficiency, (b) increase in
gear loss due to the introduction of the gear system having an idler
shaft between the steady-flow turbine and the auxiliary supercharger,
and (c) loss caused by throttling the auxiliary supercharger, which
includes both the increase in supercharger work and the loss in
engine power due to higher intake-manifold temperatures. These
losses, in units of brake mean effective pressure, have been rounded
off to the nearest integer or to zero. The difference in power
between the variable-component system and the fixed-component system
is the sum of the three losses. The ratio of auxiliary-supercharger
impeller tip speed to steady-flow-turbine-wheel pitch-line velocity
u_t/u_s used to compute the performance at each point of engine oper-
ation is also shown in table I.

At the design operating conditions at 30,000 feet altitude; cruise power (an engine speed of 2100 rpm at an intake-manifold pressure of 35 in. Hg absolute), and at rated power (an engine speed of 2415 rpm at an intake-manifold pressure of 50 in. Hg absolute), the power output was decreased a maximum of 4 percent as compared with the power output of the variable-component system. Larger power losses were incurred at an engine speed of 2730 rpm for the take-off and for high-power operation at altitude because at this engine speed it was always necessary to throttle the auxiliary-stage supercharger. Different choices of speed ratio than those discussed, or a different choice of operating altitudes, could be made in order to favor other desired engine operating conditions.

Auxiliary-Propeller System

At the suggestion of Mr. John G. Lee of United Aircraft Corporation, calculations have been made of the performance obtainable when a variable-pitch auxiliary propeller is used to absorb the excess power of the steady-flow turbine. The propeller, which is geared to the turbine and the auxiliary supercharger, controls the engine intake-manifold pressure by controlling the supercharger speed. This type of system is schematically shown in figure 13.

Choice of components. - A propeller diameter of $7\frac{1}{2}$ feet was assumed for the computation of propeller performance and the propeller efficiencies. The calculations were based on current test data of a two-blade propeller at high forward speeds over a range of free-stream Mach numbers. In the calculation of propeller performance, it was assumed that the airplane velocity was 350 miles per hour at an altitude of 30,000 feet for a brake power output from the variable-component system of 2800 horsepower per engine. Values of airplane velocities at other altitudes and powers were obtained assuming that the velocity varied as the cube root of the quotient of the total power output of the variable-component system to the altitude density ratio.

The efficiencies of both the steady-flow turbine and the blow-down turbine were assumed to vary parabolically with blade-to-jet-speed ratio and had their maximum efficiency of 0.7 at a blade-to-jet-speed ratio of 0.4.

The computations were made for a fixed nozzle area for the steady-flow turbine of 14 square inches, which was previously chosen for engine operation in the region of minimum specific fuel consumption. A pitch-line diameter for the steady-flow turbine of 13.25 inches

was chosen by scaling up the dimensions of an existing exhaust-gas turbine to provide the required nozzle area. A gear ratio of 10.92:1 between the steady-flow turbine and the auxiliary propeller was chosen from considerations of maximum allowable turbine velocity and propeller speeds for good efficiency. The blowdown turbine was so geared to the engine that the ratio of blowdown-turbine pitch-line velocity to engine speed was 17 feet per engine revolution.

A steady-flow turbine of the dimensions given probably will have a stress-limited pitch-line velocity of approximately 1200 feet per second. At this speed, maximum turbine efficiency occurs at a theoretical jet velocity across the turbine buckets of 3000 feet per second. For some conditions, the maximum combined power of the turbine and the jet-propulsion nozzle ideally occurs at turbine-jet velocities and wheel speeds higher than 3000 and 1200 feet per second, respectively. For these cases, the turbine-wheel speed was arbitrarily limited to 1200 feet per second; the resulting small decrease in turbine efficiency was neglected in the computation of the jet velocity across the turbine buckets.

The speed ratios of the assumed two-speed-and-disengaged auxiliary supercharger were chosen in the following manner: A high supercharger-to-turbine speed ratio of 1.2 was chosen to correspond to the greatest demand speed of the supercharger when the turbine was operating at maximum allowable speed. (This speed occurs at an altitude of 45,000 ft, an engine speed of 2100 rpm, and an engine intake-manifold pressure of 50 in. Hg absolute.) A low supercharger-to-turbine speed ratio of 0.7 was chosen as a satisfactory compromise for that range of conditions where small-to-medium boost is required. A 15-inch-diameter impeller was selected in order to obtain desirable supercharger performance characteristics with the required air flow at high powers and high altitudes.

Power of auxiliary-propeller system. - It is assumed that the blowdown turbine and the engine-stage supercharger could be geared to the engine in the manner shown in figure 11 and that the power of the steady-flow turbine could be distributed to the auxiliary supercharger and propeller by means of the system of gears shown in figure 10. The total brake power would then be given by

$$\text{Brake power} = (P_i - P_f) + (P_b - P_{es}) \, \eta_g + \left(P_t \, \eta_{g,1} - \frac{P_{as}}{\eta_{g,1}}\right)\left(\frac{\eta_{ap}}{\eta_p}\right)\eta_{g,2} + P_j$$

$$(3)$$

where

P_{as} power required for auxiliary-stage supercharger, (ft-lb/sec)

P_b shaft power of blowdown turbine, (ft-lb/sec)

P_{es} power required for engine-stage supercharger, (ft-lb/sec)

P_f loss in engine power due to friction, (ft-lb/sec)

P_i indicated engine power, (ft-lb/sec)

P_t shaft power of steady-flow turbine, (ft-lb/sec)

P_j net brake power credited to engine from jet propulsion,
               (ft-lb/sec)

η_{ap} auxiliary-propeller efficiency

η_g gear efficiency, 0.85

$\eta_{g,1}$ gear efficiency in power transmission between turbine or
               supercharger shaft and idler shaft, 0.90

$\eta_{g,2}$ gear efficiency in power transmission between idler shaft
               and auxiliary-propeller shaft, 0.95

η_p main propeller efficiency, 0.85

Performance of auxiliary-propeller system. - The computed brake
specific fuel consumptions and brake mean effective pressures for
the auxiliary-propeller system are listed in table II together with
the brake specific fuel consumptions for the variable-component sys-
tem and the difference in brake mean effective pressure between the
variable-component system and the auxiliary-propeller system. The
fixed ratio of auxiliary-supercharger impeller tip speed to steady-
flow-turbine-wheel pitch-line velocity u_s/u_t, which was governed
in part by turbine-speed limits, is also shown.

With the exception of one condition of engine operation, the
specific fuel consumptions obtained with the auxiliary-propeller
system were never more than 5 percent greater than those obtained
with the variable-component system. In some cases, the computed
brake specific fuel consumption for the auxiliary-propeller system
was lower than that obtained with the variable-component system.
Where this condition occurs, the efficiency of the auxiliary propeller

computed from the test data and the calculated airspeed was greater than the average value of 0.85 assumed for the main propeller. For a few of the engine operating conditions shown in table II, the brake specific fuel consumption for the auxiliary-propeller system was not computed because the operating conditions for the auxiliary propeller are outside the range of the test data previously mentioned. (For the particular propeller diameter and ratio of steady-flow-turbine speed to propeller speed chosen, the power coefficients of the propeller are too high.) In practice, however, operation at these exceptional adverse conditions may be avoided by adjusting the engine operating conditions so as to raise the steady-flow-turbine-wheel speed. One such adjustment would be to raise the intake-manifold pressure and to lower the engine speed. For the engine conditions analyzed, the poor fuel economies occurred at low turbine-blade-to-jet-speed ratios. If the turbine speed is raised, the blade-to-jet-speed ratio will be increased to a value more nearly corresponding to maximum turbine efficiency and the auxiliary-propeller power coefficient will be lowered into the range of normal operation of the propeller.

The auxiliary-propeller system, as compared with the fixed-component system, has a wider range of altitudes for which the high powers and the low specific fuel consumptions characteristic of the variable-component system are approached. The use of the auxiliary propeller as a variable-speed device eliminates throttling of the supercharger and results in a small increase in steady-flow-turbine efficiency. From considerations of over-all operating economy, the increased weight of an auxiliary propeller may, however, offset this advantage.

SUMMARY OF RESULTS

The following results were obtained from the analysis of the performance of several composite engines, each consisting of an internal-combustion engine, a blowdown turbine, and a steady-flow turbine; all excess power from the turbines above that required to drive a stage of supercharging was utilized in various ways for propulsion of the airplane:

1. A brake specific fuel consumption of 0.336 pound per horsepower-hour for the variable-component system using turbine and supercharger efficiencies of 70 percent and a gear efficiency of 85 percent was computed for an altitude of 30,000 feet, an intake-manifold pressure of 50 inches of mercury absolute, and an engine speed of 2100 rpm. When for the same case the efficiencies of the steady-flow turbine and superchargers were increased to 85 percent

(the efficiency of the blowdown turbine remaining 70 percent), the brake specific fuel consumption was reduced to 0.303 pound per horsepower-hour.

2. With a blowdown turbine in series with a steady-flow turbine, a fixed blowdown-turbine-nozzle area could be so chosen that at any given engine speed nearly maximum power could be obtained from the combination of a blowdown turbine and an engine at any speed from 2100 rpm to 2730 rpm.

3. Two steady-flow-turbine nozzle areas could be so chosen that one would cause the ratio of engine exhaust pressure to intake-manifold pressure to fall in the range of maximum power output and the other in the range for minimum brake specific fuel consumption at all engine speeds and powers at altitudes from sea level to 45,000 feet.

4. When used in series with a steady-flow turbine, the blowdown turbine could be geared to the engine with a single gear ratio and operate between 92 and 100 percent of peak efficiency for all conditions analyzed.

5. A fixed-component system intended to operate in the restricted altitude range from sea level to 30,000 feet was so designed that the performance at cruise and rated power was within 4 percent of that of the variable-component system. Substantial power losses due to supercharger throttling were incurred at high engine speed at emergency power rating.

6. An auxiliary-propeller system was so designed that the performance for all powers and engine speeds analyzed was within 5 percent of that of the variable-component system for altitudes from sea

level to 45,000 feet. The variable-speed feature of the auxiliary
propeller permits elimination of throttling losses.

Flight Propulsion Research Laboratory,
     National Advisory Committee for Aeronautics,
          Cleveland, Ohio, July 21, 1947.

APPENDIX A

GENERAL CALCULATIONS

The reciprocating-engine data are represented by the dimensionless ratio ϕ of the indicated mean effective pressure of the engine to the intake-manifold pressure. The value of ϕ for the engine with stub exhaust stacks having no restriction is ϕ_0. The ratio ϕ_0 is shown in reference 4 to be a function of the ratio of engine exhaust pressure to intake-manifold pressure.

For a given ratio of engine exhaust pressure to intake-manifold pressure, ϕ_0 is essentially independent of intake-manifold pressure and varies slightly with engine speed. The variation of ϕ_0 with engine speed is, however, different for different engines. The values of ϕ_0 for the single-cylinder engine when operating at a constant intake-manifold temperature decrease with increasing engine speeds above approximately 2000 rpm. On the other hand, most multicylinder data corrected to a constant intake-manifold temperature show that ϕ_0 increases with increasing engine speed up to 2200 rpm and is substantially constant for engine speeds between 2200 and 2600 rpm. The volumetric efficiency $\eta_{v,o}$ for both engines varied with engine speed in a manner similar to the variation of ϕ. Because ϕ_0 and $\eta_{v,o}$ vary with engine speed in different directions for different engines, an average condition was approximated by the use of a single faired set of values of ϕ_0 and $\eta_{v,o}$ regardless of the engine speed or the intake-manifold pressure. The faired values of ϕ_0 and $\eta_{v,o}$ obtained from the single-cylinder tests at an engine speed of 1700 rpm, a fuel-air ratio of 0.10, and an intake-manifold temperature of 540° R are shown in the following table:

	Ratio of engine exhaust pressure to engine intake-manifold pressure							
	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6
ϕ_0	13.25	13.03	12.71	12.12	11.02	9.96	9.05	8.28
$\eta_{v,o}$	1.040	1.034	1.017	0.976	0.894	0.828	0.778	0.737

The loss in ϕ imposed on the reciprocating engine by the area restriction in the nozzles of the blowdown turbine $\Delta\phi$ was determined from figure 10 of reference 4, which shows the decrease in ϕ due to nozzle restriction in jet stacks having S-shape bends.

The power and the air flow of the engine were assumed to vary inversely as the square root of the absolute dry intake-manifold temperature (computed neglecting fuel vaporization). The values for ϕ_o and $\eta_{v,o}$ used in the analysis were based on a standard total intake-manifold temperature T'_s of 540° R.

The indicated power of the engine P_i is then given by

$$P_i = (\phi_o + \Delta\phi) \frac{P_m \, v_d \, N}{120} \sqrt{\frac{T'_s}{T'_m}} \qquad (4)$$

and the mass flow of charge air M_a by

$$M_a = (\eta_{v,o} + \Delta\eta_v) \frac{P_m \, v_d \, N}{120 \, g \, R \, T'_s} \sqrt{\frac{T'_s}{T'_m}} \qquad (5)$$

where

ϕ ratio of indicated mean effective pressure of engine to intake-manifold pressure

ϕ_o ratio of indicated mean effective pressure of engine with stub stacks having no restriction to intake-manifold pressure

$\Delta\phi$ change in ϕ due to stack restriction

η_v volumetric efficiency of engine

$\eta_{v,o}$ volumetric efficiency of engine with stub stacks having no restriction

$\Delta\eta_v$ change in η_v due to stack restriction (assumed zero)

P_m intake-manifold absolute static pressure, lb/sq ft

v_d displacement volume of engine, cu ft

N engine speed, rpm

T'_m intake-manifold total temperature, $^\circ$R

g acceleration of gravity, 32.2 ft/sec^2

R gas constant for air, 53.35 ft-lb/(lb)($^\circ$F)

The loss in engine power due to friction P_f was computed by the following equation:

$$P_f = K(N)^2 \qquad (6)$$

where

K constant, 1.768×10^{-2} (ft-lb)/(sec)(min^2)

The value of K corresponding to the bore, stroke, and number of cylinders of the engine was determined from an emperical equation based on a large amount of test data obtained on various types of reciprocating engine. This engine friction power is the sum of the powers due to rubbing friction and the valve and gear losses and does not include pumping power.

Blowdown-turbine calculations. - The data used to calculate the mean exhaust-gas jet velocity $\overline{V}_e$ developed at the nozzle of the blowdown turbine were taken from figure 10 of reference 5.

The shaft power of the blowdown turbine P_b is given by the equation

$$P_b = \frac{1}{2} M_a (1 + f) \overline{V}_e^2 \overline{\eta}_b \qquad (7)$$

where $\overline{\eta}_b$ is the mean blowdown-turbine efficiency, which was assumed to have a maximum value of 0.7 at a blade-to-jet-speed ratio of 0.4. This mean blowdown-turbine efficiency is described in reference 3.

Exhaust-gas temperatures. - The power per pound of charge air that is available in the exhaust gases of an internal-combustion engine is proportional to the quantity $(1 + f) R_e T_e'$ where R_e is the gas constant for the exhaust gas and T_e' is the total exhaust-gas temperature measured with no work abstraction from the exhaust gas. The variation of the quantity $(1 + f) R_e T_e'$ with the ratio of engine-exhaust static pressure to intake-manifold pressure p_e/p_m is shown in figure 14. These data, from unpublished multicylinder tests, are for an engine speed of 2000 rpm and an intake-manifold pressure of 40 inches of mercury absolute. At higher or lower engine power levels, the magnitude of $(1 + f) R_e T_e'$ will be slightly greater or slightly smaller, respectively, than that shown in figure 14.

In the region of principal interest (p_e/p_m = 0.6 to 1.2), the value of $(1 + f) R_e T'_e$ varies less than 2 percent from the value 12.11×10^4 foot-pounds per pound, which was assumed in the analysis. The temperature of the exhaust gas as it entered the steady-flow turbine was calculated by subtracting the temperature drop corresponding to the work abstraction in the blowdown turbine from T'_e.

Steady-flow turbine and jet-propulsion power. - The total power available to drive the steady-flow turbine and for jet propulsion depends upon the absolute static pressure and the total temperature at the exit of the blowdown turbine and the absolute ambient-air pressure p_0. In the analysis, this static pressure and the total temperature were assumed equal to the total pressure p'_b and total temperature T'_b existing in the nozzle box of the steady-flow turbine.

Within the accuracy of the data, it is sufficient to assume that the variation of specific heat of the exhaust gas with temperature and pressure during the expansion through the steady-flow turbine is negligible. The specific heat was evaluated at the temperature T'_b.

The ideal jet velocity V that would be obtained from a complete expansion through the pressure ratio p'_b/p_0 is given by the

$$V^2 = 2 \frac{\gamma_b}{\gamma_b - 1} g R_e T'_b \left[1 - \left(\frac{p_0}{p'_b}\right)^{\frac{\gamma_b - 1}{\gamma_b}} \right] \qquad (8)$$

where γ_b is the ratio of specific heats for exhaust gas evaluated at the themperature T'_b.

The ideal jet velocity of the gas at the nozzles of the steady-flow turbine V_t obtained by expanding to the steady-flow-turbine-discharge static pressure p_t is given by the equation

$$V_t^2 = 2 \frac{\gamma_b}{\gamma_b - 1} g R_e T'_b \left[1 - \left(\frac{p_t}{p'_b}\right)^{\frac{\gamma_b - 1}{\gamma_b}} \right] \qquad (9)$$

The shaft power of the steady-flow turbine P_t is given by the relation

$$P_t = \frac{1}{2} M_a (1 + f) V_t^2 \eta_t \qquad (10)$$

where η_t is the steady-flow-turbine efficiency based on the inlet total and discharge static pressures of the turbine. Two values of η_t, 0.7 and 0.85, were assigned as maximum turbine efficiencies occurring at a blade-to-jet-speed ratio of 0.4.

The total temperature at the exit of the steady-flow turbine T_t' was calculated from the equation

$$\frac{T_t'}{T_b'} = 1 - \frac{V_t^2 \, \eta_t}{2 \, \dfrac{\gamma_b}{\gamma_b - 1} \, g \, R_e \, T_b'} \tag{11}$$

A computation showed that the average discharge losses from a steady-flow turbine amounted to 7 percent of the energy available to the turbine. It was assumed that these discharge losses could be utilized for jet propulsion with an efficiency of 70 percent. The velocity of the exhaust-gas discharged from the jet-propulsion nozzle V_4, taking into account the temperature drop of the gas in passing through the steady-flow turbine, is given by the equation

$$V_j^2 = 0.049 \, V_t^2 + \frac{V^2 - V_t^2}{\eta_{n,d}} \left(\frac{T_t}{T_b'} \right) \tag{12}$$

where $\eta_{n,d}$ is a nozzle efficiency equal to unity when $(V^2 - V_t^2)$ is greater than zero or a diffuser efficiency equal to 0.8 when $(V^2 - V_t^2)$ is less than zero. The calculations were simplified by assuming that the temperature ratio T_t/T_b' in equation (12) could be replaced by T_t'/T_b'. A sample calculation for a few representative cases showed that the error introduced by this approximation had negligible effect on the total power of the composite engine.

The net brake power that can be credited to the engine from jet propulsion P_j after subtracting the drag of receiving the inlet charge air to the engine is given by the equation

$$P_j = M_a \, (1 + f) \left(\frac{V_0}{\eta_p} \right) \left(V_j - \frac{V_0}{1 + f} \right) \tag{13}$$

where η_p is the main-propeller efficiency and V_0 is the airplane velocity in feet per second.

For each set of engine conditions, a value of p_t in equation (9) was so chosen that the combined steady-flow turbine power and jet power was a maximum.

Supercharger calculations. - The power required for supercharging was calculated on the basis of the following assumptions:

1. NACA standard air temperature and air pressure were used throughout the analysis except at sea level where an ambient-air temperature of 540° R is assumed.

2. The supercharging of the engine-intake charge air to the desired intake-manifold pressure is accomplished with two compressors driven by two turbines.

3. The air scoop to the auxiliary supercharger operates at full-ram temperature and pressure.

4. An intercooler with an effectiveness of 50 percent is used between stages to decrease the temperature of the charge air entering the intake manifold.

5. In order to compensate for intercooler and duct losses, a pressure drop of 2 inches of mercury between stages is assumed.

6. Fuel is injected after the engine charge air has been completely supercharged.

The pressure-rise and temperature-rise ratios due to ram are given by

$$\frac{T'_{as}}{T_0} = \left(\frac{p'_{as}}{p_0}\right)^{\frac{\gamma-1}{\gamma}} = 1 + \frac{V_0^2}{2\frac{\gamma}{\gamma-1}g R T_0} \tag{14}$$

where

T'_{as}, p'_{as} total temperature and absolute total pressure at entrance to auxiliary supercharger, $^{\circ}$R and lb/sq ft

T_0 ambient-air temperature, $^{\circ}$R

γ ratio of specific heats for air, 1.4

The pressure and temperature rise across the auxiliary-stage supercharger are related by the equation

$$\frac{T'_{ic} - T'_{as}}{T'_{as}} = \frac{1}{\eta}\left[\left(\frac{p'_{ic}}{p'_{as}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{15}$$

where T'_{ic} and p'_{ic} are the total temperature and pressure at the inlet to the intercooler and η is the supercharger temperature-rise efficiency.

The assumed intercooler between stages causes a temperature drop in the charge air leaving the auxiliary-stage supercharger

$$T'_{ic} - T'_{es} = \eta_{ic}\left(T'_{ic} - T'_{as}\right) \tag{16}$$

where T'_{es} is the total temperature at the inlet to the engine-stage supercharger and η_{ic} is the intercooler efficiency.

The pressure entering the engine-stage supercharger will be the pressure leaving the auxiliary-stage supercharger minus a pressure drop of 2 inches of mercury. The intake-manifold pressure may be obtained from

$$\left(\frac{p_m}{p'_{es}}\right)^{\frac{\gamma-1}{\gamma}} = 1 + q\left[\frac{\left(\frac{\pi\ D\ N\ r}{60}\right)^2}{\frac{\gamma}{\gamma-1}\ g\ R\ T'_{es}}\right] \tag{17}$$

where

p'_{es} absolute total pressure at inlet to engine-stage supercharger, lb/sq ft

q supercharger pressure-rise coefficient based on inlet total pressure and outlet static pressure

D engine-stage supercharger-impeller diameter, 0.917, ft

r gear ratio of engine-stage supercharger, 7.6

The total dry intake-manifold temperature is given by

$$T'_m - T'_{es} = \left[\frac{\left(\dfrac{\pi\, D\, N\, r}{60}\right)^2}{\dfrac{\gamma}{\gamma - 1}\, g\, R}\right]\frac{q}{\eta} \qquad (18)$$

The powers necessary to drive the auxiliary-stage and the engine-stage superchargers are given, respectively, by

$$P_{as} = \frac{\gamma}{\gamma - 1}\, g\, R\, M_a\, (T'_{ic} - T'_{as}) \qquad (19)$$

$$P_{es} = \left(\frac{\pi\, D\, N\, r}{60}\right)^2 \left(\frac{q}{\eta}\right) M_a \qquad (20)$$

APPENDIX B

SYMBOLS

All symbols used in the text and appendix A are defined here in alphabetical order for convenience of reference.

A exhaust-stack-nozzle area, sq ft

A_b blowdown-turbine-nozzle area, sq ft

D engine-stage supercharger-impeller diameter, 0.917 ft

f fuel-air ratio

g acceleration of gravity, 32.2 ft/sec^2

M_a mass flow of charge air to engine, slugs/sec

N engine speed, rpm

n engine speed, rps

P_{as} power required for auxiliary-stage supercharger, ft-lb/sec

P_b shaft power of blowdown turbine, ft-lb/sec

P_{es} power required for engine-stage supercharger, ft-lb/sec

P_f loss in engine power due to friction, ft-lb/sec

P_i indicated engine power, ft-lb/sec

P_j net brake power credited to engine from jet propulsion, ft-lb/sec

P_t shaft power of steady-flow turbine, ft-lb/sec

p'_{as} absolute total pressure at entrance to auxiliary super-charger, lb/sq ft

p'_b absolute total pressure at entrance of steady-flow turbine (assumed equal to static pressure at exit of blowdown turbine), lb/sq ft

p_e absolute static pressure of exhaust gas leaving engine, lb/sq ft

p'_{es} absolute total pressure at inlet to engine-stage supercharger, lb/sq ft

p'_{ic} absolute total pressure at inlet to intercooler, lb/sq ft

p_m intake-manifold absolute static pressure, lb/sq ft

p_0 absolute ambient-air pressure, lb/sq ft

p_t absolute static pressure at exit of steady-flow turbine, lb/sq ft

q   supercharger pressure-rise coefficient based on inlet total pressure and outlet static pressure

R   gas constant for air, 53.35 ft-lb/(lb)($^\circ$F)

R_e gas constant for exhaust gas, ft-lb/(lb)($^\circ$F)

r   gear ratio of engine-stage supercharger, 7.6

T'_{as} total temperature at entrance to auxiliary supercharger, $^\circ$R

T'_b total temperature at entrance of steady-flow turbine (assumed equal to total temperature at exit of blowdown turbine), $^\circ$R

T'_e total temperature of exhaust gas leaving engine, $^\circ$R

T'_{es} total temperature at inlet to engine-stage supercharger, $^\circ$R

T'_{ic} total temperature at inlet to intercooler, $^\circ$R

T'_m total temperature in intake manifold, $^\circ$R

T_0 ambient-air temperature, $^\circ$R

T'_s standard total temperature (for these computations taken as 540° R in intake manifold), $^\circ$R

T_t static temperature at exit of steady-flow turbine, $^\circ$R

T'_t total temperature at exit of steady-flow turbine, $^\circ$R

u_s auxiliary-supercharger impeller tip speed, ft/sec

u_t pitch-line velocity of steady-flow-turbine wheel, ft/sec

V ideal jet velocity corresponding to total power available to drive steady-flow turbine and for jet propulsion, ft/sec

$\bar{V}_e$ mean exhaust-gas jet-velocity developed at nozzles of blow-down turbine, ft/sec

V_0 airplane velocity, ft/sec

V_t ideal jet velocity of gas at nozzles of steady-flow turbine, ft/sec

v_d displacement volume of engine, cu ft

γ ratio of specific heats for air, 1.4

γ_b ratio of specific heats for exhaust gas at exit of blowdown turbine

η supercharger temperature-rise efficiency

η_{ap} auxiliary-propeller efficiency

$\bar{\eta}_b$ mean blowdown-turbine efficiency

η_g gear efficiency, 0.85

$\eta_{g,1}$ gear efficiency in power transmission between turbine or supercharger shaft and idler shaft, 0.90

$\eta_{g,2}$ gear efficiency in power transmission between idler shaft and auxiliary-propeller shaft, 0.95

η_{ic} intercooler efficiency, 0.50

$\eta_{n,d}$ nozzle and diffuser efficiency

η_p main propeller efficiency, 0.85

η_t steady-flow-turbine efficiency

η_v volumetric efficiency of engine

$\eta_{v,o}$ volumetric efficiency of engine with stub stacks having no restriction

ϕ ratio of indicated mean effective pressure of engine to intake-manifold pressure

ϕ_0 ratio of indicated mean effective pressure of engine with
        stub exhaust stacks having no restriction to intake-manifold
        pressure

ΔP change in net power of engine and blowdown turbine, ft-lb/sec

$\Delta \eta_v$ change in η_v due to stack restriction (assumed zero in this
        analysis)

$\Delta \phi$ change in ϕ due to stack restriction

$\Delta \Phi$ $\dfrac{\Delta P}{\dfrac{p_m \, v_d \, n}{2}}$

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TABLE I - PERFORMANCE OF FIXED-COMPONENT SYSTEM AND

INDIVIDUAL POWER LOSSES THAT MAKE UP DIFFERENCE IN

POWER BETWEEN VARIABLE-COMPONENT AND

FIXED-COMPONENT SYSTEMS

[Computations made for steady-flow-turbine nozzle
area equal to 21 square inches (nozzle
area for maximum power).]

Altitude (ft)	Engine speed (rpm)	Intake-manifold pressure p_m (in. Hg abs.)	Performance		Power losses bmep, (lb/sq in.)			u_t/u_s
			bsfc (lb/hp-hr)	bmep (lb/sq in.)	(a)	(b)	(c)	
Sea level	2100	50	0.370	274	2	0	0	0
		65	.364	362	0	3	2	1.0
	2415	50	0.381	257	4	0	0	0
		65	.375	337	0	3	18	1.0
	2730	50	0.398	238	6	0	0	0
		65	.393	309	0	4	33	1.0
15,000	2100	35	0.396	197	1	1	7	1.0
		50	.369	283	1	5	9	1.6
	2415	35	0.396	181	1	2	15	1.0
		50	.362	287	0	3	0	1.0
	2730	35	0.391	183	2	0	0	0
		50	.379	261	0	3	14	1.0
30,000	2100	35	0.365	209	3	3	0	1.6
		50	----------	----------	----	----	------	-----
	2415	35	0.379	190	2	4	11	1.6
		50	.361	286	6	6	0	1.6
	2730	35	0.375	192	1	2	3	1.0
		50	.389	250	5	8	24	1.6

[a]Loss due to decreased turbine efficiency.
[b]Increase in gear loss due to use of gear system with idler shaft.
[c]Loss caused by throttling auxiliary supercharger.

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TABLE II – COMPARISON OF NET BRAKE SPECIFIC FUEL CONSUMPTION AND POWER OF AUXILIARY-PROPELLER SYSTEM WITH THAT OBTAINED BY VARIABLE-COMPONENT SYSTEM

[Computations made for a nozzle area of steady-flow turbine equal to 14 square inches (nozzle area for minimum fuel consumption).]

Altitude (ft)	Engine speed (rpm)	Intake-manifold pressure (in. Hg abs.)	bsfc of auxiliary-propeller system (lb/hp-hr)	bmep of auxiliary-propeller system (lb/sq in.)	bsfc of variable-component system (lb/hp-hr)	bmep of variable-component system minus bmep of auxiliary-propeller system (lb/sq in.)	u_s/u_t
Sea level	2100	35	0.398	161	0.399	1	0
		50	--------	--------	.363	--------	.7
	2415	35	0.413	151	0.413	0	0
		50	.368	253	.371	-1	0
	2730	35	0.437	138	0.435	11	0
		50	.383	235	.385	-1	0
15,000	2100	35	0.362	198	0.364	0	0.7
		50	.351	287	.348	3	.7
	2415	35	--------	--------	0.370	--------	0.7
		50	0.349	274	.351	-1	.7
	2730	35	0.383	171	0.384	-1	0
		50	.365	251	.358	5	.7
30,000	2100	35	0.357	200	0.349	6	1.2
		50	.347	289	.337	9	1.2
	2415	35	0.355	193	0.354	0	0.7
		50	.351	271	.340	12	1.2
	2730	35	0.370	177	0.363	2	1.2
		50	--------	--------	.346	--------	1.2
45,000	2100	35	0.363	190	0.345	11	1.2
		50	.352	272	.338	11	1.2
	2415	35	0.364	181	0.350	7	1.2
		50	.354	259	.340	11	1.2
	2730	35	--------	--------	0.360	--------	1.2
		50	0.364	241	.347	12	1.2

——— — ——— Exhaust-gas flow

——— — — — — — Intake charge-air flow

Engine-stage supercharger

T_e'

T_m' p_m

T_e'

Blowdown turbine

T_{ms}' p_{es}'

Engine

Intercooler

p_b T_b'

T_{ic}' p_{ic}'

T_{as}'

T_t'

Jet propulsion

p_t

p_{as}'

T_o

p_o

Steady-flow turbine

Auxiliary-stage supercharger

NACA
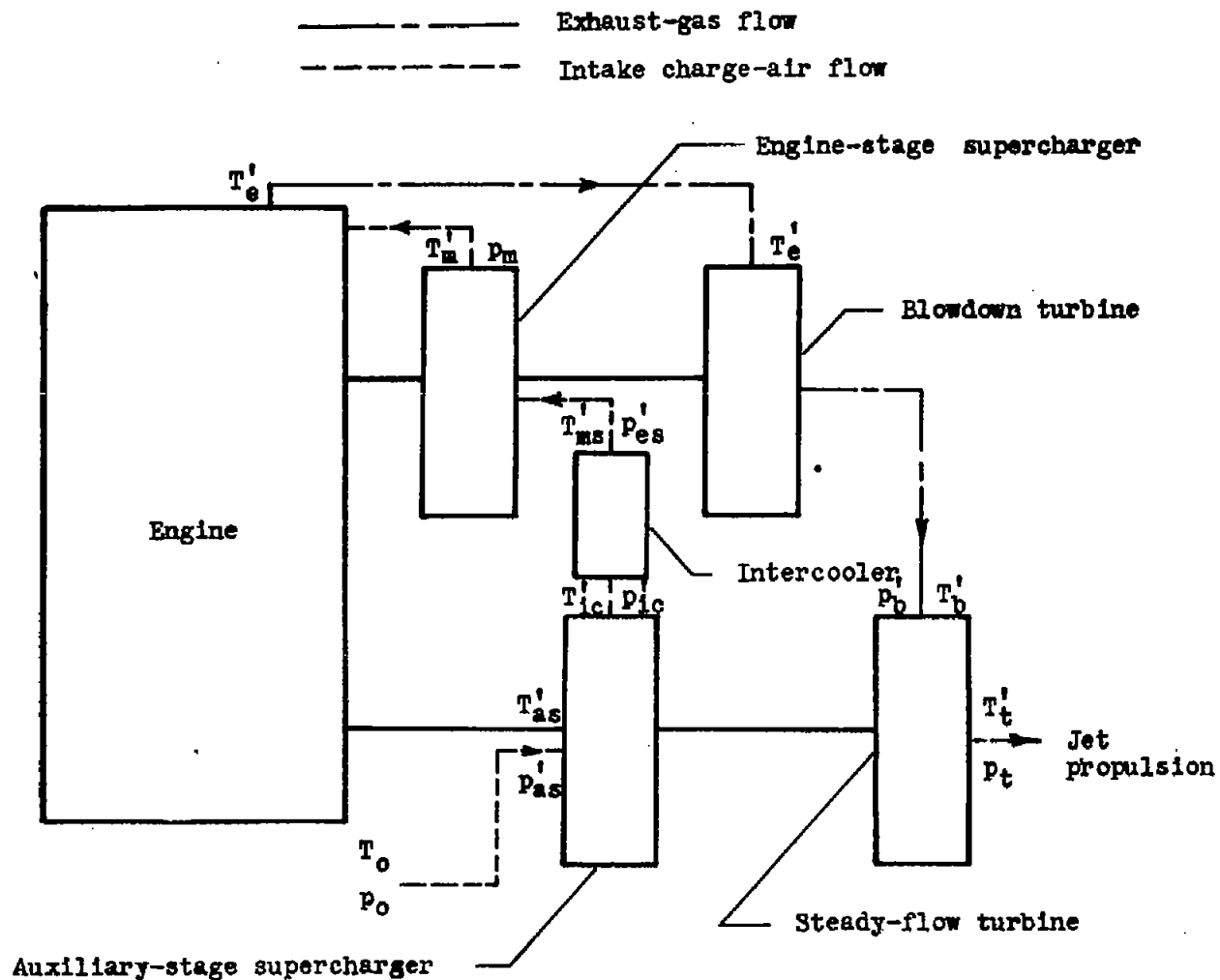
Figure 1. – Schematic diagram of variable-component system composed of blowdown and steady-flow turbines connected to engine through gear trains.
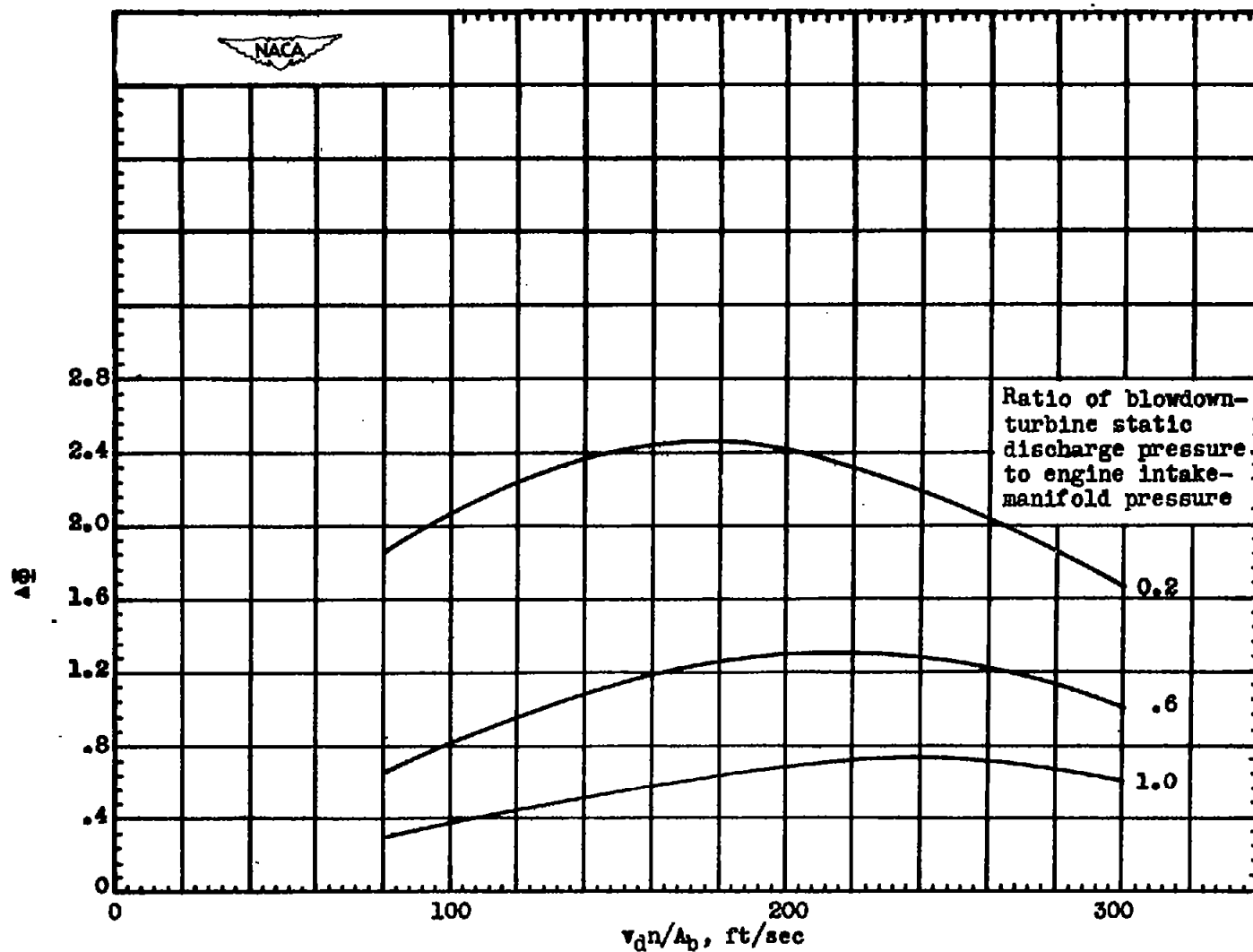
Figure 2. - Variation of net change in engine and blowdown-turbine power with ratio $v_d n/A_b$. Single-cylinder-engine data.
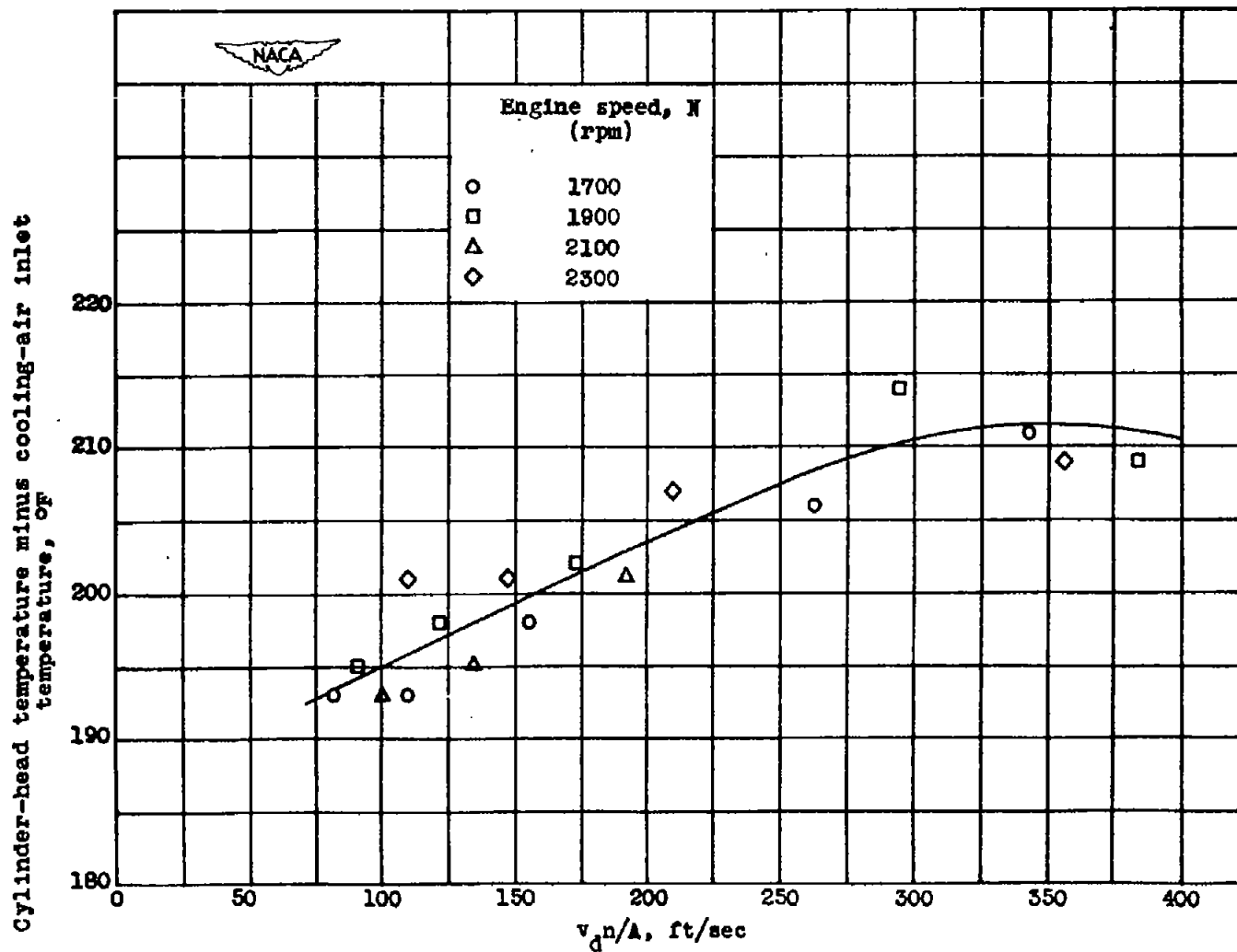
Figure 3. - Variation of cylinder-head temperature with exhaust-stack nozzle area for constant cooling conditions. Single-cylinder-engine data; intake-manifold pressure, 30 inches mercury absolute; exhaust pressure, 24 inches mercury absolute; fuel-air ratio, 0.08.
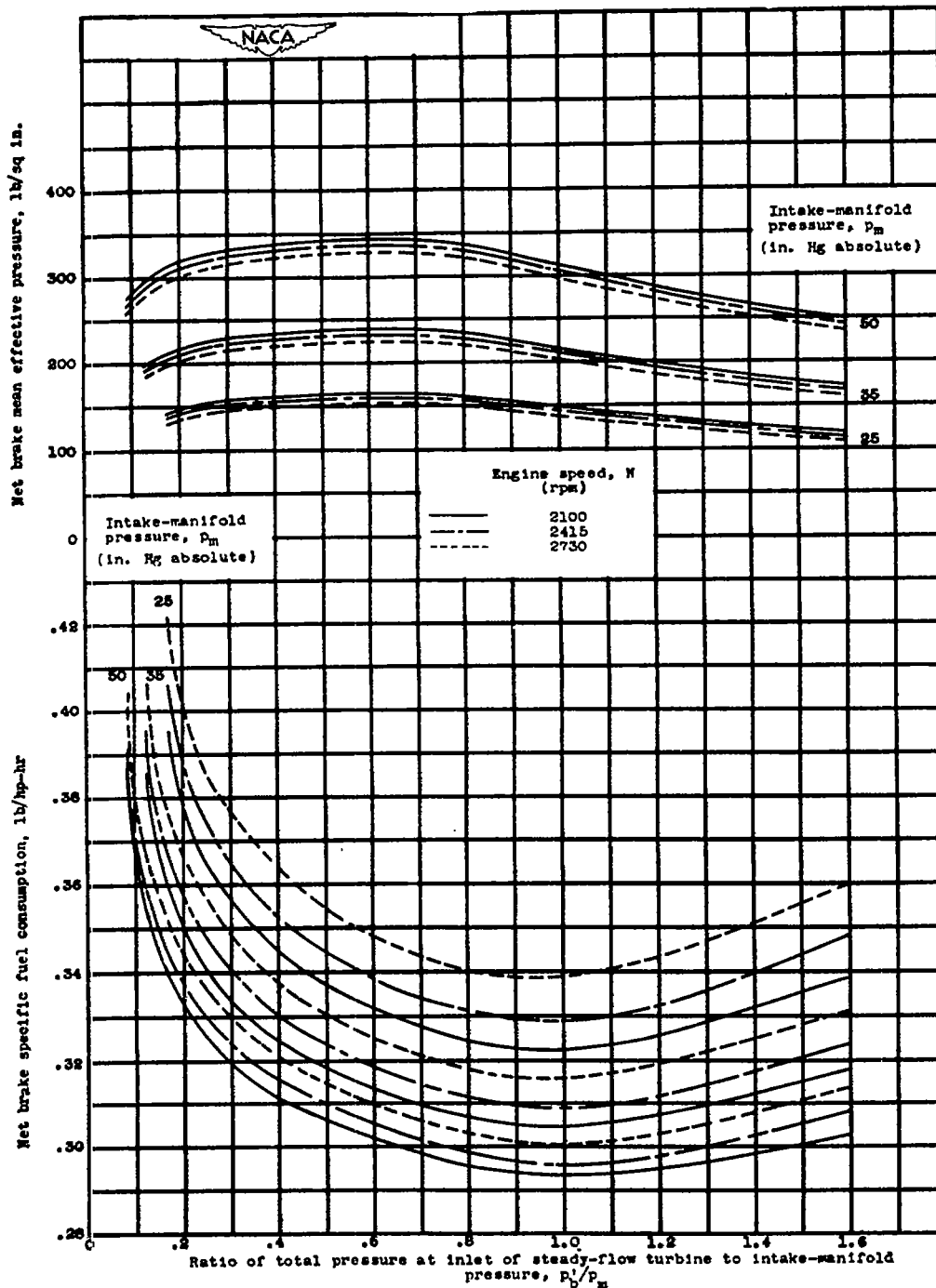
807
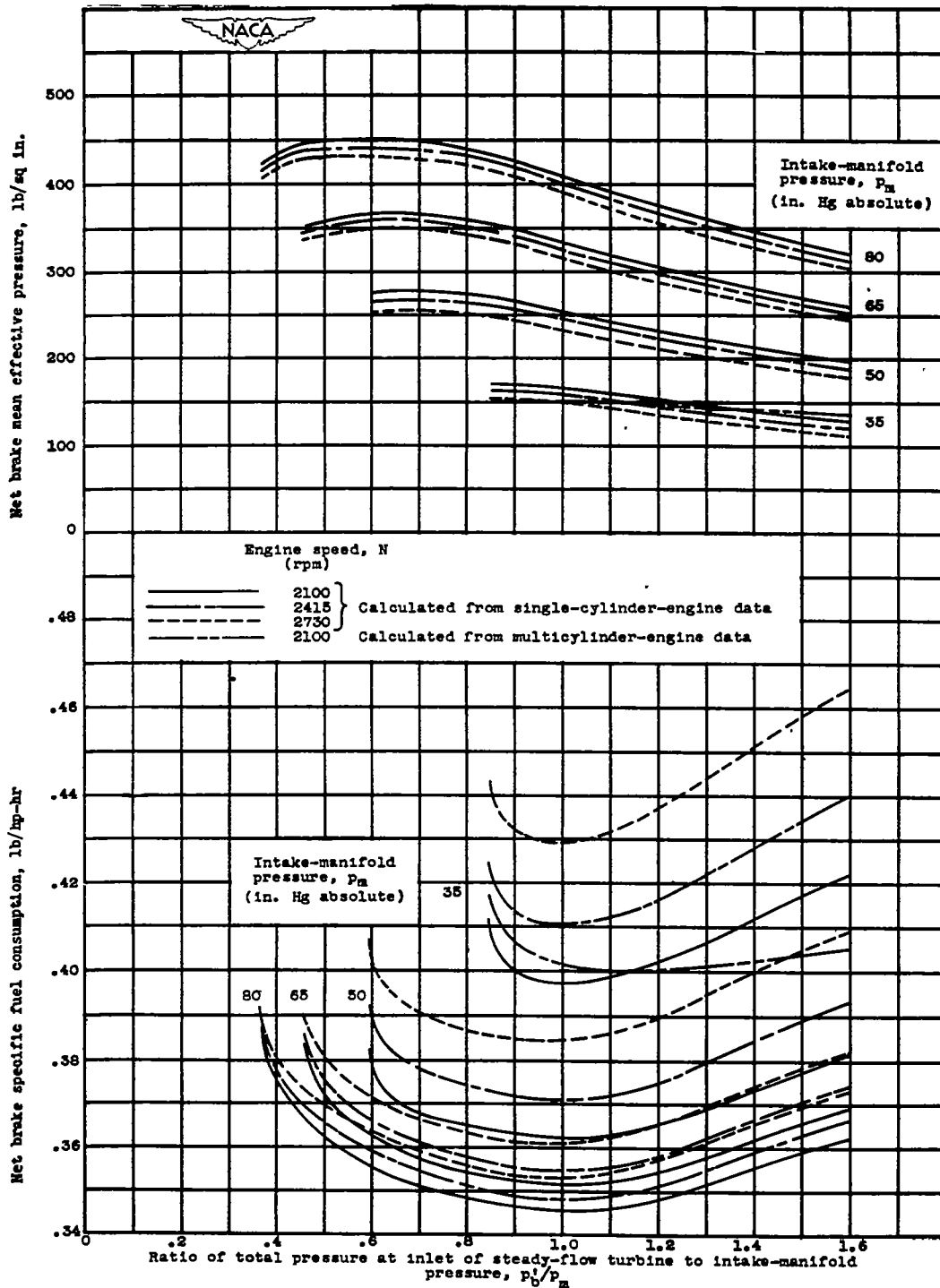
(a) Altitude, sea level.

Figure 4. - Net brake mean effective pressure and brake specific fuel consumption of variable-component system for various intake-manifold pressures and engine speeds. Fuel-air ratio, 0.067; turbine and supercharger efficiencies, 70 percent; gear efficiencies, 85 percent.
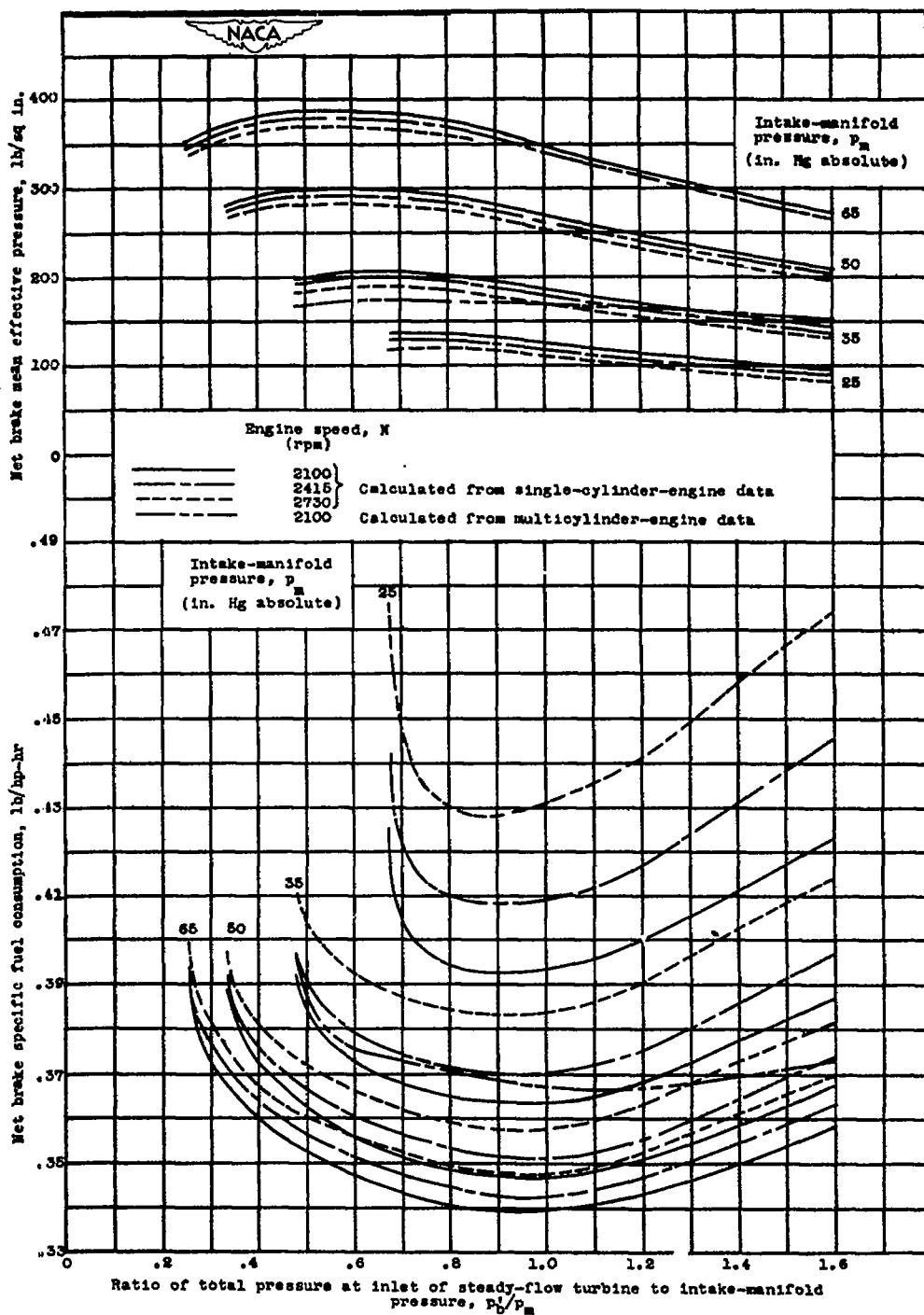
(b) Altitude, 15,000 feet.

Figure 4. - Continued.   Net brake mean effective pressure and brake
specific fuel consumption of variable-component system for various in-
take-manifold pressures and engine speeds.   Fuel-air ratio, 0.067;
turbine and supercharger efficiencies, 70 percent; gear efficiencies,
85 percent.
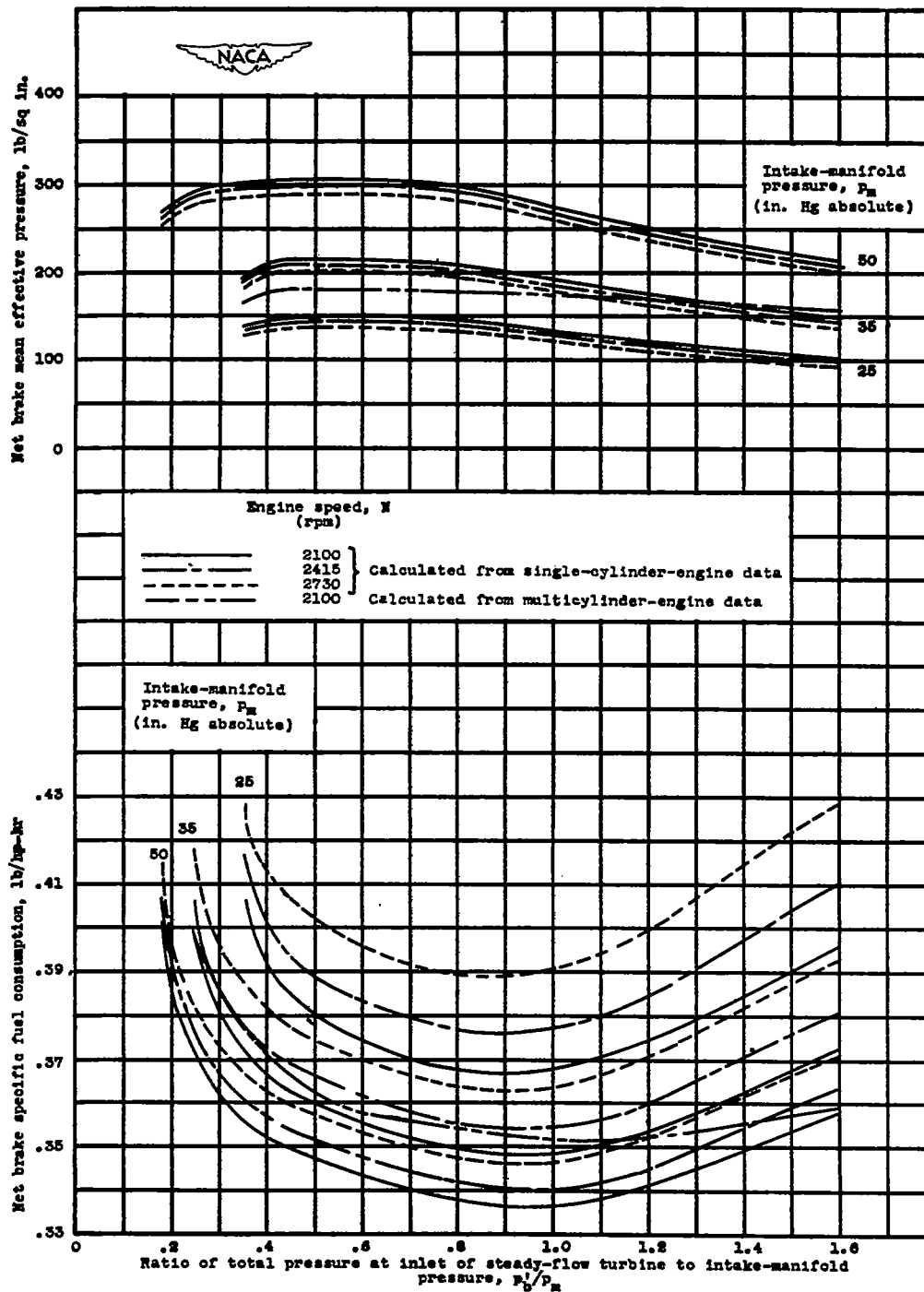
(c) Altitude, 30,000 feet.

Figure 4. - Continued. Net brake mean effective pressure and brake
specific fuel consumption of variable-component system for various in-
take-manifold pressures and engine speeds. Fuel-air ratio, 0.067;
turbine and supercharger efficiencies, 70 percent; gear efficiencies,
85 percent.

(d) Altitude, 45,000 feet.
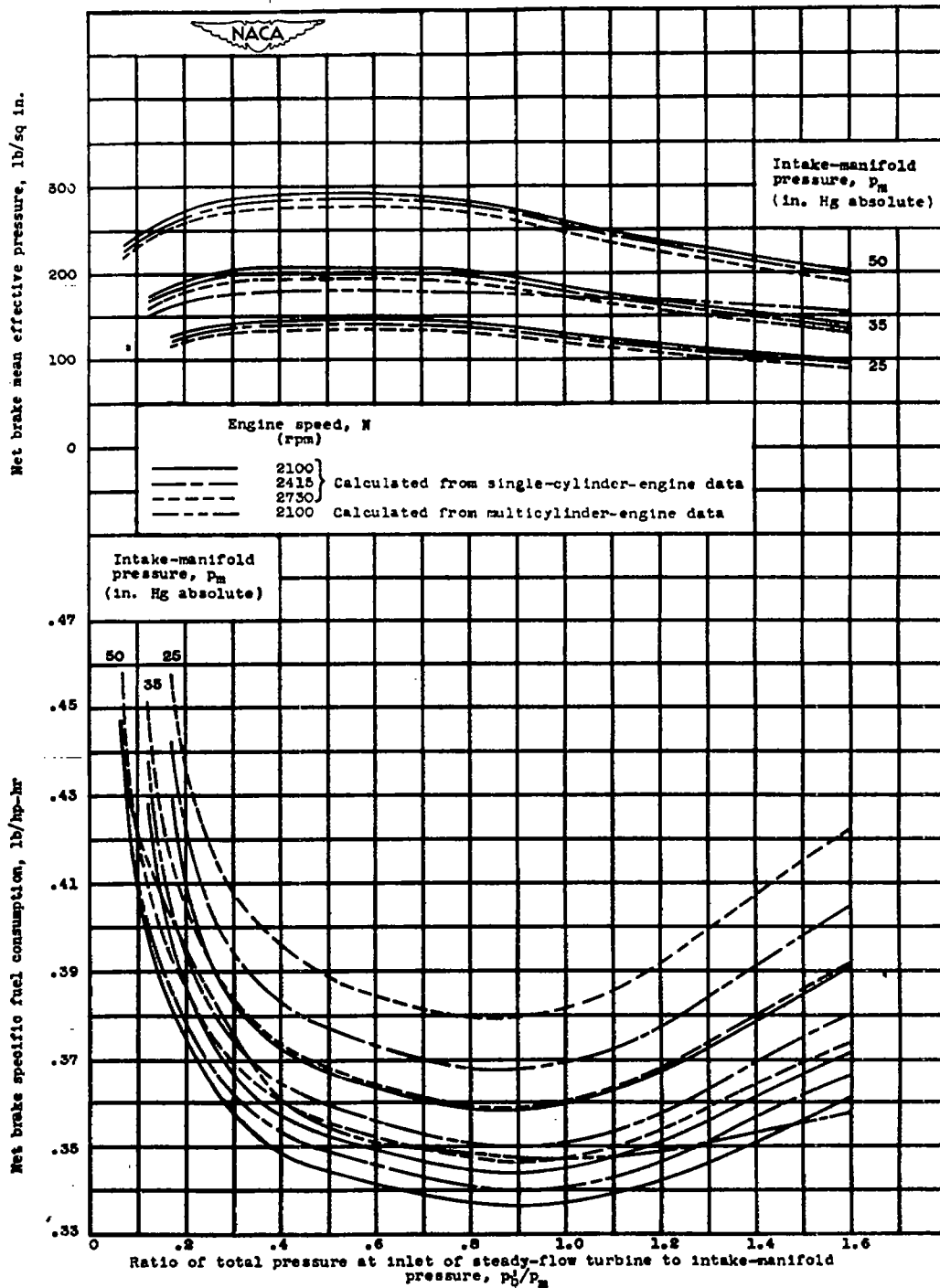
Figure 4. - Concluded.   Net brake mean effective pressure and brake specific fuel consumption of variable-component system for various intake-manifold pressures and engine speeds.   Fuel-air ratio, 0.067; turbine and supercharger efficiencies, 70 percent; gear efficiencies, 85 percent.
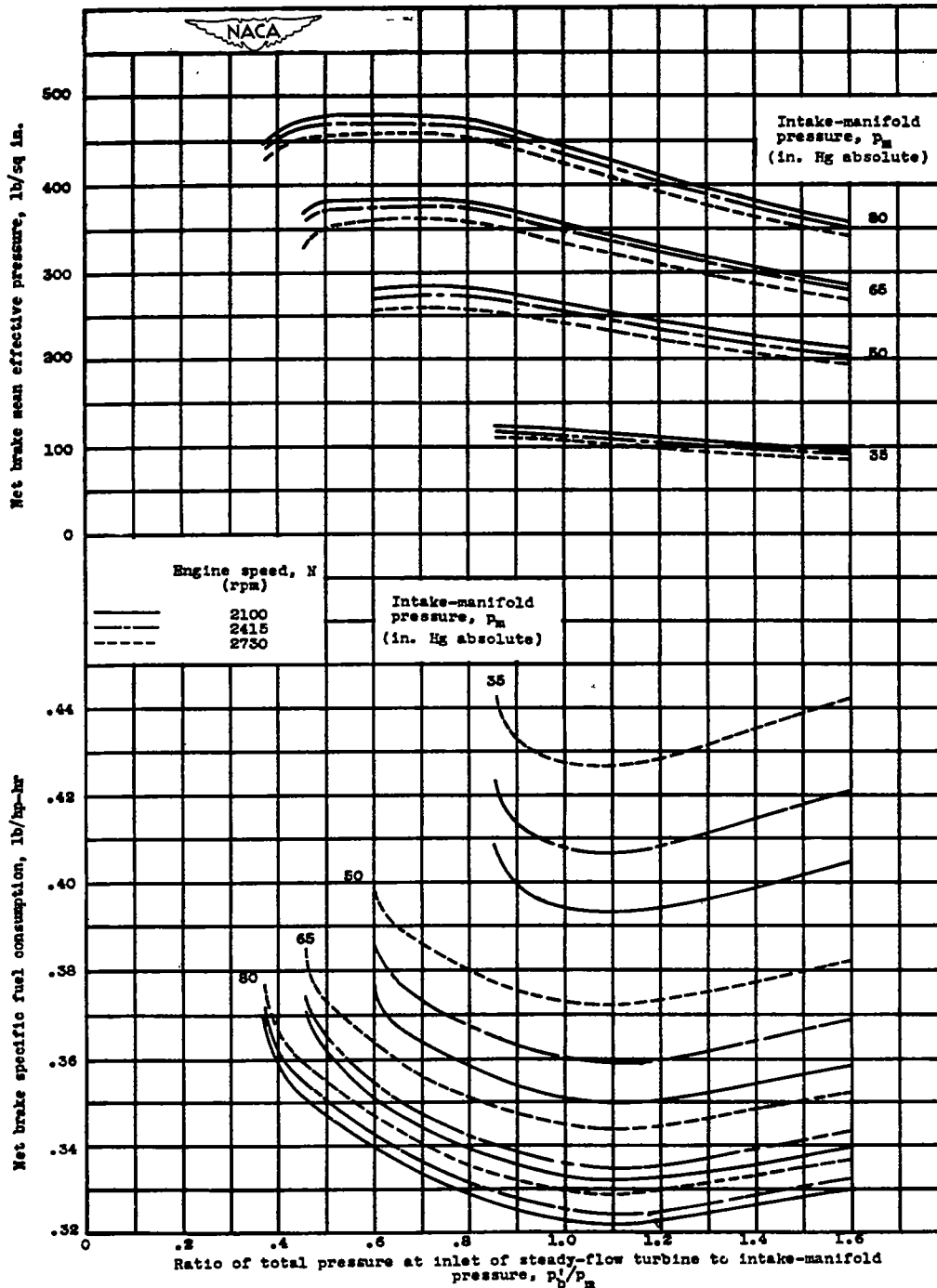
Figure 5. – Net brake mean effective pressure and brake specific fuel
consumption of variable-component system for various intake-manifold
pressures and engine speeds. Single-cylinder-engine data; fuel-air
ratio, 0.067; blowdown-turbine efficiency, 70 percent; steady-flow
turbine and supercharger efficiencies, 85 percent; gear efficiencies,
95 percent.
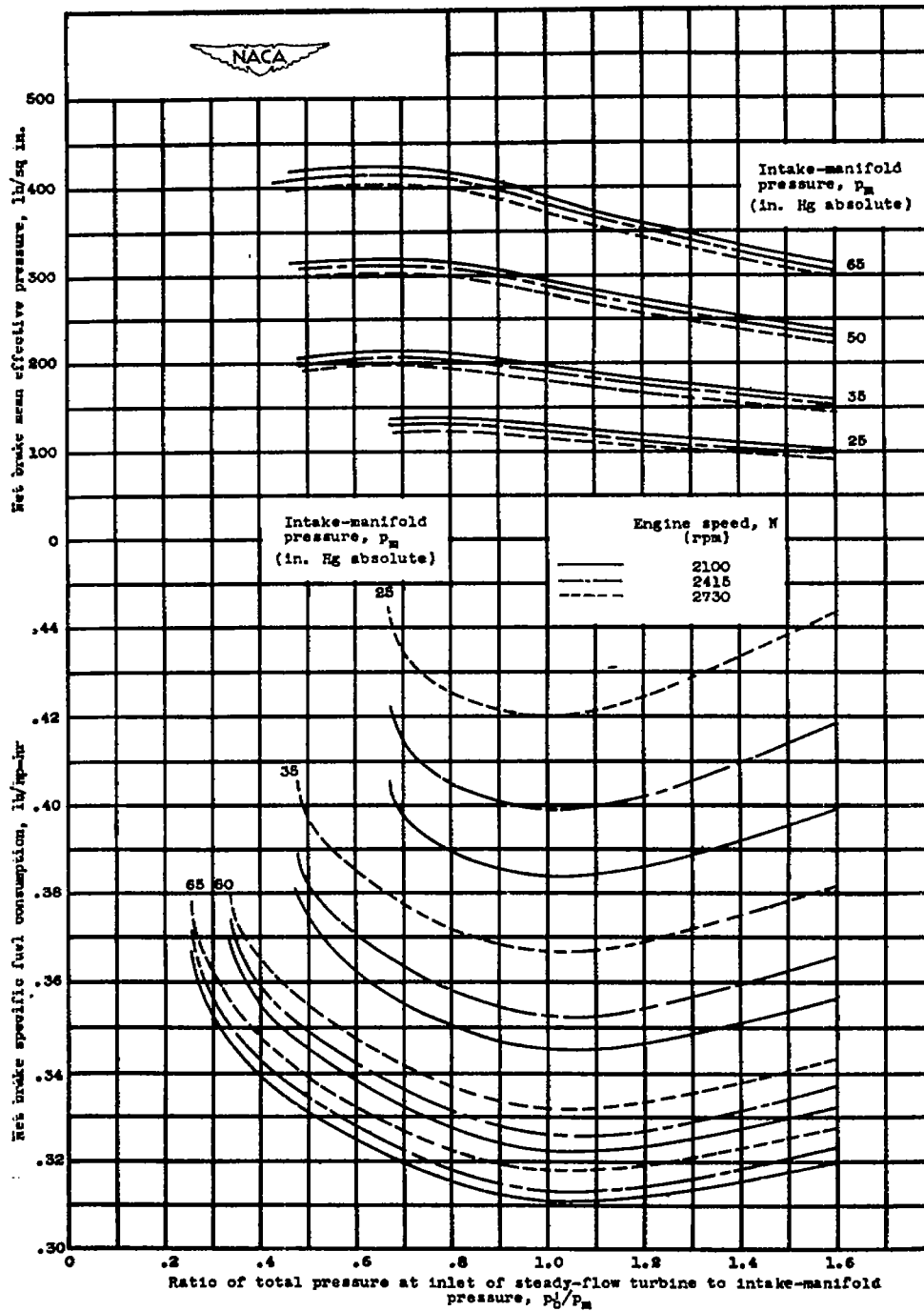
(b) Altitude, 15,000 feet.

Figure 5. - Continued. Net brake mean effective pressure and brake
  specific fuel consumption of variable-component system for various in-
  take-manifold pressures and engine speeds. Single-cylinder-engine
  data; fuel-air ratio, 0.067; blowdown-turbine efficiency, 70 percent;
  steady-flow turbine and supercharger efficiencies, 85 percent; gear
  efficiencies, 95 percent.
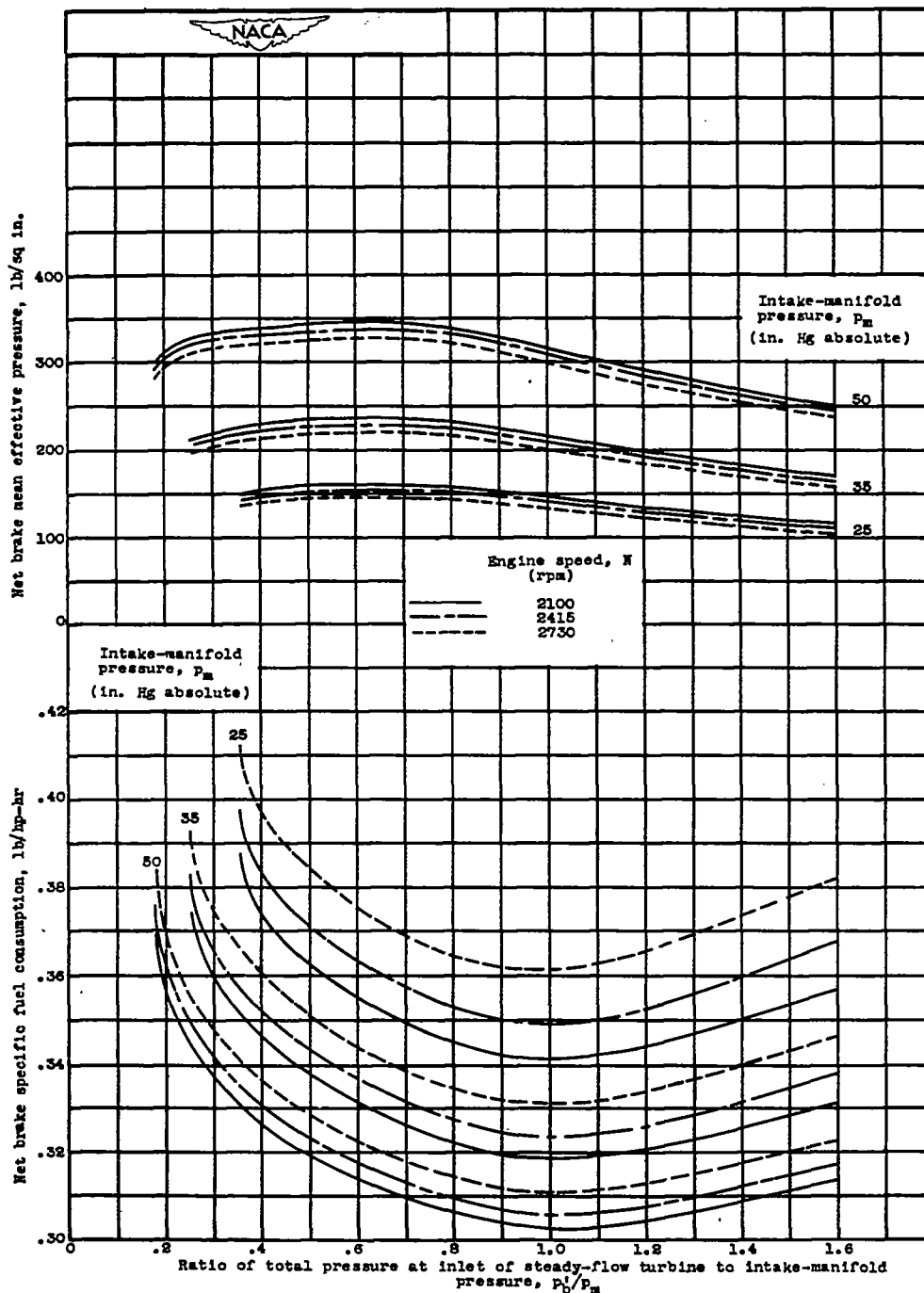
(c) Altitude, 30,000 feet.

Figure 5. - Continued. Net brake mean effective pressure and brake
specific fuel consumption of variable-component system for various in-
take-manifold pressures and engine speeds. Single-cylinder-engine
data; fuel-air ratio, 0.067; blowdown-turbine efficiency, 70 percent;
steady-flow turbine and supercharger efficiencies, 85 percent; gear
efficiencies, 95 percent.

(d) Altitude, 45,000 feet.

Figure 5. - Concluded. Net brake mean effective pressure and brake
specific fuel consumption of variable-component system for various in-
take-manifold pressures and engine speeds. Single-cylinder-engine
data; fuel-air ratio, 0.067; blowdown-turbine efficiency, 70 percent;
steady-flow turbine and supercharger efficiencies, 85 percent; gear
efficiencies, 95 percent.
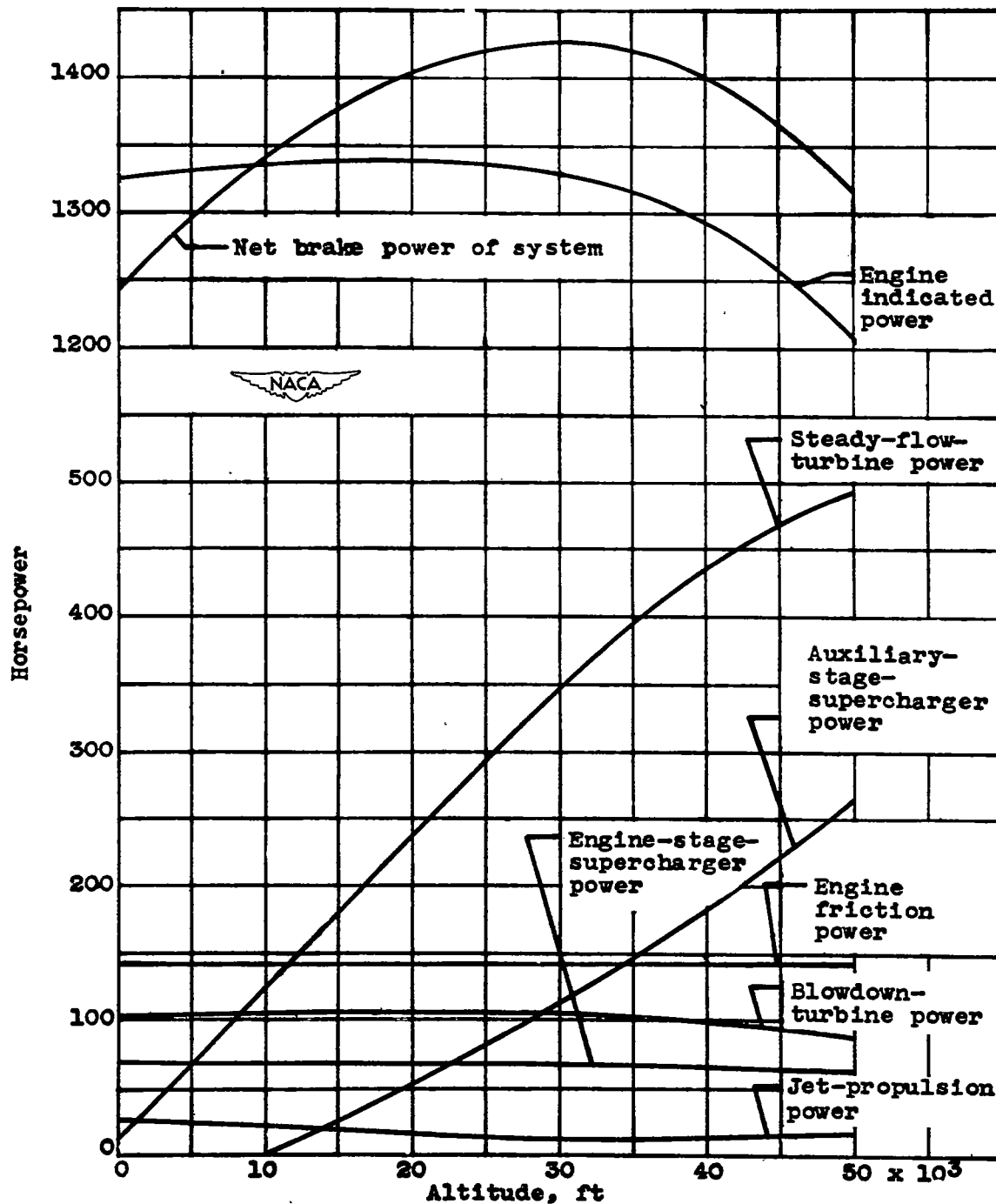
Figure 6. – Variation of power of components of variable-component system with altitude. Single-cylinder-engine data; intake-manifold pressure, 35 inches mercury absolute; blowdown-turbine discharge pressure, 35 inches mercury absolute; engine speed, 2100 rpm; turbine and supercharger efficiencies, 70 percent.
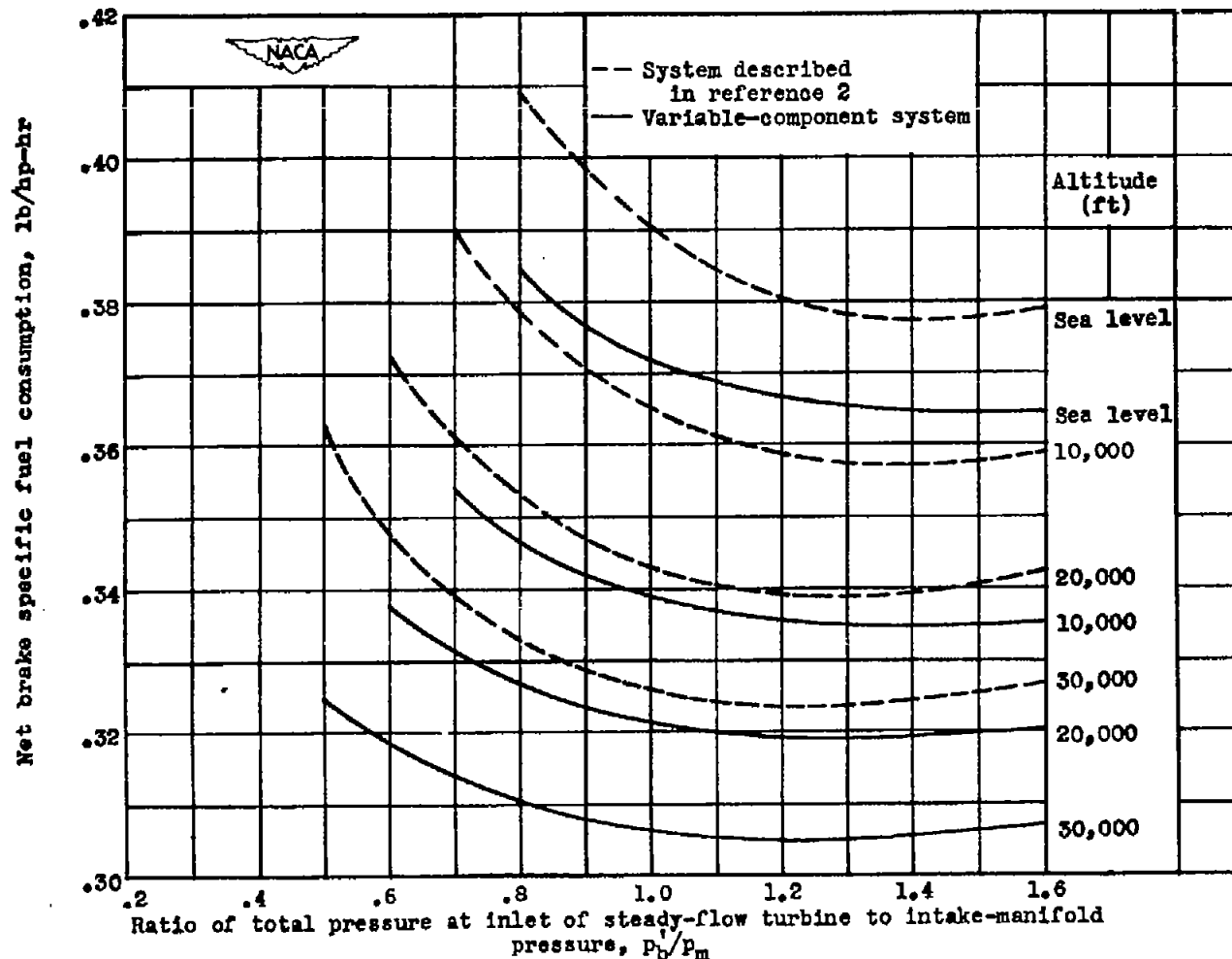
Figure 7. – Comparison of net brake specific fuel consumption obtained with variable-component system to that obtained with system composed of steady-flow turbine as described in reference 2. Intake-manifold pressure, 40 inches mercury absolute; engine speed, 2000 rpm; fuel-air ratio, 0.063; blow-down-turbine efficiency, 70 percent; steady-flow turbine and supercharger efficiencies, 85 percent; gear efficiencies, 95 percent.
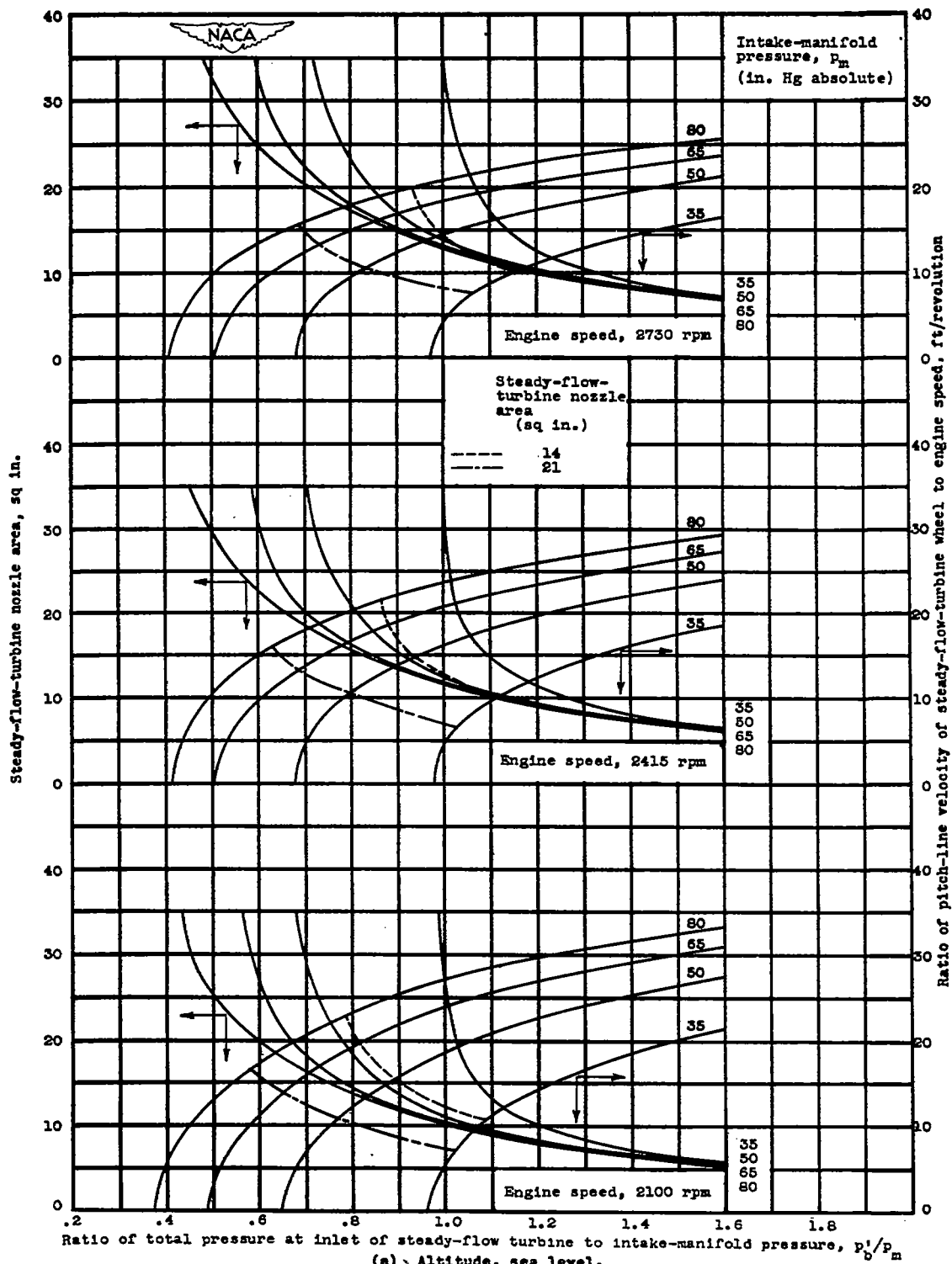
Figure 8. - Optimum speed and required nozzle area of steady-flow tur-
bine for various intake-manifold pressures and engine speeds. Single-
cylinder-engine data.

(b) Altitude, 15,000 feet.
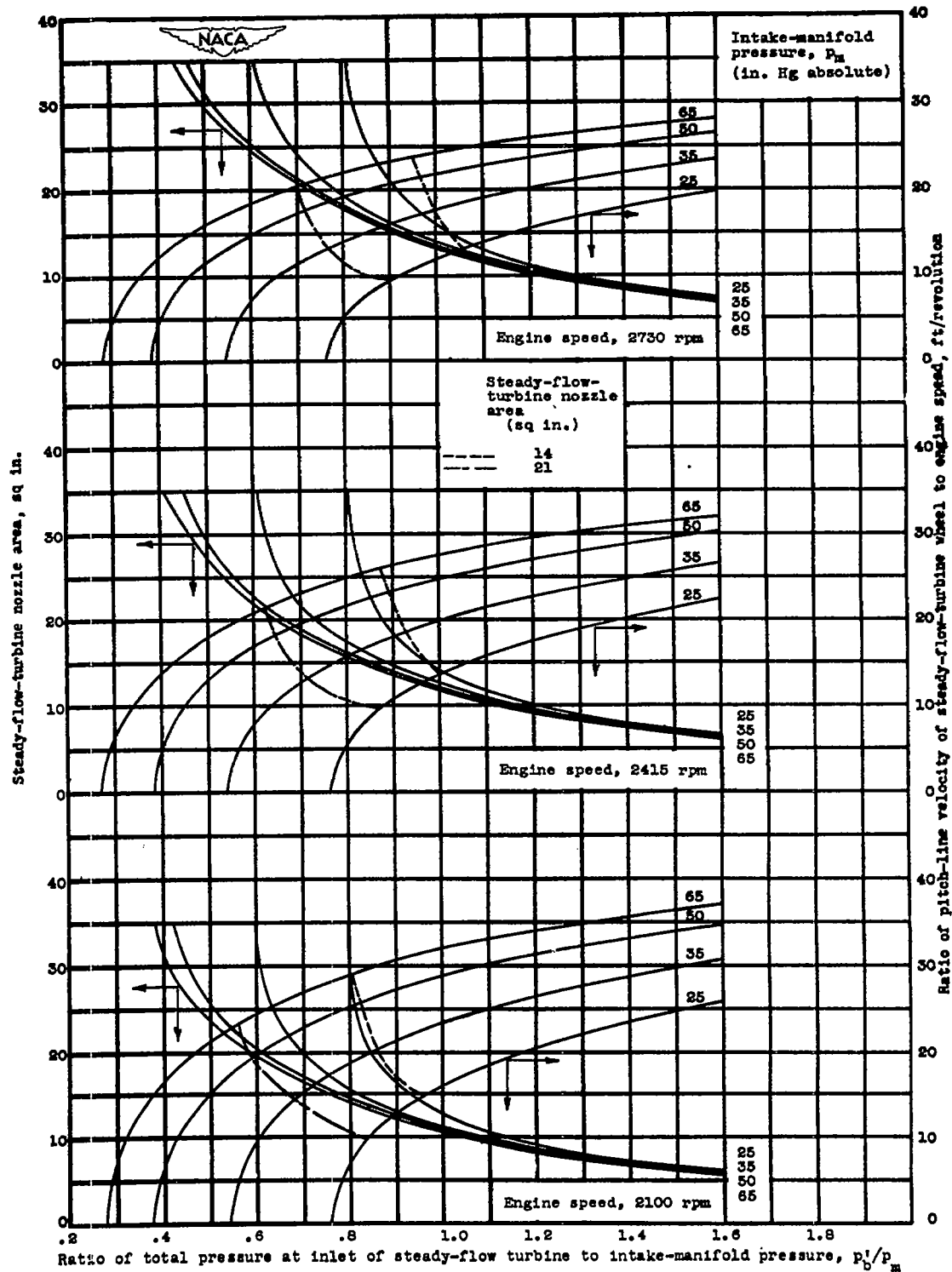
Figure 8. - Continued.   Optimum speed and required nozzle area of steady-flow turbine for various intake-manifold pressures and engine speeds.   Single-cylinder-engine data.
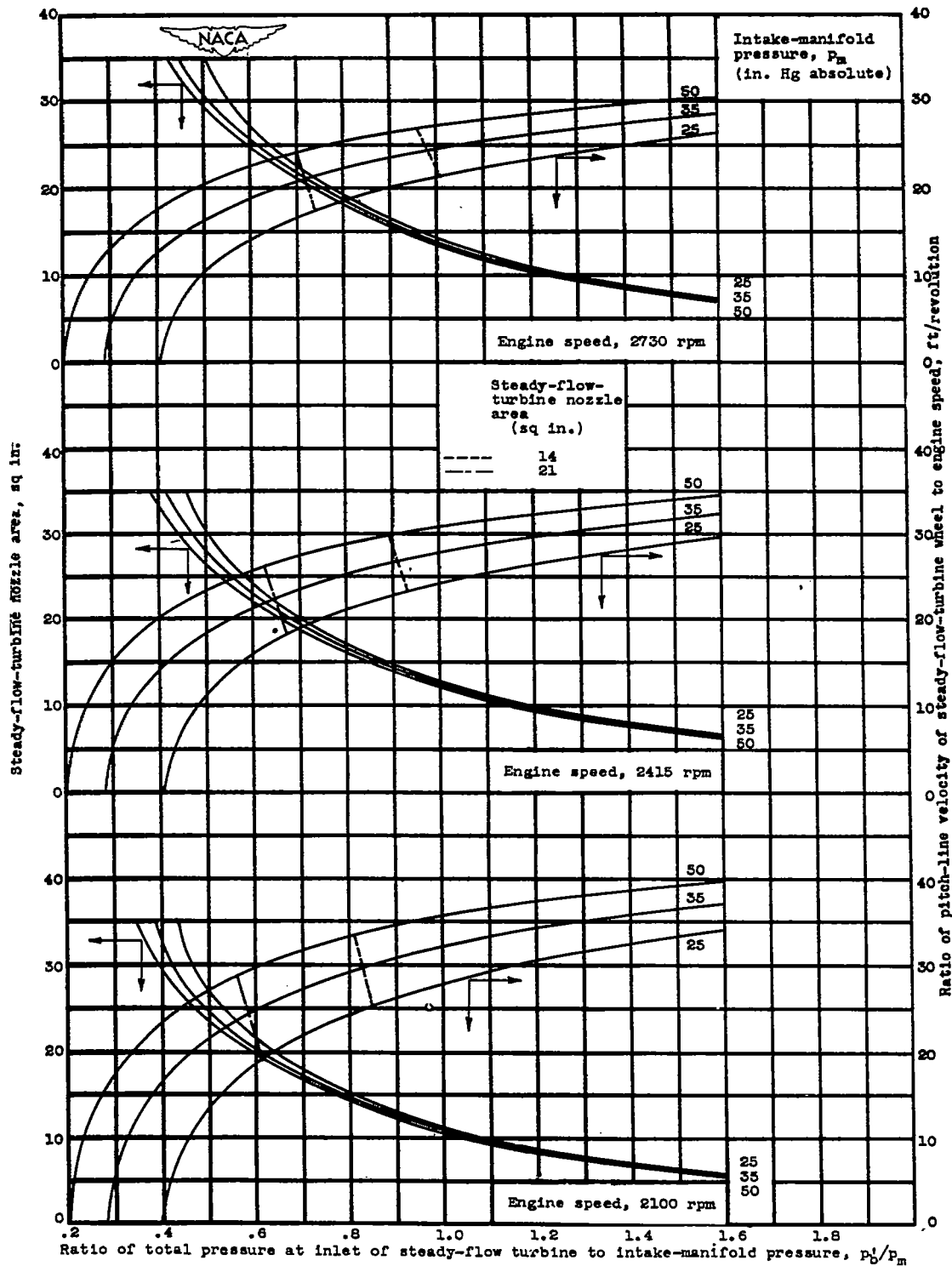
(c) Altitude, 30,000 feet.

Figure 8. - Continued. Optimum speed and required nozzle area of steady-flow turbine for various intake-manifold pressures and engine speeds. Single-cylinder-engine data.
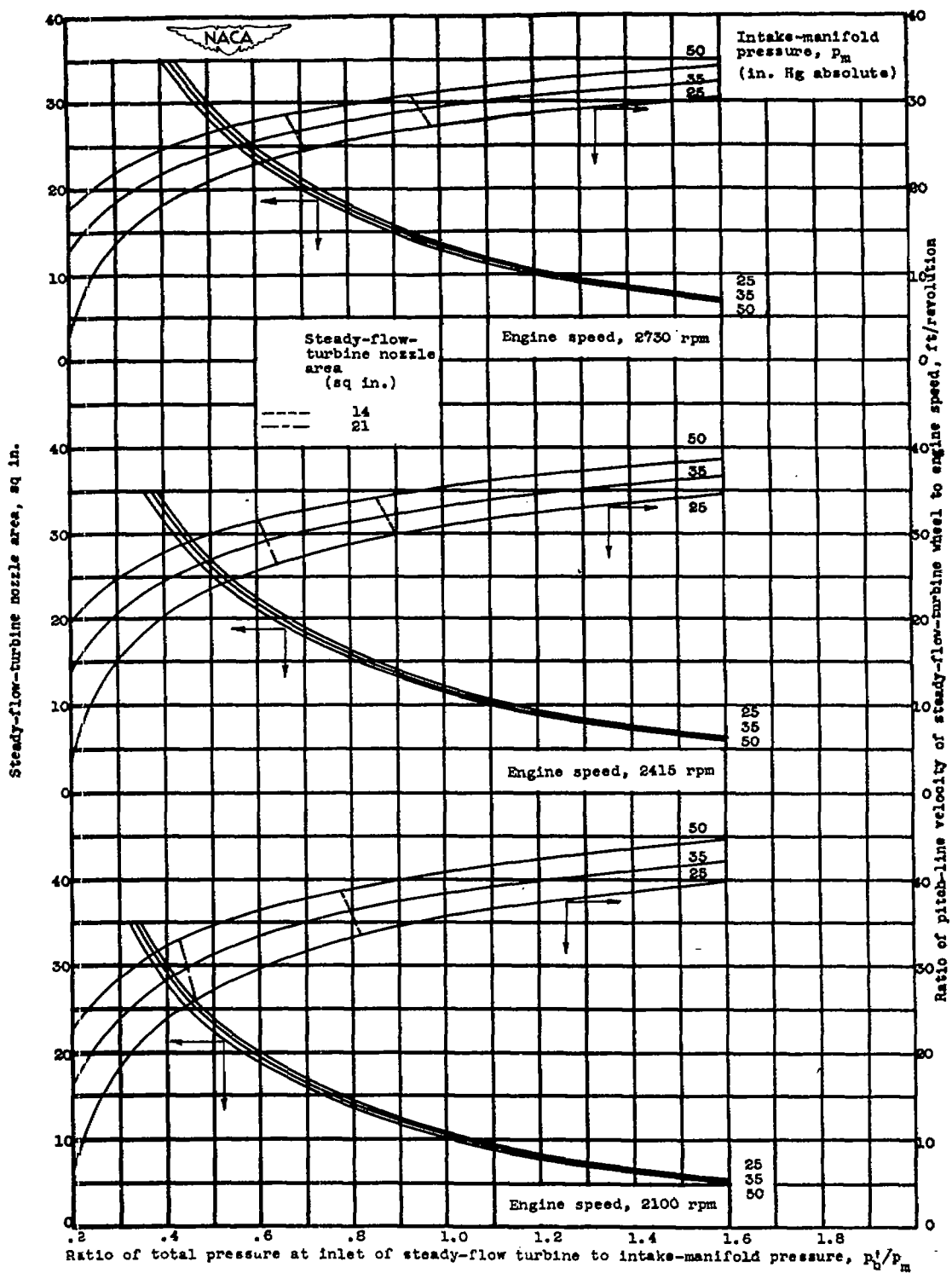
(d) Altitude, 45,000 feet.

Figure 8. - Concluded. Optimum speed and required nozzle area of
steady-flow turbine for various intake-manifold pressures and engine
speeds. Single-cylinder-engine data.
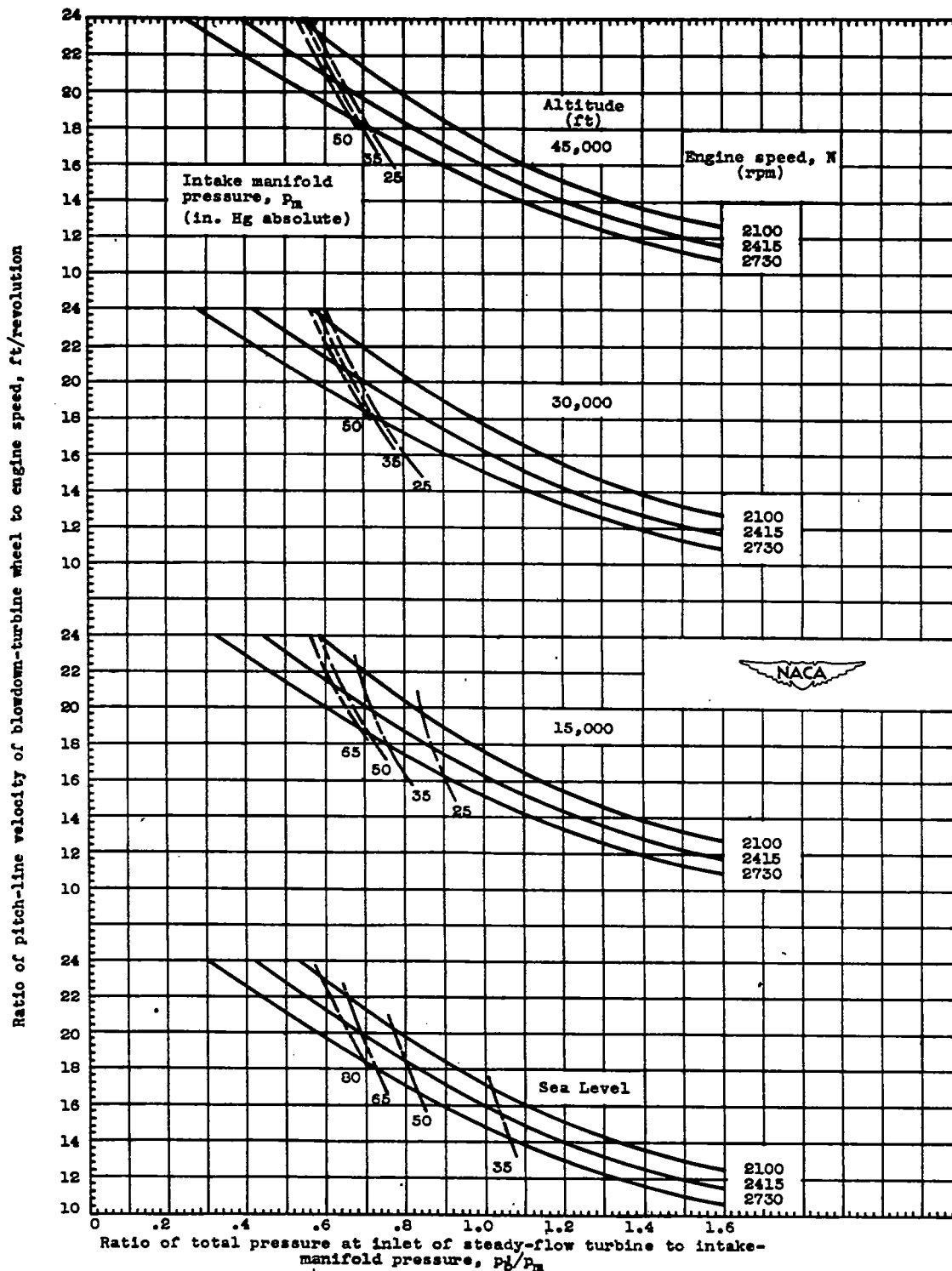
(a) Steady-flow-turbine nozzle area for maximum power (21 square in.).

Figure 9. - Optimum speed of blowdown turbine for fixed steady-flow-turbine nozzle area.
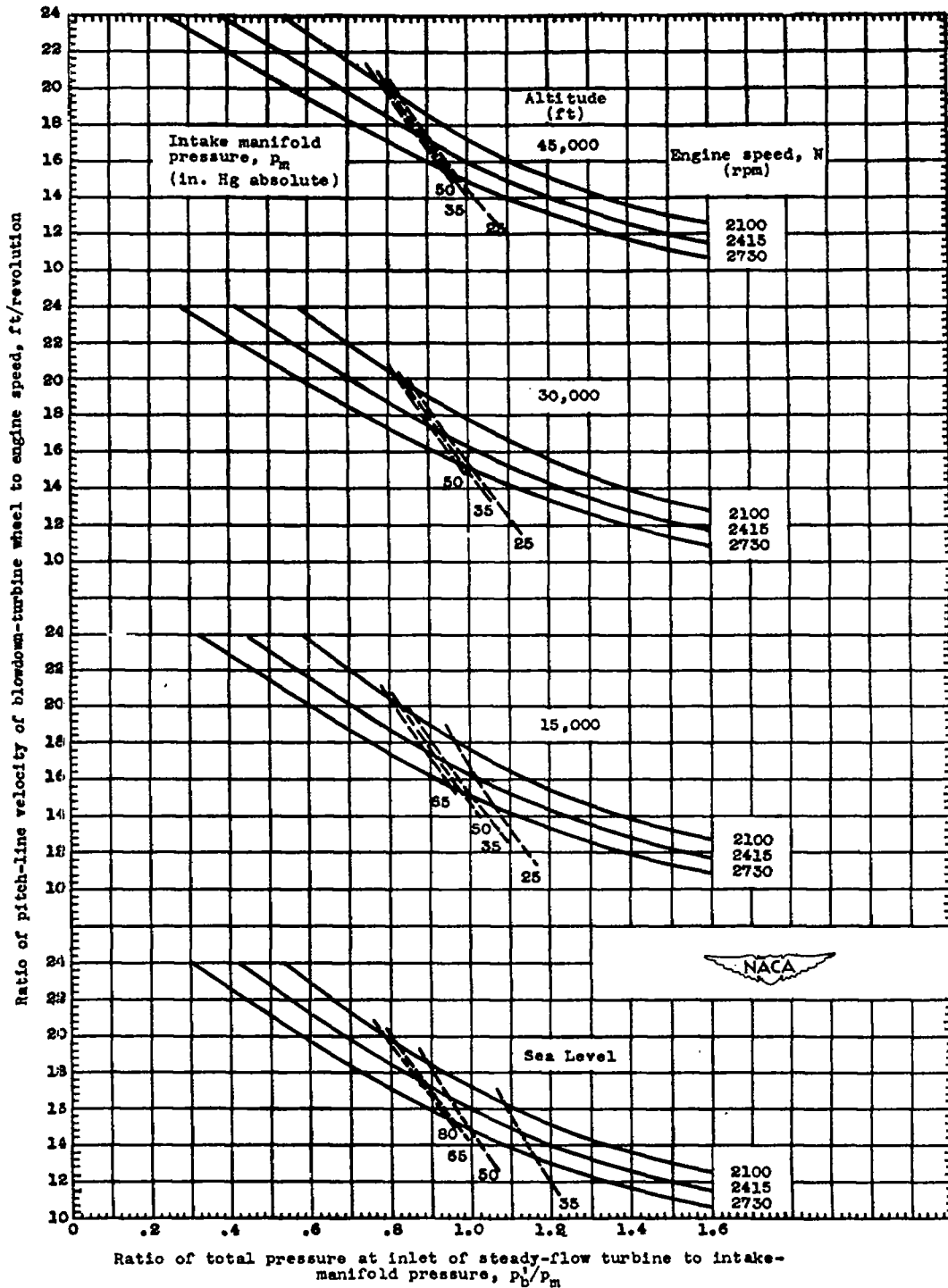
(b) Steady-flow-turbine nozzle area for minimum specific fuel consumption
(14 square in.).

Figure 9. - Concluded.   Optimum speed of blowdown turbine for fixed
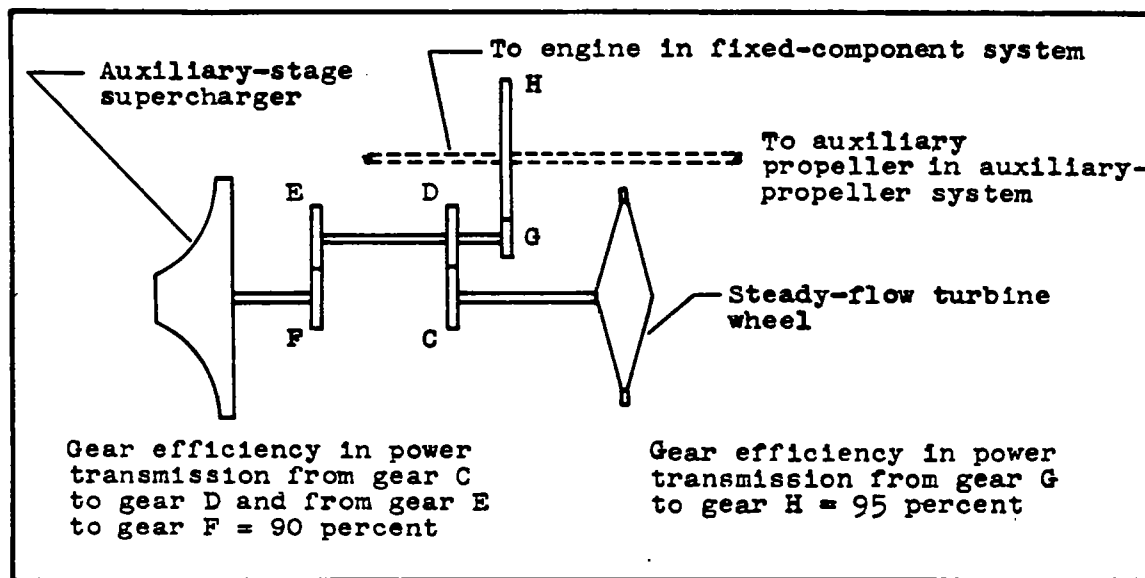steady-flow-turbine nozzle area.

Figure 10. - Schematic diagram of method of gearing auxiliary-stage supercharger and steady-flow turbine for fixed-component system or auxiliary-propeller system.
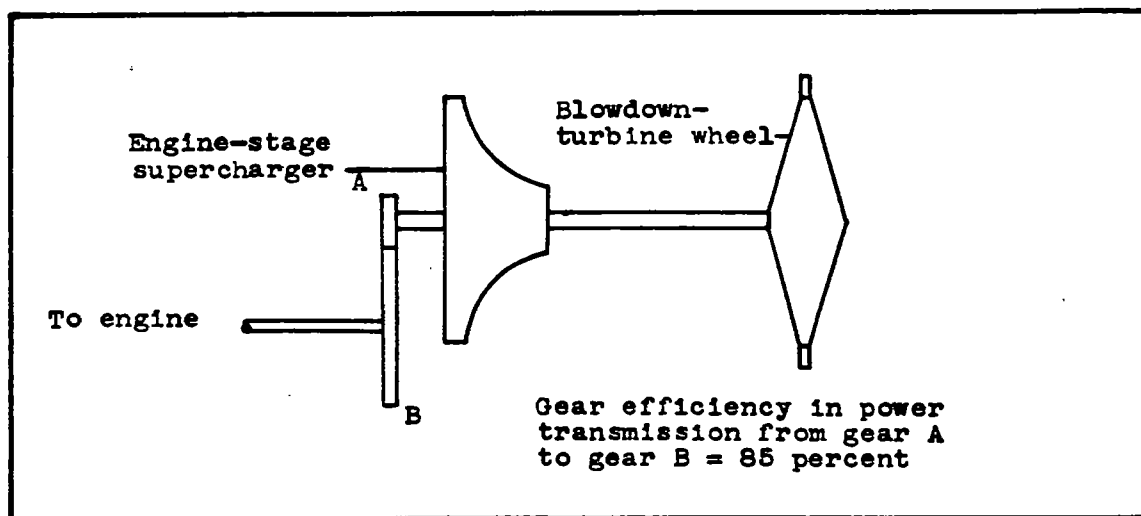

Figure 11. - Schematic diagram of method of gearing blowdown turbine and engine-stage supercharger to engine.
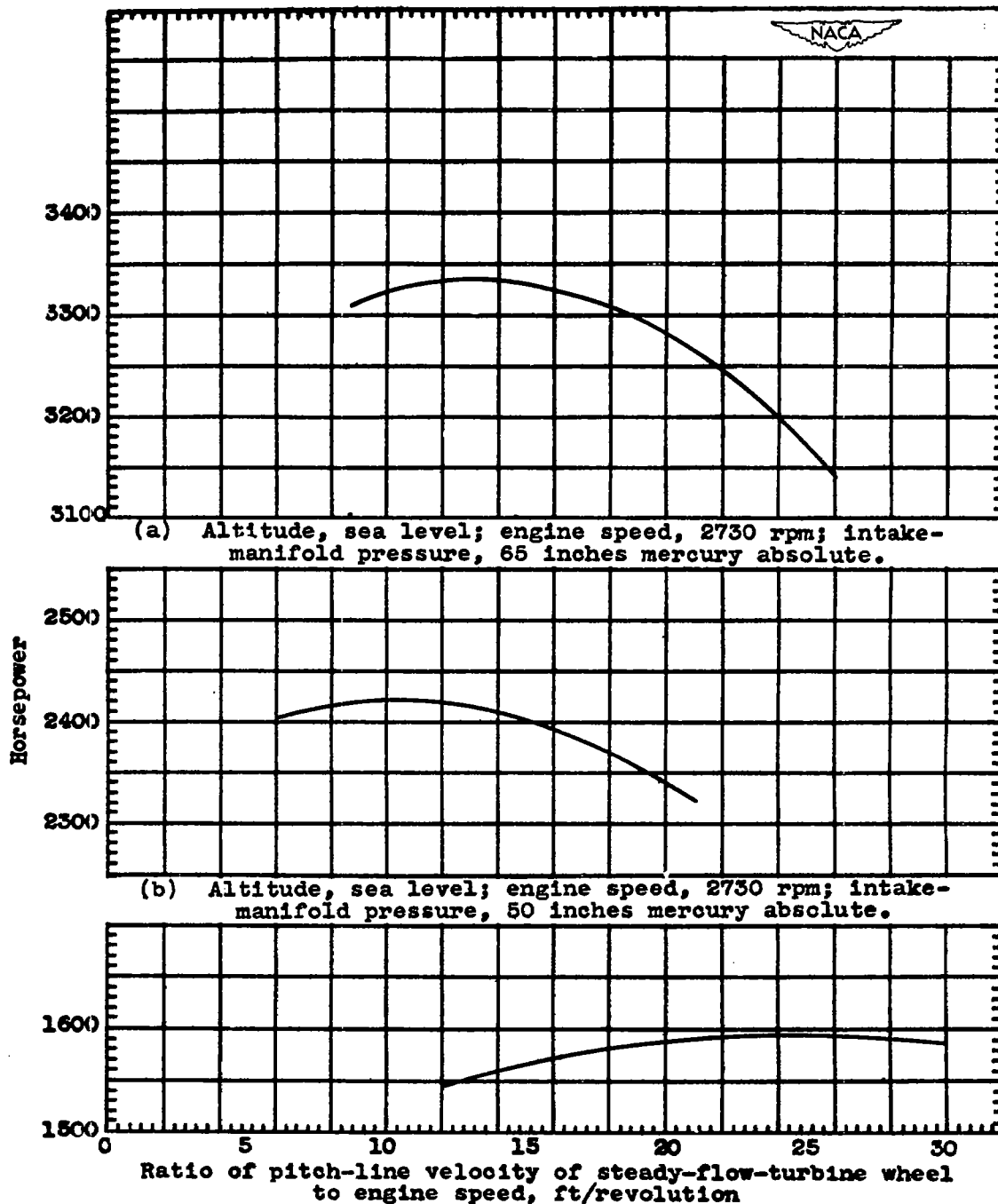
(a) Altitude, sea level; engine speed, 2730 rpm; intake-
        manifold pressure, 65 inches mercury absolute.

(b) Altitude, sea level; engine speed, 2730 rpm; intake-
        manifold pressure, 50 inches mercury absolute.

Ratio of pitch-line velocity of steady-flow-turbine wheel
                    to engine speed, ft/revolution

(c) Altitude, 30,000 feet; engine speed, 2100 rpm; intake-
        manifold pressure, 35 inches   mercury absolute.

Figure 12. - Variation of power of composite engine with steady-flow
  turbine speed. Single-cylinder-engine data; turbine and supercharger
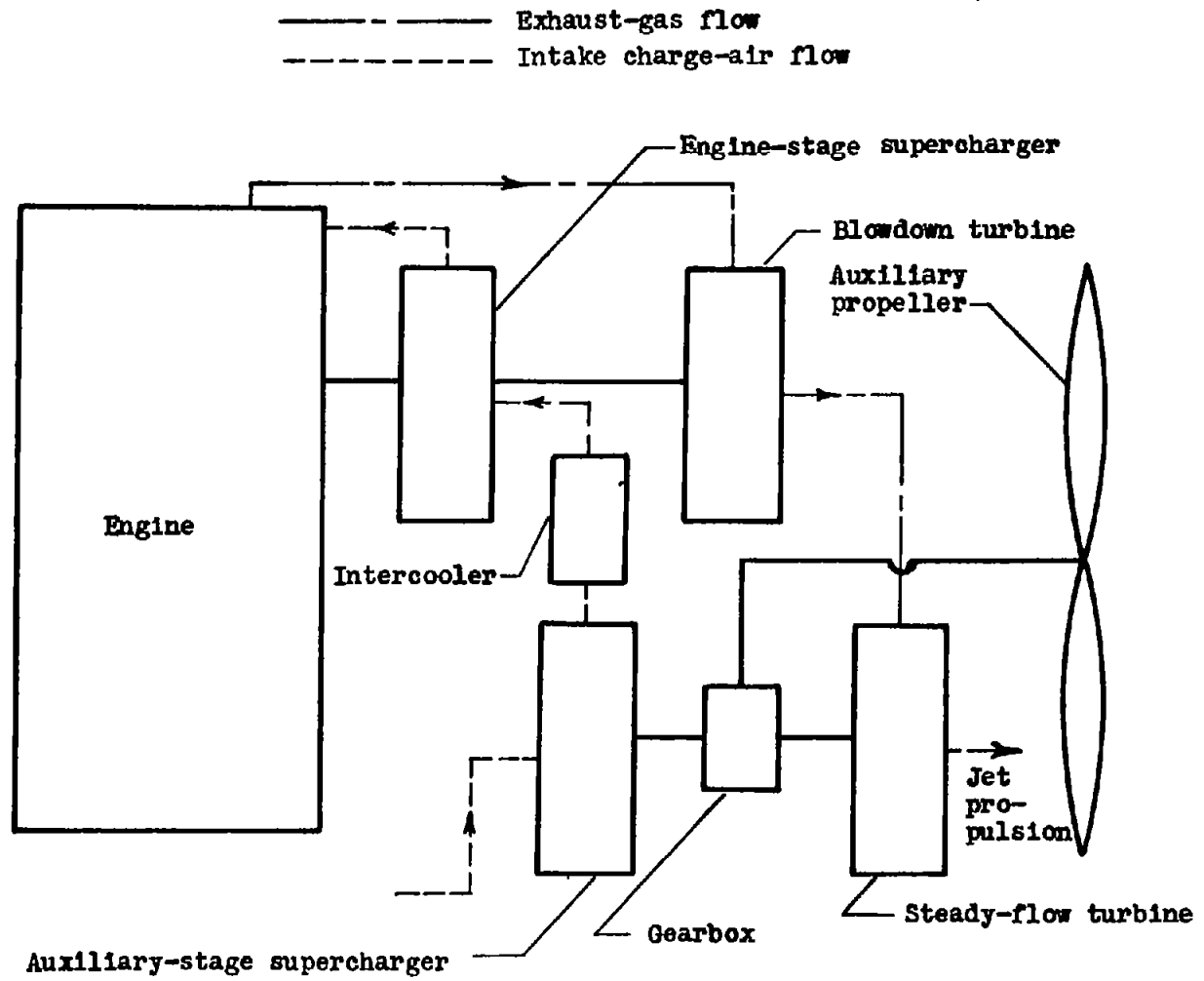 efficiencies, 70 percent.

Figure 13. - Schematic diagram of auxiliary-propeller system in which excess power from steady-flow turbine is used to drive an auxiliary propeller.
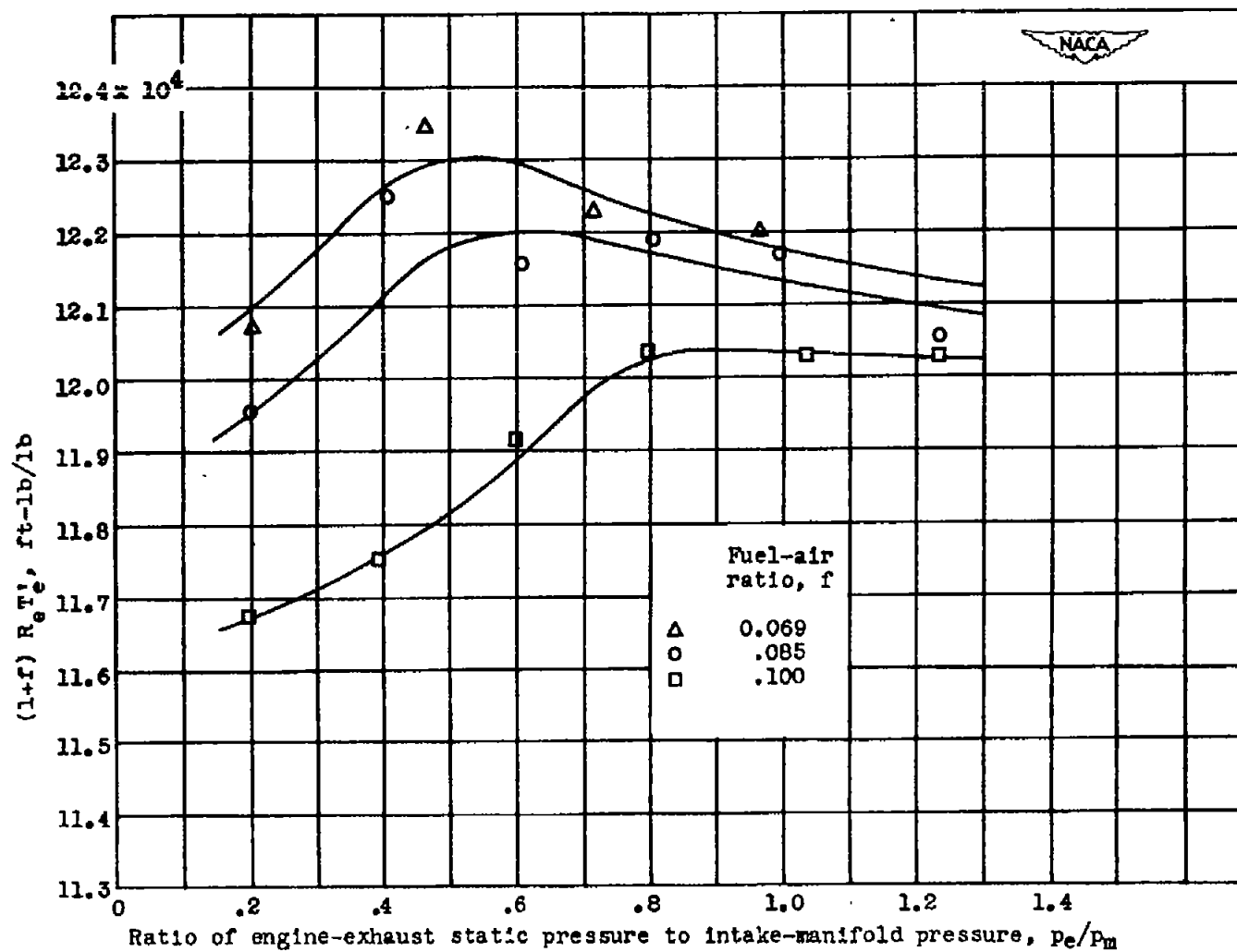
Figure 14. – Variation of $(1+f) R_e T'_e$ with exhaust pressure and fuel-air ratio. 18-cylinder multi-cylinder-engine data; intake-manifold pressure, 40 inches mercury absolute; engine speed, 2000 rpm.