NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1602

CALCULATED PERFORMANCE OF 12-CYLINDER LIQUID-COOLED ENGINE WITH EXHAUST-GAS TURBINE GEARED TO CRANKSHAFT

By Leland G. Desmon and Ronald B. Doyle

Flight Propulsion Research Laboratory
Cleveland, Ohio

Washington
June 1948

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1602

CALCULATED PERFORMANCE OF 12-CYLINDER LIQUID-COOLED ENGINE WITH EXHAUST-GAS TURBINE GEARED TO CRANKSHAFT

By Leland G. Desmon and Ronald B. Doyle

SUMMARY

Computations were made of the horsepower and specific fuel consumption of a compound engine composed of an exhaust-gas turbine and an auxiliary supercharger geared to the crankshaft of a 12-cylinder liquid-cooled engine. The required reciprocating-engine data were obtained from the results of a dynamometer-stand investigation made to determine the effect of exhaust pressure on engine performance. The turbine and the auxiliary supercharger were assumed to have constant values of efficiency.

The calculations covered a range of engine speeds from 1600 to 3200 rpm, fuel-air ratios from 0.063 to 0.100, inlet-manifold pressures from 30 to 60 inches of mercury absolute, and altitudes from sea level to 45,000 feet. The effects of changes in the system variables on compound-engine performance and a comparison with a turbosupercharged engine are shown. The effect of operation at fuel-air ratios richer than stoichiometric and provision of enough air in the engine exhaust system to afterburn the exhaust gas and to cool it to a turbine-inlet temperature of 2260° R is also given.

The compound engine investigated herein is compared with two other compound engines of the same general configuration but each including a different model of an 18-cylinder air-cooled engine.

Additional calculations were made on an engine system in which the engine-stage supercharger and the intercooler are removed and all the supercharging is done by a turbine-driven supercharger with aftercooling.

INTRODUCTION

The results of calculations made to determine the performance of compound engines composed of a steady-flow turbine and an auxiliary supercharger mounted on the same shaft and geared to the engine crankshaft have been presented in references 1, 2, and 3. These references show that the compound engine produces more power with higher efficiency than that produced by either the conventional geared or the turbosupercharged engine.

The results of references 1 and 2 are based on data obtained from two different models of an 18-cylinder air-cooled engine. Results of calculations made at the NACA Cleveland laboratory similar to those of references 1 and 2 but based on data obtained from a 12-cylinder liquid-cooled engine (reference 4) and assuming the same general system configuration are presented herein.

The effect of changes in engine speed, fuel-air ratio, inlet-manifold pressure, altitude, and exhaust pressure on net brake horsepower and specific fuel consumption are shown for several constant values of turbine, auxiliary-supercharger, and drive-gear efficiency.

An investigation was made of the effect on performance of operation at reciprocating-engine fuel-air ratios richer than stoichiometric and of addition, by means of an additional supercharger, of sufficient air to the engine exhaust gas to complete combustion of the unburned fuel and to cool the resultant mixture to a temperature of 2260° R at the turbine inlet. A comparison is made with a turbosupercharged engine and also with the systems incorporating the two air-cooled engines.

Additional calculations were made on an engine system in which the engine-stage supercharger and intercooler are removed and all the supercharging is done by a turbine-driven supercharger with aftercooling.

METHODS AND ASSUMPTIONS

A schematic diagram of the compound power plant assumed in this report is shown in figure 1. The turbine and the auxiliary supercharger are on a single shaft connected, through a gearbox, to the engine which, as in reference 4, incorporates an engine-stage supercharger. The charge air enters the auxiliary supercharger and passes through the intercooler, the carburetor, and the engine-stage supercharger to the inlet manifold. The engine exhaust gas expands through the turbine and is directed rearwardly by an exhaust nozzle. At low altitudes and certain engine conditions, the engine-stage supercharger could provide the desired inlet-manifold pressure and for these conditions the auxiliary supercharger and the intercooler were omitted from the calculations.

Although the performance of the reciprocating engine is based on experimental data, that of the remainder of the compound power plant is obtained by calculation.

Reciprocating engine. - The performance of the 12-cylinder liquid-cooled engine (including the engine-stage supercharger) was obtained from the results of the dynamometer-stand investigation reported in reference 4. The 12-cylinder liquid-cooled V-type engine has a displacement volume of 1710 cubic inches. Other pertinent engine specifications are:

Compression ratio	6.65
Valve overlap, deg	74
Engine-stage supercharger	
Impeller diameter, in.	9.5
Gear ratio	8.1:1
Spark advance, deg B.T.C.	
Inlet por side	28
Exhaust port side	34

Turbine and auxiliary supercharger. - The turbine horsepower is that obtained by expanding all the exhaust gas from engine exhaust pressure and temperature to ambient altitude pressure and was calculated using the variable-specific-heat data of reference 5.

The auxiliary supercharger horsepower is that required to compress the charge air from ambient altitude pressure and temperature to full-throttle carburetor-top-deck pressure with an allowance for duct pressure losses.

Unless otherwise specified, the turbine, auxiliary-supercharger, and drive gears are assumed to have constant efficiencies of 80, 80, and 95 percent, respectively. The assumption of constant efficiencies demands that the three components be redesigned at each successive point of calculation.

The intercooler is assumed to have a constant effectiveness of 50 percent.

Calculation of net brake performance. - The net brake horsepower of the compound power plant when the turbine power is greater than the auxiliary supercharger power is given by

$$nbhp = bhp + \eta_g \, (thp - shp) \tag{1}$$

where

bhp reciprocating-engine brake horsepower

nbhp compound-power-plant net brake horsepower

shp auxiliary-supercharger horsepower

thp turbine horsepower

η_g drive-gear efficiency

For the conditions at which the auxiliary-supercharger horsepower is greater than the turbine horsepower, the net brake horsepower is given by

$$nbhp = bhp - \frac{1}{\eta_g} (shp - thp) \tag{2}$$

The net brake specific fuel consumption is

$$nbsfc = \frac{W_f}{nbhp} \tag{3}$$

where

nbsfc net brake specific fuel consumption, pounds per horsepower-hour

W_f fuel flow, pounds per hour

Calculation of net thrust performance. - Net thrust performance was also calculated for several conditions. These calculations were made assuming an airplane speed of 400 miles per hour, 85-percent ram-pressure recovery, and a propeller efficiency of 85 percent.

Net thrust horsepower of the compound power plant is given by

$$nthp = \eta_p \, (nbhp) + jhp - php + chp \tag{4}$$

940

where

chp cooling-air horsepower

jhp exhaust-jet thrust horsepower

nthp net thrust horsepower of power plant

php horsepower required to take on board charge air

η_p propeller efficiency

The cooling horsepower was obtained from the relation

$$chp = \frac{M}{550} (V_1 - V_o) V_o \tag{5}$$

where

M mass flow of cooling air, slugs per second

V_1 velocity of cooling air at cowling exit, feet per second

V_o airplane velocity, feet per second

The cooling-air mass flow and the cowling-exit velocity were obtained from the performance characteristics of an aluminum-tube-and-fin radiator with a face area of 3 square feet. The area was determined by the condition that the radiator provide adequate cooling at an airplane speed of 120 miles per hour in the initial climbing condition from sea level. The cooling-air drag powers of the intercooler and the oil cooler are not included in the net thrust horsepower because calculations show them to be negligible.

The following ranges of engine conditions are covered in calculating the performance of the compound power plant:

Engine speed, rpm	1600 to 3200
Inlet-manifold pressure, in. Hg absolute	30 to 60
Fuel-air ratio	0.063 to 0.100
Altitude, ft	0 to 45,000

In order to obtain the best engine operating conditions for the compound power plant, three of the following reference conditions are held constant when the effect of varying the fourth condition is investigated.

940

Engine speed, rpm	2600
Inlet-manifold pressure, in. Hg absolute	40
Fuel-air ratio	0.069
Altitude, ft	30,000

Turbosupercharged engine. - The performance of a turbosupercharged engine is included herein for purposes of comparison and is also based on the engine data of reference 4. All the engine exhaust gas is assumed to go through the turbine at a turbine-inlet pressure equal to engine exhaust pressure. For these computations, the turbine-inlet pressure is that at which the turbine power is just equal to the power required by the auxiliary supercharger, the efficiencies of both components being 80 percent.

In addition to the previously discussed system, the comparative performances of compound and turbosupercharged engines is shown for systems in which the engine-stage supercharger is assumed to be removed and all the supercharging is done by a single turbine-driven compressor with aftercooling.

Afterburning. - Calculations were also made in which the reciprocating engine is assumed to be operating at fuel-air ratios richer than stoichiometric and excess air, provided by a separate supercharger, is added to the engine exhaust gas in sufficient quantity to complete combustion of the unburned fuel and to cool the resultant mixture to a turbine-inlet temperature of 2260° R. The horsepower of the supplementary-air supercharger is that required to compress the mass flow of supplementary air, as determined from the charts of reference 6, from altitude pressure and temperature to engine exhaust (turbine inlet) pressure. The supplementary-air supercharger has a constant efficiency of 80 percent and is assumed to be on the same shaft as the turbine and the auxiliary supercharger.

The entire mass of the final gas mixture passes through the turbine and the difference in power between that of the turbine and the sum of the auxiliary plus supplementary-air superchargers is transmitted through suitable gearing to the engine crankshaft.

Estimation of engine weight and frontal area. - For convenience in making further calculations, an estimate was made of the weight of the various engine systems and of their frontal area. Most of the data was obtained from manufacturers' literature, military technical orders, and actual measurement. When the data could not be obtained in this way, an estimate based on similar equipment was made.

The estimated weights of the various engine systems are:

Turbosupercharged engine, lb	3300
Compound engine, lb	3350
Compound engine with afterburning equipment, lb	3650

These weights include the propeller, the instruments, the controls, the coolers, and the normal supplies of oil and coolant.

From manufacturers' drawings it is estimated that a nacelle with a frontal area of $8\frac{1}{2}$ square feet would be required to accommodate any one of the three aforementioned engine systems if the intercooler, oil cooler, and coolant radiators could be submerged in the airplane. If limitations require that additional frontal area be provided for the aforementioned coolers, the following estimates may be used:

Intercooler, (air-to-air), sq ft	$1\frac{1}{2}$ to 2
Oil cooler, sq ft	1
Coolant radiator, sq ft	3

RESULTS AND DISCUSSION

The performance of the compound power plant is, in general, represented by net brake horsepower and net brake specific fuel consumption. The effects of engine speed, fuel-air ratio, inlet-manifold pressure, altitude, and component efficiency on performance are presented in plots of power and fuel consumption against the ratio of engine exhaust pressure to inlet-manifold pressure p_e/p_m for several values of one of the previous variables when the others are maintained constant.

Upon completion of the investigation of the effect of each variable on performance, a value is assigned to that variable for the remainder of the analysis. This value is usually a compromise between power and economy at cruising conditions with most of the emphasis placed on low specific fuel consumption.

Engine exhaust pressure. - The effect of engine exhaust pressure on performance is shown in figures 2 to 5, which will be discussed in more detail with respect to the other variables, where net brake horsepower and specific fuel consumption are shown plotted against p_e/p_m. The curves show that independent of engine speed, fuel-air ratio, inlet-manifold pressure, and component efficiency at an altitude of 30,000 feet, net brake horsepower is near maximum at a p_e/p_m of 0.8 and specific fuel consumption is near minimum at a p_e/p_m of 1.0. This is in general agreement with the results of references 1, 2, and 3.

Engine speed. - The effect of engine speed and p_e/p_m on performance is shown in figure 2. Net brake horsepower increases at a decreasing rate as engine speed is raised. Brake specific fuel consumption is minimum for an engine speed of 2000 rpm and although it increases as speed is changed from this value, the total spread in fuel consumption at a p_e/p_m of 1.0 for the speed range from 1600 to 3000 rpm is about 4 percent. Operating the engine at 2600 rpm rather than 2000 rpm produces an increase in power of 20 percent with an increase in fuel consumption of only about 1 percent.

Fuel-air ratio. - The effect of fuel-air ratio and p_e/p_m on performance is shown in figure 3. The curves indicate that the maximum value of net brake horsepower occurs in the region of fuel-air ratio between 0.069 and 0.085 and that the minimum value of specific fuel consumption occurs in the region of fuel-air ratio between 0.063 and 0.069. At best-power p_e/p_m, however, the system produces 10 percent more power at a fuel-air ratio of 0.069 than at 0.063 with negligible difference in specific fuel consumption.

Inlet-manifold pressure. - The effect of inlet-manifold pressure and p_e/p_m on net brake horsepower and specific fuel consumption is shown in figure 4. Net brake horsepower increases almost linearly and specific fuel consumption decreases at a decreasing rate as inlet-manifold pressure is increased. The inlet-manifold pressure for most efficient operation is then the highest value of this pressure at which the engine will run. The highest inlet-manifold pressure at which an engine will operate properly is, of course, limited by the knock characteristics of the fuel used. NACA investigations indicate that the engine of reference 4 operating at an engine speed of 2600 rpm and a fuel-air ratio of 0.069 will have just reached the knock limit at an inlet-manifold pressure of 50 inches of mercury absolute at sea-level exhaust pressure with the fuel used in the investigation of reference 4 (AN-F-28, Amendment 2). Although operation at an inlet-manifold pressure of 50 inches of mercury absolute is desirable for both high power and low specific fuel consumption, the brake mean effective pressure is considerably higher than that usually associated with cruising conditions. At an engine speed of 2600 rpm, a fuel-air ratio of 0.069, an inlet-manifold pressure of 40 inches mercury absolute (the reference conditions), and a p_e/p_m of 0.8; however, the brake mean effective pressure of the present engine is 180 pounds per square inch or only about 15 to 20 percent higher than the usual values for cruising operation.

Turbine, auxiliary-supercharger, and drive-gear efficiency. - The effect of component efficiency and p_e/p_m on performance is shown in figure 5 where the net brake horsepower and specific fuel consumption resulting from individually reducing the efficiency of the components (turbine, auxiliary supercharger, and drive gear) 10 points from the standard values of 80, 80, and 95 percent is plotted. A decrease of about 4 percent in net brake horsepower and the same increase in specific fuel consumption is caused by the 10-point reduction in turbine efficiency at best-power p_e/p_m.

Effect of altitude. - The effect of altitude and p_e/p_m on net brake performance is shown in figure 6. The figure shows that the values for both best-power p_e/p_m and best-economy p_e/p_m decrease with increase in altitude; the value of p_e/p_m for best power changes from 0.9 at sea level to 0.8 at 45,000 feet, whereas that for best economy changes from 1.15 at sea level to 1.0 at 45,000 feet.

Net brake horsepower increases with altitude from sea level to about the tropopause (approximately 35,000 ft). As altitude is further increased, net brake horsepower decreases because of the combined effects of the assumption of an intercooler of constant effectiveness, the increased auxiliary-supercharger temperature-rise ratio, and the constant ambient temperature. These factors cause inlet-manifold temperature to increase sharply, resulting in a decreased indicated horsepower. Net brake specific fuel consumption decreases as altitude is increased throughout the range investigated.

The data of figure 6 are cross-plotted in figure 7 to show the effect of altitude on the performance of the compound engine at best-power p_e/p_m and best-economy p_e/p_m. As in figure 6, the engine speed is 2600 rpm, the fuel-air ratio is 0.069, and the inlet-manifold pressure is 40 inches of mercury absolute.

The increase in compound-engine power from sea level to the tropopause is 27 percent for best-power p_e/p_m and 32 percent for best-economy p_e/p_m. For both best-power and best-economy p_e/p_m, the decrease in economy for this increase in altitude is about 19 percent.

Comparison of compound and turbosupercharged engines. - The performance of the turbosupercharged engine is also included in figure 7 for the purpose of comparison with the performance of the compound engine.

The turbosupercharged-engine net brake horsepower increases about 9 percent from sea level to 25,000 feet and the specific fuel consumption is nearly constant with altitude. At an altitude of 35,000 feet, the compound engine operating at best-power p_e/p_m produces 21 percent more power than the turbosupercharged engine with 23 percent lower specific fuel consumption. Each point on these curves is a design point in that the turbine and auxiliary supercharger are selected for operation at that point.

Performance at high-power levels. - The performance of the compound engine at high-power levels is shown in figure 8. Representative curves are presented for engine speeds from 2600 to 3200 rpm and inlet-manifold pressures of 50 and 60 inches of mercury absolute. The fuel-air ratio of 0.083 for 3200 rpm at an inlet-manifold pressure of 60 inches of mercury absolute was obtained by adding 10 percent to the knock-limited fuel-air ratio indicated by previously obtained NACA knock data. The compound engine operating at these engine conditions and an altitude of 30,000 feet has a net brake horsepower of 2137 at best-power p_e/p_m with a corresponding specific fuel consumption of 0.419 pound per horsepower-hour.

Effect of afterburning. - The effect of adding air to rich-mixture exhaust gas to afterburn and cool the resultant mixture to 2260° R before expanding through the turbine is shown in figure 9. The curves for an engine speed of 3000 rpm, a fuel-air ratio of 0.100, and an inlet-manifold pressure of 50 inches of mercury absolute show that afterburning increases the net brake horsepower at best-power p_e/p_m by 31 percent and decreases the corresponding specific fuel consumption by 24 percent. Increasing the fuel-air ratio from 0.069 to 0.085 and 0.100 at the assigned cruising condition (engine speed, 2600 rpm; inlet-manifold pressure, 40 in. Hg absolute) and afterburning increased the maximum power 18 and 30 percent, respectively, with increases of 6 and 14 percent in the corresponding specific fuel consumption.

Comparison between 12-cylinder liquid-cooled compound engine and two 18-cylinder air-cooled compound engines. - The effects of p_e/p_m, altitude, and afterburning on the specific fuel consumption of the 12-cylinder liquid-cooled engine system and the two 18-cylinder air-cooled engine systems of reference 2 are compared in figure 10. The liquid-cooled engine has a valve overlap of 74° and the two air-cooled engines have valve overlaps of 40° and 62°, respectively. The cruising speed and fuel-air ratio of both air-cooled systems were given as 2200 rpm and 0.063, respectively.

The figure is constructed for an inlet-manifold pressure of 40 inches of mercury absolute, turbine and auxiliary supercharger efficiencies of 80 percent and a drive-gear efficiency of 95 percent. The efficiency of the liquid-cooled engine system (valve overlap, 74°) is between the efficiencies of the two air-cooled engine systems (valve overlap, 40° and 62°) in the region of p_e/p_m between 0.6 and 1.2 (fig. 10(a)) without afterburning. At a p_e/p_m of 1.0, the fuel consumption for the 62°-valve-overlap air-cooled engine system is higher than that for the liquid-cooled engine system by about 6 percent and that for the 40° valve overlap engine is lower than that for the liquid-cooled engine system by about 6 percent.

The specific-fuel-consumption curves for the 62°-valve-overlap air-cooled engine system and the liquid-cooled engine system are essentially the same when both systems are operating at cruising speed and inlet-manifold pressure at a fuel-air ratio of 0.100 with afterburning.

The effect of altitude at best-economy p_e/p_m on the three engine systems is shown in figure 10(b). As in figure 10(a), the values of specific fuel consumption for the liquid-cooled compound engine fall between those for the two air-cooled compound engines.

The similarity in curve trends and levels between the air-cooled compound engines of reference 2 and the liquid-cooled compound engine exists also for various engine speeds, fuel-air ratios, inlet-manifold pressures, and component efficiencies.

Comparison of these three engines on the basis of net thrust specific fuel consumption would not change the relative performance appreciably from that which has been shown in figure 10.

Modified system. - The compound and turbosupercharged engines, the performance of which has been shown in the preceding figures, represent practical arrangements that would require no modification of the engine and engine-stage supercharger investigated except for the addition of auxiliary supercharger, intercooler, turbine, and gears for connecting the components where necessary. Improved performance may be obtained, however, by modifying the systems.

The engine-stage supercharger and intercooler are removed from the previously assumed systems and replaced by a turbine-driven supercharger and an aftercooler in the modified systems. Charge air enters the supercharger where it is compressed from inlet total pressure to engine-inlet-manifold pressure with an allowance for duct and aftercooler pressure losses. The charge air then passes through an aftercooler and into the engine inlet manifold. All the engine exhaust gas passes through the turbine and the discharge nozzle to the atmosphere. The discharge-nozzle inlet pressure is assumed to be that for maximum net power of the system. The turbine and the supercharger are each assumed to have an efficiency of 80 percent at each point of calculation; the aftercooler has an effectiveness of 50 percent.

As is implied, maximum net power at any combination of inlet and exhaust conditions in the system was obtained by varying the discharge-nozzle inlet pressure. For the compound engine, maximum power occurs when the discharge-nozzle inlet pressure is at ambient altitude pressure because the turbine can convert the exhaust energy into useful power more efficiently than the discharge nozzle. For the turbosupercharged engine, however, the turbine can utilize only that part of the exhaust energy required to do the work of supercharging, the rest of the energy becoming available to the discharge nozzle. If the nozzle-inlet pressure is increased, the engine exhaust pressure is increased to a value sufficient to allow the turbine to drive the supercharger. This increase in engine exhaust pressure causes a reduction in charge flow and engine brake horsepower but because of the increase in nozzle-inlet pressure, the exhaust-jet power is increased. Inasmuch as charge flow and engine brake horsepower decrease at an increasing rate as engine exhaust pressure is increased and exhaust-jet power increases at a decreasing rate as nozzle-inlet pressure is raised, a nozzle-inlet pressure higher than ambient altitude pressure exists such that the net power of the turbosupercharged engine system is at its maximum value. Inasmuch as the thrust power developed by the exhaust jet is included, the system performance is presented on a net-thrust basis.

The computed performance of the modified engine is better than the original engine system, which included the engine-stage supercharger and an intercooler, because: (1) aftercooling provides more reduction of the engine inlet-manifold temperature than intercooling and (2) a higher efficiency (80 percent) was assumed for the turbine-driven supercharger than was obtained from the relatively inefficient fixed engine-stage supercharger. In addition, the modified engine does not introduce the throttling losses incurred by the original engine system at low altitudes.

The altitude performance of both the modified engine and the original engine (designated in fig. 11 as two supercharger) in both the compound and turbosupercharged configurations is shown in figure 11 for an airplane speed of 400 miles per hour.

The increase in net thrust horsepower of the modified compound engine when altitude is increased from sea level to 33,000 feet (maximum-power altitude) is approximately 26 percent for best-power p_e/p_m with a corresponding decrease in specific fuel consumption of about 19 percent. The increase in net thrust horsepower of the modified turbosupercharged engine resulting when altitude is increased from sea level to 28,000 feet (approximately maximum-power altitude) is about 16 percent with a corresponding decrease in specific fuel consumption of about 10 percent.

The curves also show that both the compound and turbosupercharged engines of the modified system produce higher power than those of the original (two supercharger) system over the altitude range investigated.

The improvement in net thrust horsepower and specific fuel consumption in changing from the original (two supercharger) system to the modified system is greater for the turbosupercharged engine than it is for the compound engine. At an altitude of 33,000 feet, the compound engine of the modified system produces 12 percent higher net thrust horsepower than the compound engine of the original (two supercharger) system. The corresponding specific fuel consumption is 4 percent lower for the modified system. At an altitude of 28,000 feet, the turbosupercharged engine of the modified system produces about 27 percent higher net thrust horsepower than the turbosupercharged engine of the original (two supercharger)system with a corresponding reduction of 18 percent in specific fuel consumption. The improvement in turbosupercharged engine performance with change from the original to the modified system is large because in addition to the aforementioned advantages obtainable by modifying the system: (1) removal of the engine-stage supercharger shifts this load from the engine to the turbine thus making greater use of the turbine work available in the exhaust gas, and (2) increasing the inlet pressure to the exhaust nozzle to the value corresponding to maximum net power produces considerable exhaust-jet thrust. The improvement in compound engine performance with a modification of the engine under discussion is small relative to that of the turbosupercharged engine because: (1) in both the modified and original (two supercharger) systems, the turbine utilizes about the same percentage of the energy available in the exhaust gas and (2) the jet thrust of the exhaust nozzle is only that equivalent to the turbine-exit velocity.

Figure 11 shows that although the modified turbosupercharged engine produces higher power than the original (two supercharger) compound engine up to an altitude of about 40,000 feet, the modified compound engine system produces the highest power of the four systems presented over the altitude range.

SUMMARY OF RESULTS

Calculations of the performance of a compound engine having a constant-efficiency turbine and auxiliary supercharger geared to the engine crankshaft and based on data from a dynamometer-stand investigation of a 12-cylinder liquid-cooled engine, indicate that:

1. For the range of variables investigated, the best fuel economy of the reported system occurred at an engine speed of 2000 rpm, a fuel-air ratio of 0.069, an inlet-manifold pressure of 50 inches mercury absolute (knock-limited with AN-F-28, Amendment-2 fuel), and an altitude of 45,000 feet.

2. The values of the ratio of exhaust to inlet-manifold pressure at which maximum net brake horsepower and minimum net brake specific fuel consumption of the compound engine occur were nearly independent of engine speed, fuel-air ratio, inlet-manifold pressure, and component efficiency at a given altitude and decreased only slightly as altitude was increased from sea level to 45,000 feet. At an altitude of 30,000 feet, the value of the ratio of exhaust-to-inlet-manifold pressure for best power was 0.8 and that for best economy was 1.0.

3. The power of the compound engine increased with altitude up to about the tropopause and decreased as altitude was further increased. The net brake horsepower at the tropopause was 32 percent greater than that at sea level at best-economy ratio of exhaust to inlet-manifold pressure and cruising conditions. Specific fuel consumption decreased with increasing altitude over the entire calculated range (sea level to 45,000 feet) and was 19 percent lower at the tropopause than at sea level.

4. At an altitude of 35,000 feet, the compound engine produced 21 percent more power than the turbosupercharged engine (turbine driving auxiliary supercharger only) with a corresponding reduction

in specific fuel consumption of 23 percent, both operating at an engine speed of 2600 rpm, a fuel-air ratio of 0.069, and an inlet-manifold pressure of 40 inches mercury absolute.

5. Afterburning and cooling a rich-mixture exhaust gas (fuel-air ratio, 0.100) at an engine speed of 3000 rpm, an inlet-manifold pressure of 50 inches of mercury absolute, and an altitude of 30,000 feet, to a turbine-inlet temperature of 2260° R increased the maximum net brake horsepower 31 percent and decreased the corresponding net brake specific fuel consumption 24 percent.

6. The 12-cylinder liquid-cooled compound engine and the two 18-cylinder air-cooled compound engines of similar configuration produced curves of net brake specific fuel consumption that are similar in both trend and level for various ranges of exhaust-to-inlet-manifold pressure ratio, engine speed, fuel-air ratio, inlet-manifold pressure, altitude, and component efficiency.

7. The power and fuel consumption of both the compound and turbosupercharged engines of a modified system composed of an engine (with engine-stage supercharger removed), a turbine-driven supercharger, an aftercooler, and an exhaust nozzle were superior to the power and fuel consumption of respective engines of a system composed of an engine with engine-stage supercharger, auxiliary supercharger, intercooler, turbine, and exhaust nozzle.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 10, 1948.

REFERENCES

1. Hannum, Richard W., and Zimmerman, Richard H.: Calculations of Economy of 18-Cylinder Radial Aircraft Engine with Exhaust-Gas Turbine Geared to the Crankshaft. NACA Rep. No. 822, 1945.

2. Kaufman, Samuel J., and Boman, David S.: A Comparison of the Computed Performance of Composite Power Plants Using 18-Cylinder Aircraft Engines with 62° and 40° Valve Overlap. NACA TN No. 1500, 1947.

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

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

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

6. Turner, L. Richard, and Lord, Albert M.: Thermodynamic Charts for the Computation of Combustion and Mixture Temperatures at Constant Pressure. NACA TN No. 1086, 1946.

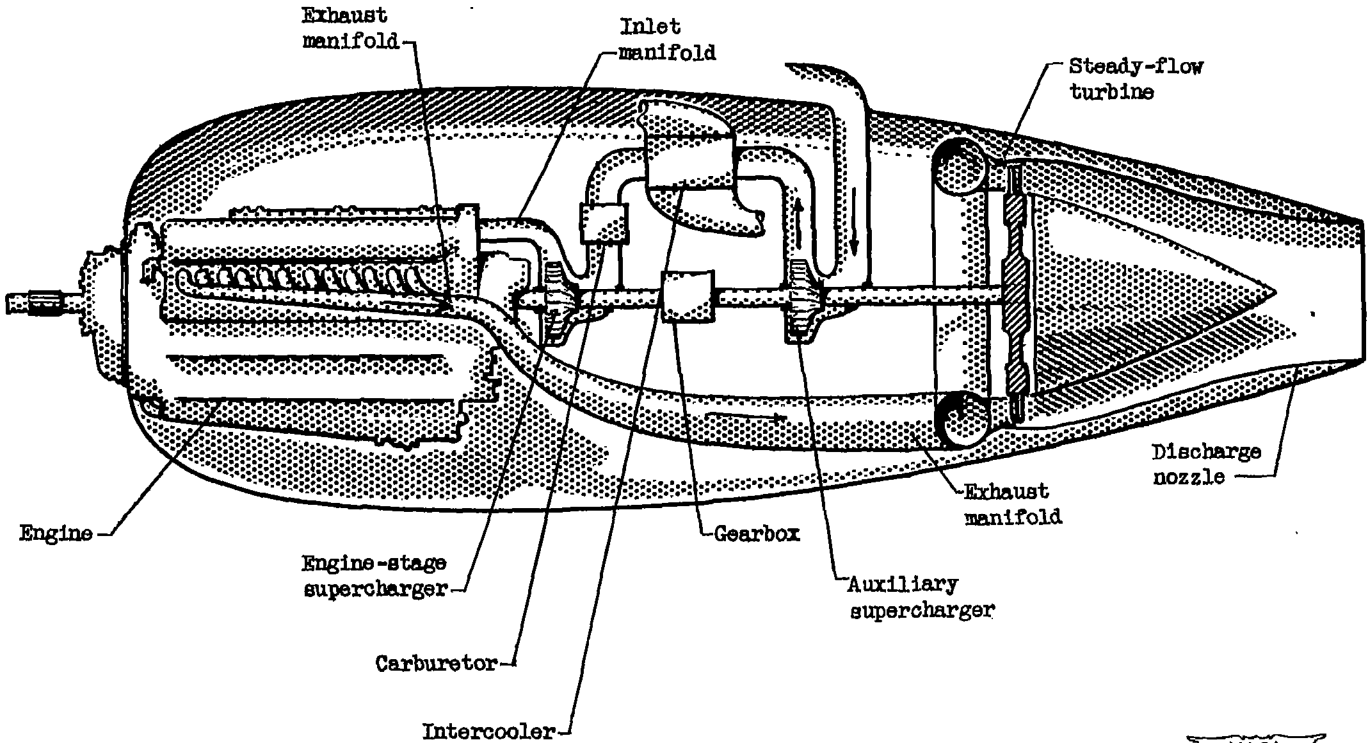


Figure 1. - Schematic diagram of compound engine.

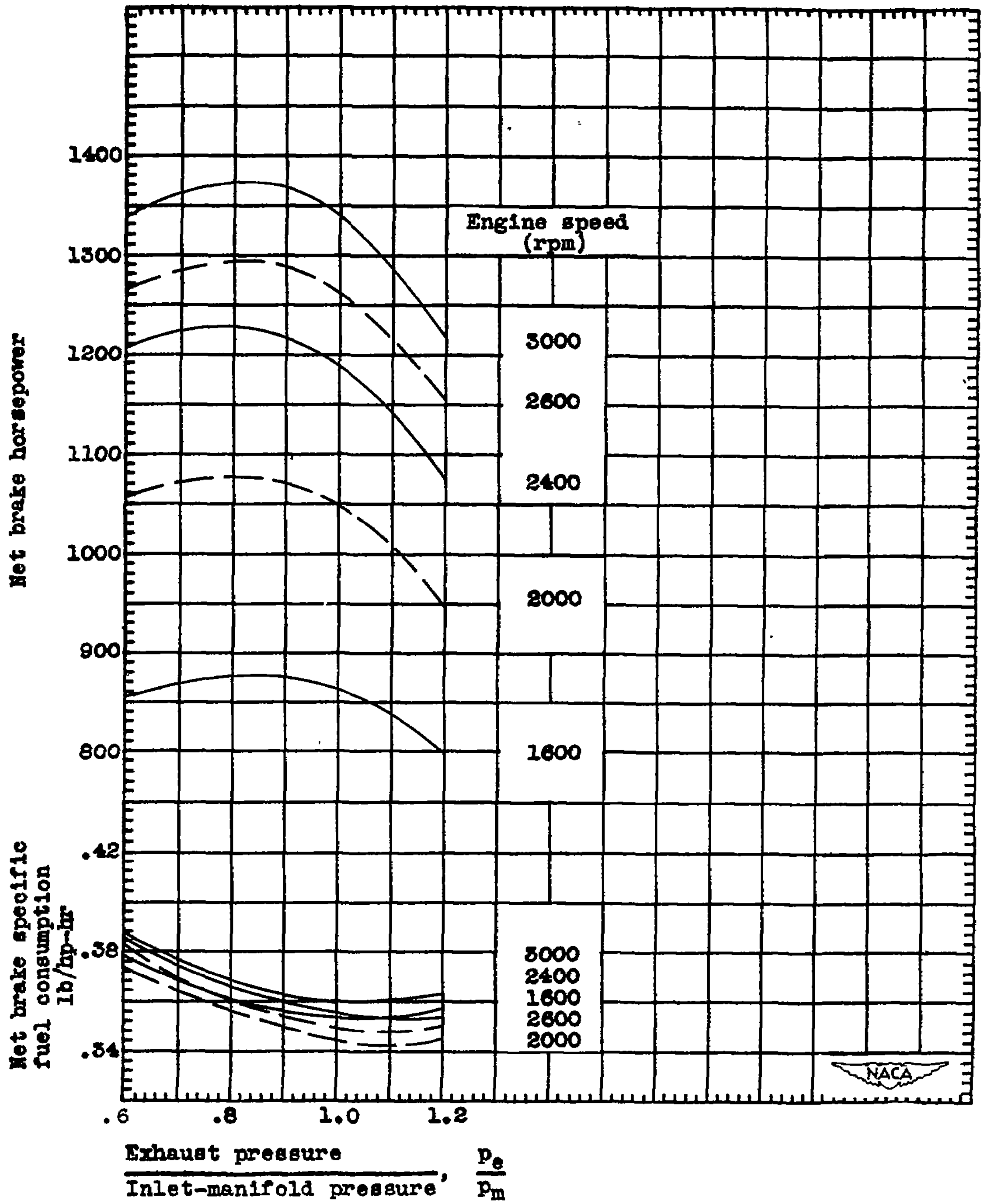


Figure 2. - Effect of p_e/p_m and engine speed on net brake horsepower and net brake specific fuel consumption. Fuel-air ratio, 0.069; inlet-manifold pressure, 40 inches mercury absolute; altitude, 30,000 feet.

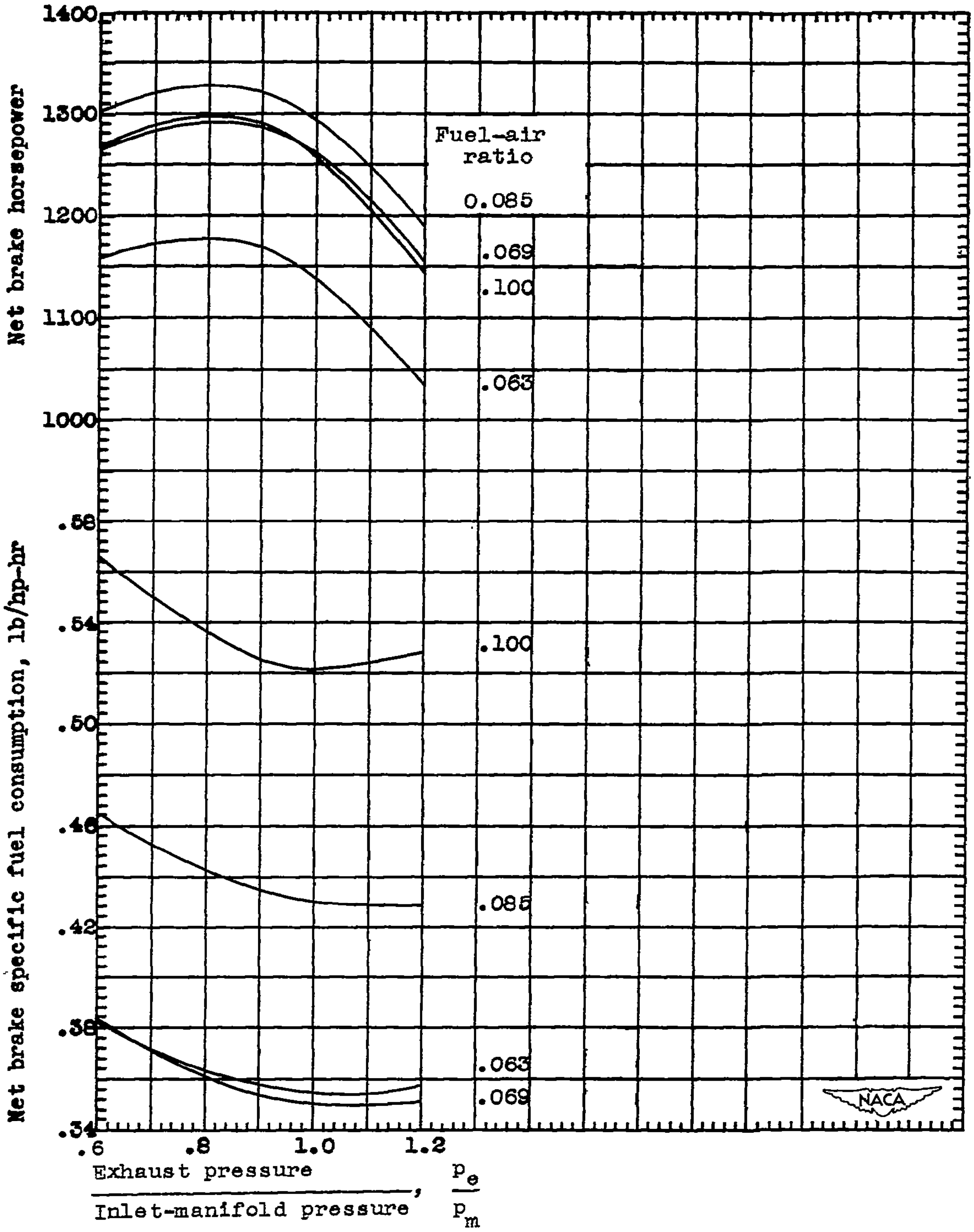


Figure 3. - Effect of p_e/p_m and fuel-air ratio on net brake horsepower and net brake specific fuel consumption. Engine speed, 2600 rpm; inlet-manifold pressure, 40 inches mercury absolute; altitude, 30,000 feet.

940

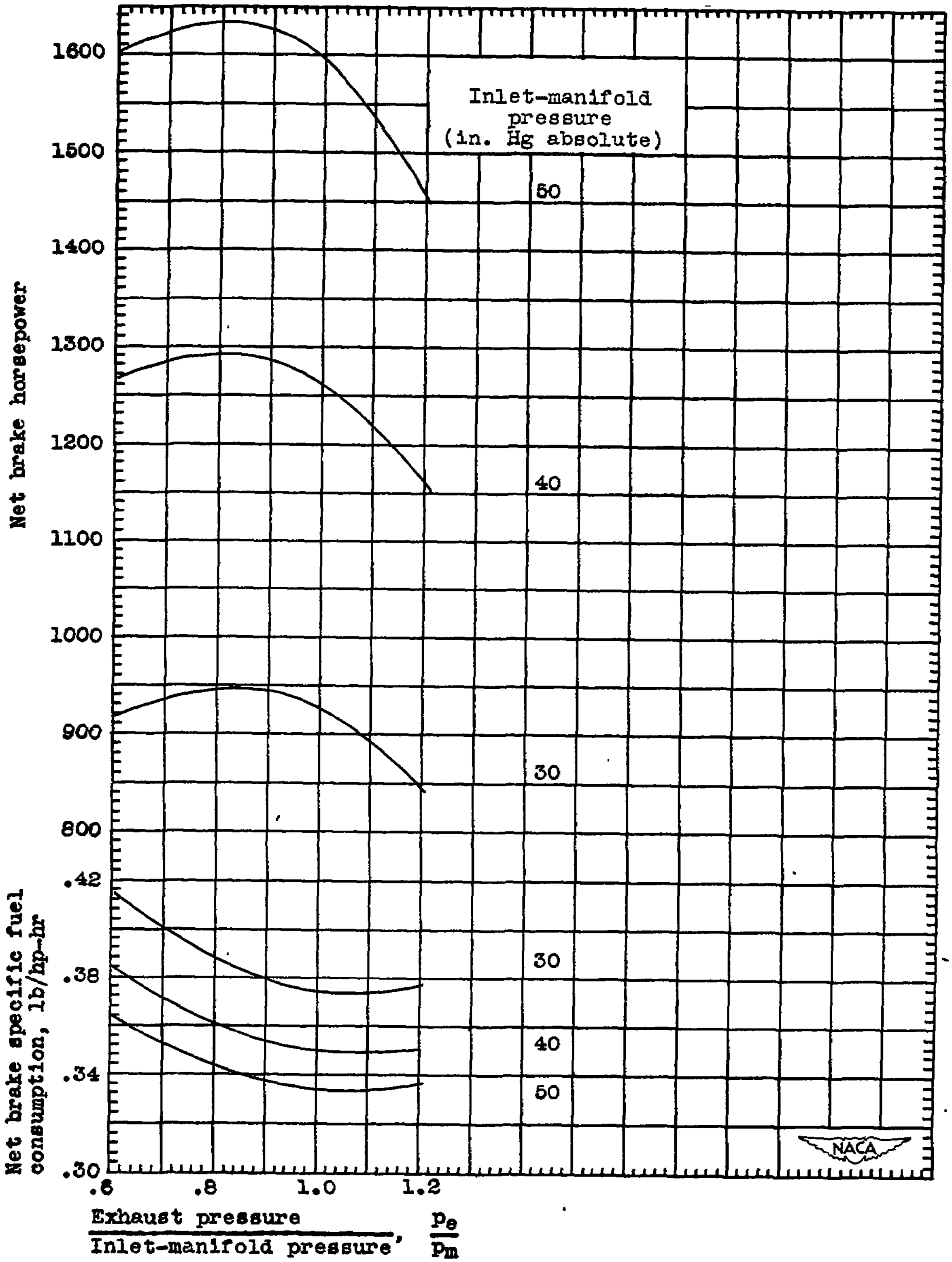


Figure 4. - Effect of p_e/p_m and inlet-manifold pressure on net brake horsepower and net brake specific fuel consumption. Engine speed, 2600 rpm; fuel-air ratio, 0.069; altitude, 30,000 feet.

940

940

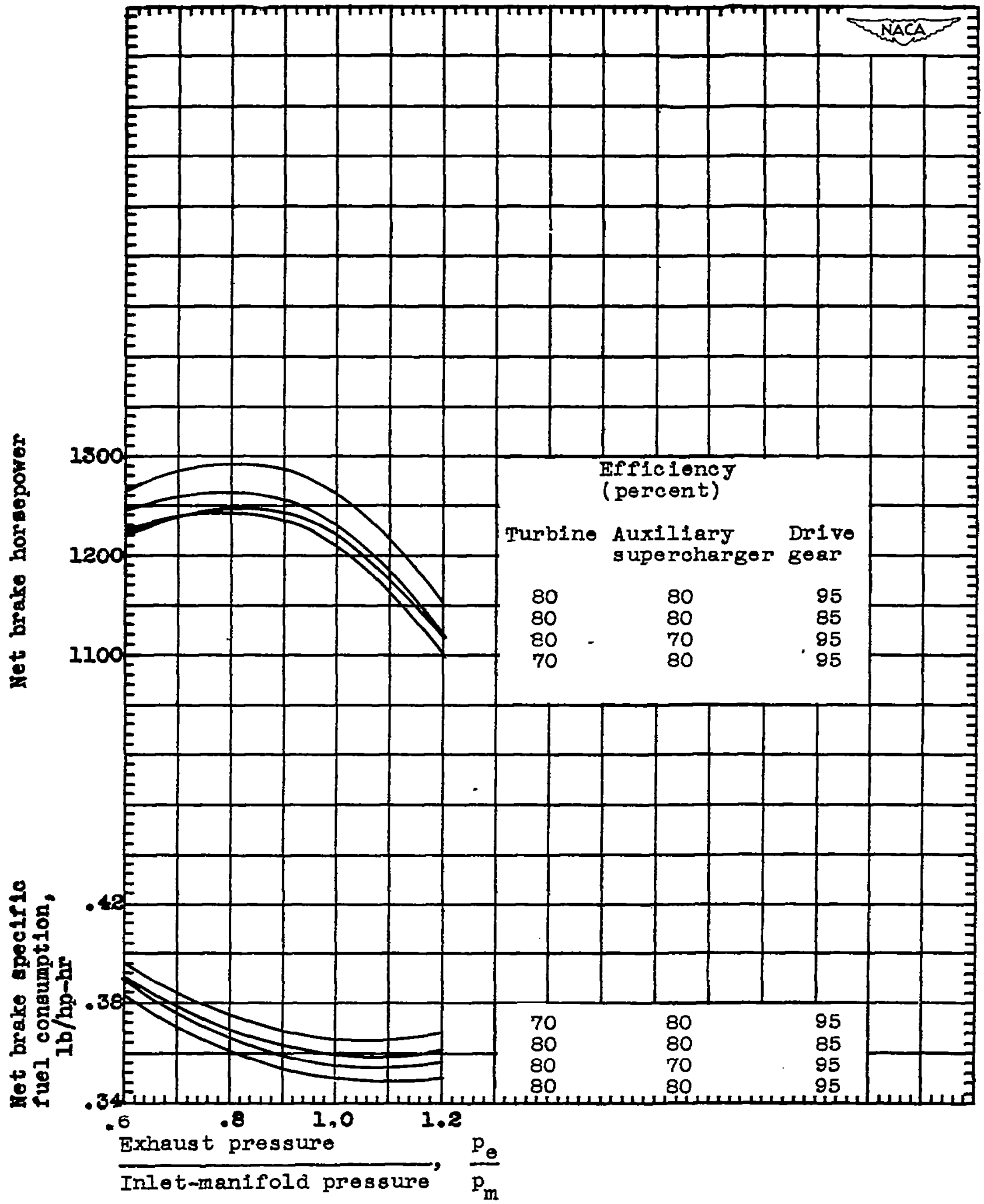


Figure 5. - Effect of p_e/p_m and component efficiency on net brake horsepower and net brake specific fuel consumption. Engine speed, 2600 rpm; fuel-air ratio, 0.069; inlet-manifold pressure, 40 inches mercury absolute; altitude, 30,000 feet.

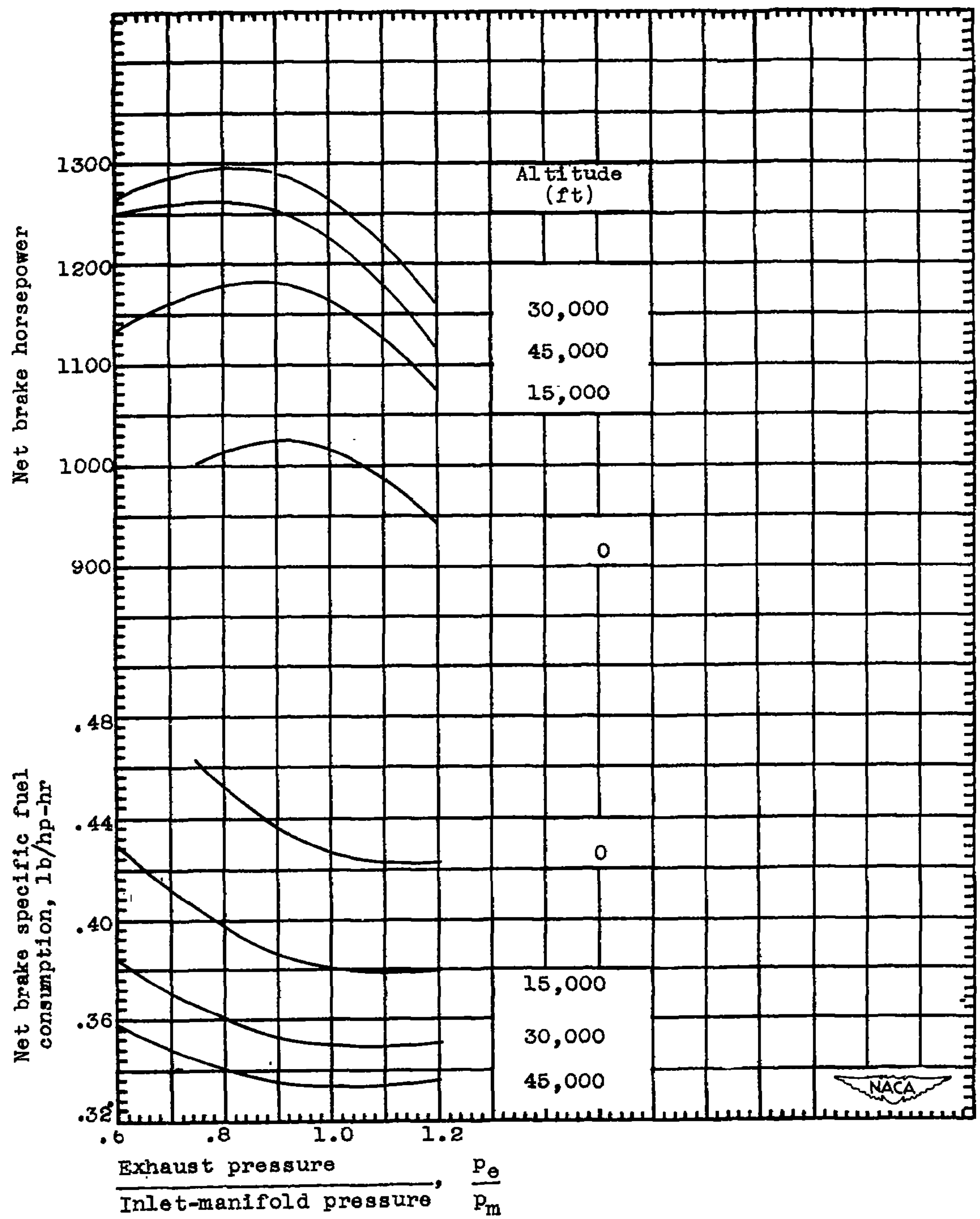


Figure 6. - Effect of p_e/p_m and altitude on net brake horsepower and net brake specific fuel consumption. Engine speed, 2600 rpm; fuel-air ratio, 0.069; inlet-manifold pressure, 40 inches mercury absolute.

940

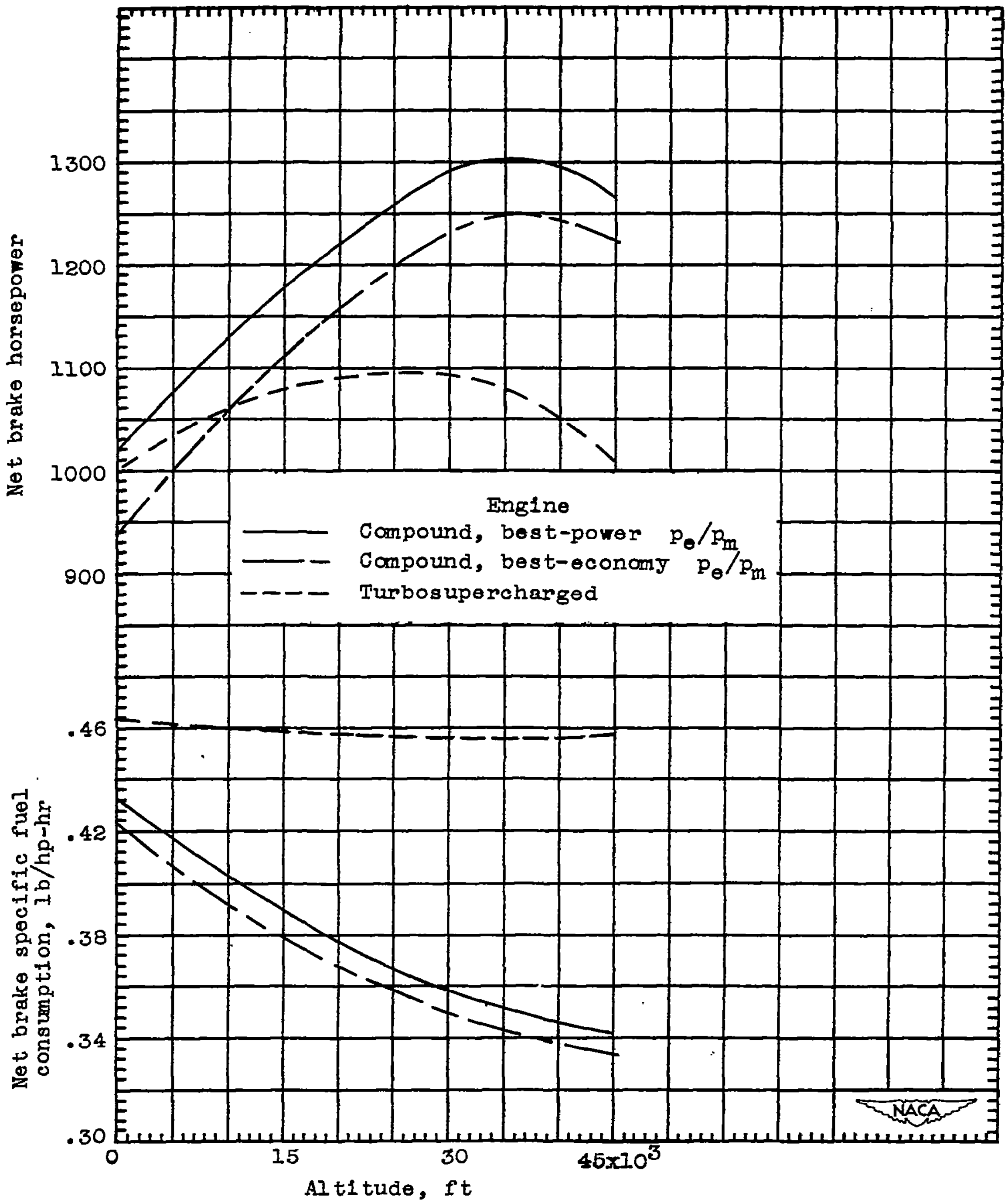


Figure 7. - Effect of altitude on net brake performance of compound and turbosupercharged engines. Engine speed, 2600 rpm; fuel-air ratio, 0.069; inlet-manifold pressure, 40 inches mercury absolute.

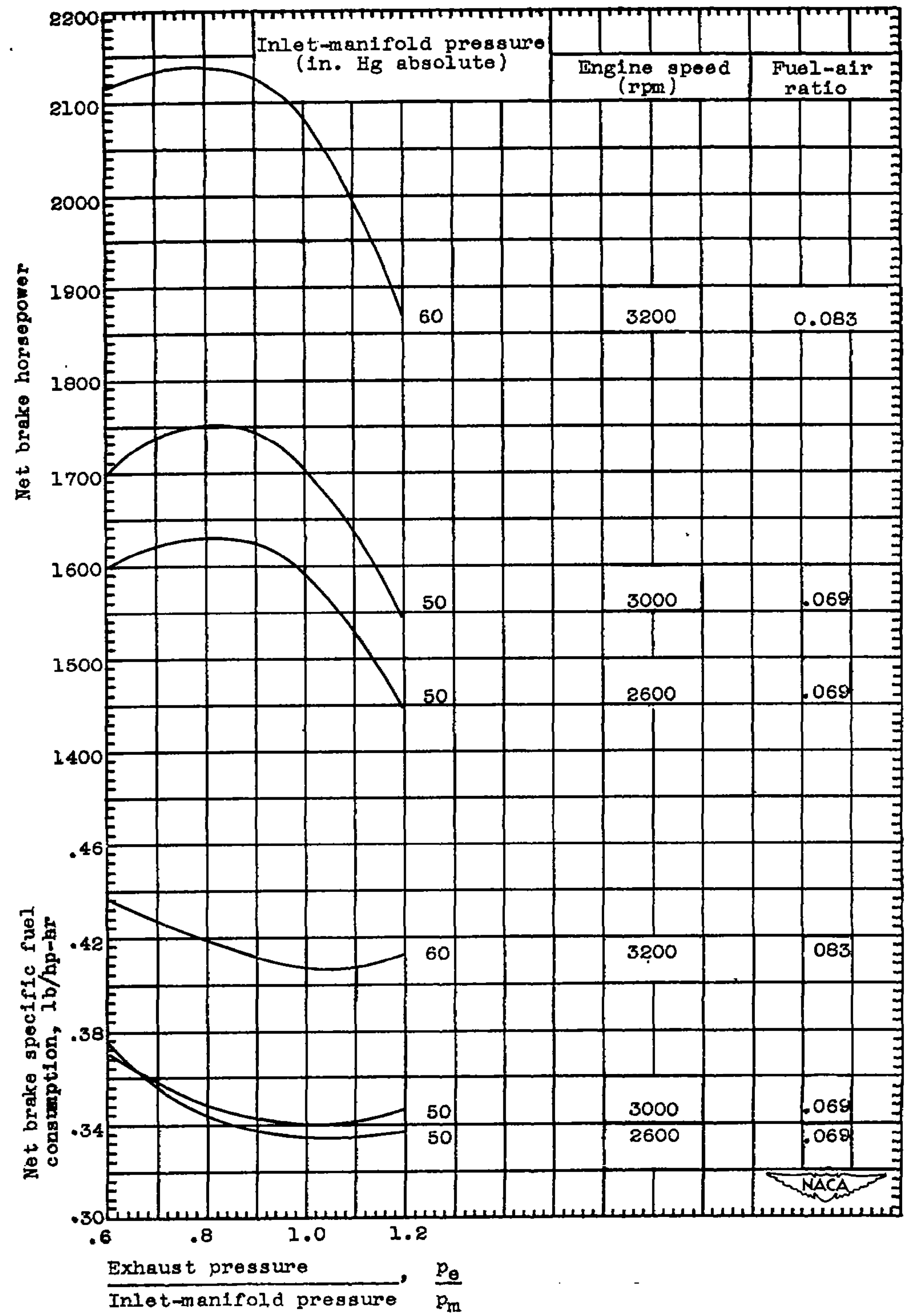


Figure 8. - Effect of p_e/p_m on high-power performance. Altitude, 30,000 feet.

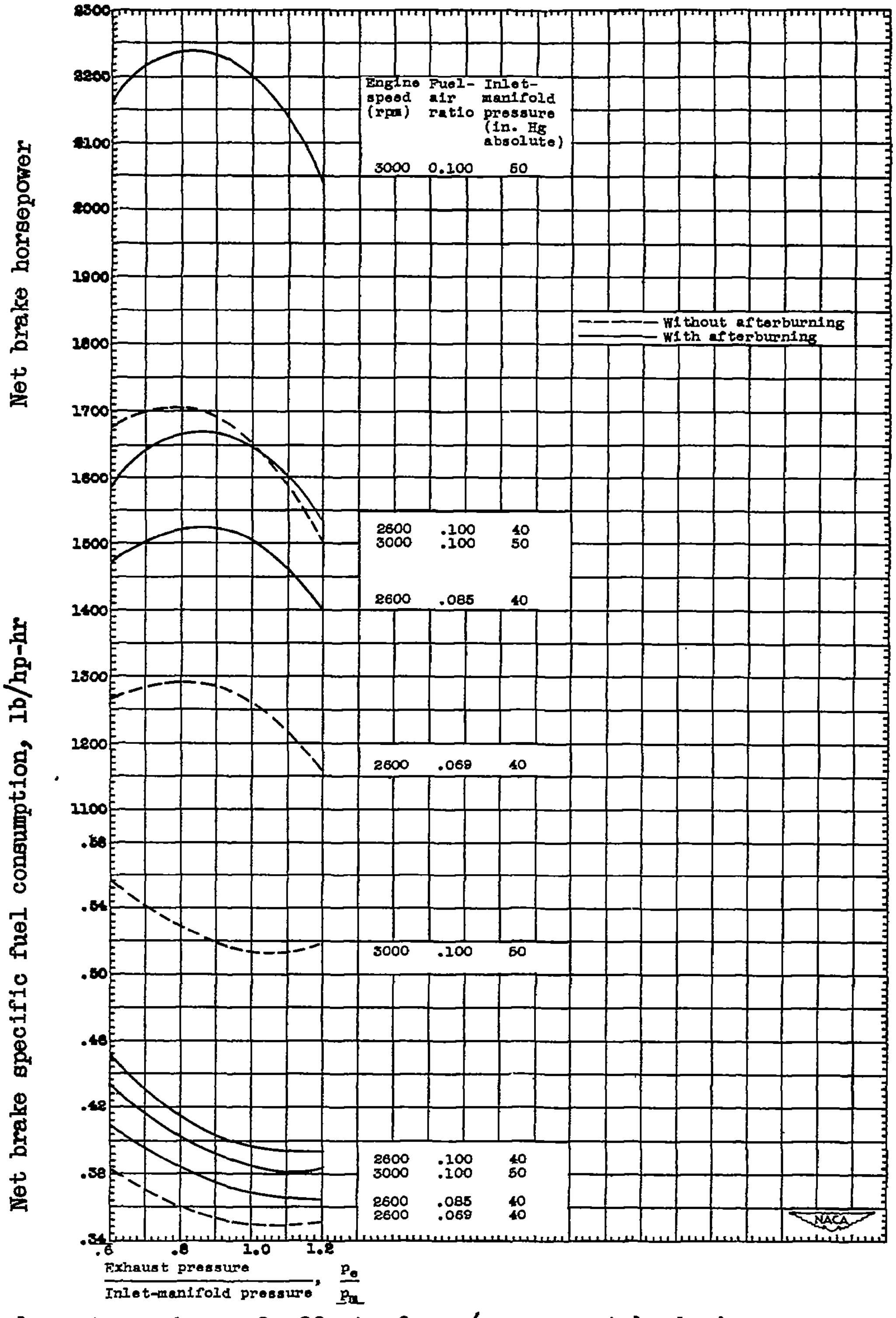
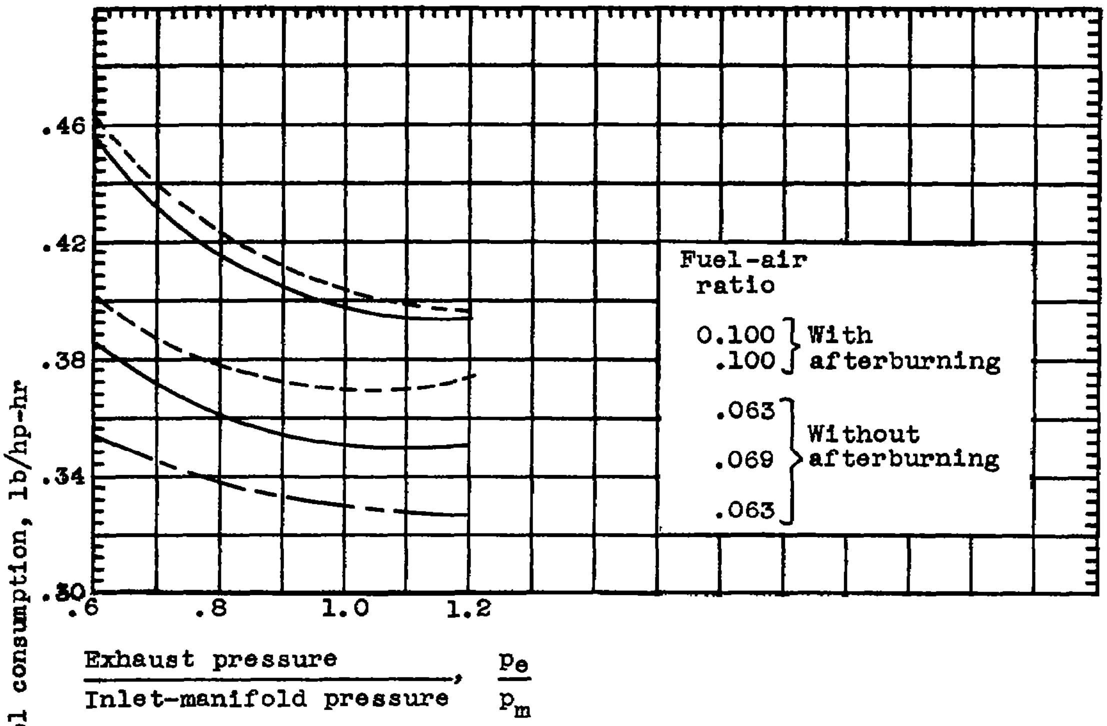
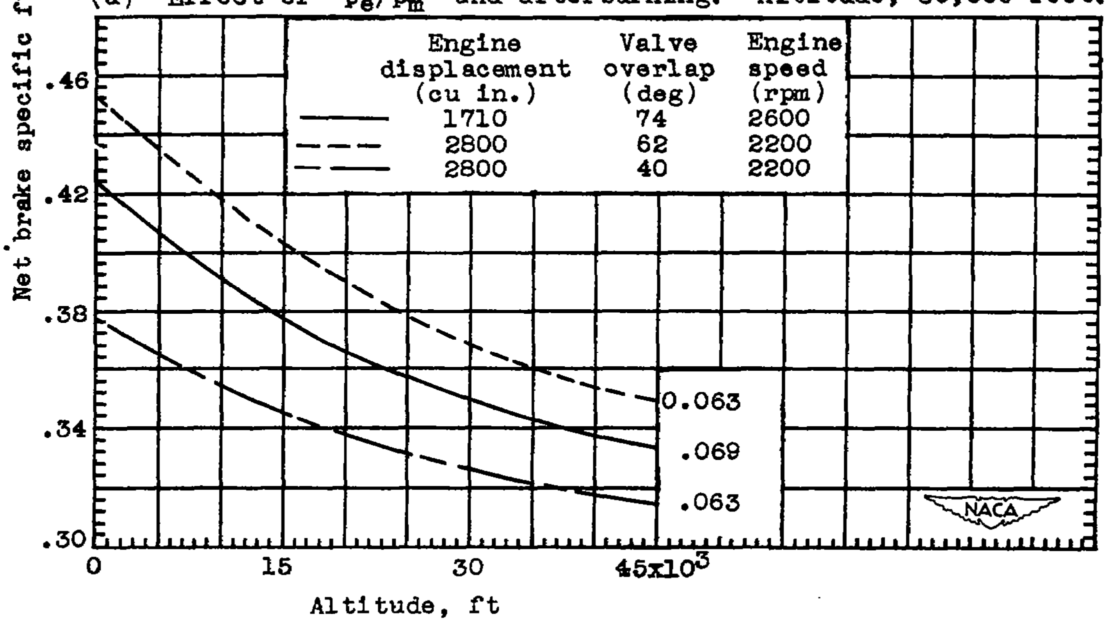


Figure 9. - Comparison of effect of p_e/p_m on net brake horsepower and net brake specific fuel consumption with and without afterburning at several engine conditions. Altitude, 30,000 feet.



(a) Effect of p_e/p_m and afterburning. Altitude, 30,000 feet.



(b) Effect of altitude at best-economy p_e/p_m.

Figure 10. - Effect of p_e/p_m, altitude, and afterburning on 1710-cubic-inch-displacement engine system and two models of the 2800-cubic-inch-displacement engine system. Inlet-manifold pressure, 40 inches mercury absolute; turbine and auxiliary supercharger efficiencies, 80 percent; drive-gear efficiency, 95 percent.

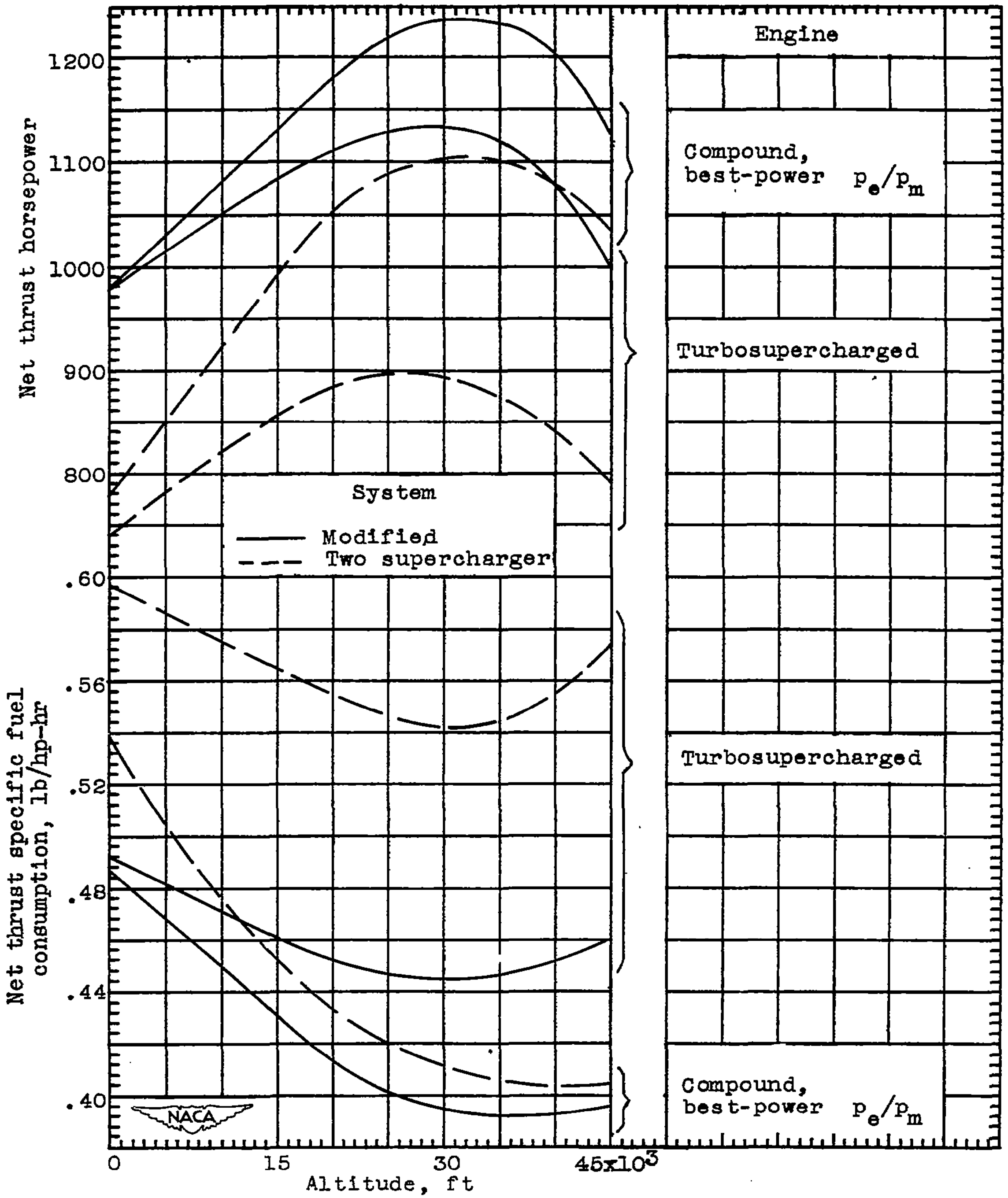


Figure 11. - Effect of altitude on net thrust performance of compound and turbosupercharged engines for modified and two-supercharger systems. Engine speed, 2600 rpm; fuel-air ratio, 0.069; inlet-manifold pressure, 40 inches mercury absolute; propeller efficiency, 85 percent; airplane speed, 400 miles per hour.