NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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COMPARISON OF COMPUTED PERFORMANCE OF COMPOSITE POWER PLANTS USING 18-CYLINDER AIRCRAFT ENGINES WITH 62° AND 40° VALVE OVERLAP

By Samuel J. Kaufman, and David S. Boman

Flight Propulsion Research Laboratory
Cleveland, Ohio

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SUMMARY

Calculations based on experimental data for 18-cylinder, radial aircraft engines with different nominal valve overlaps (62° and 40°) were made to compare the performance of two composite power plants using these engines. The composite unit included, in addition to the engine, a steady-flow turbine and an auxiliary supercharger mounted on a common shaft and geared to the engine crankshaft.

The calculations indicated that, in general, the system using the engine with 40° valve overlap was slightly more efficient and provided more power at the optimum operating conditions than the system incorporating the engine with the 62° valve overlap when fuel was introduced by means of a carburetor.

INTRODUCTION

An investigation of the performance of composite-engine power plants is being conducted at the NACA Cleveland laboratory. As part of this program, investigations of the effect of exhaust pressure on engine performance were conducted on 18-cylinder, air-cooled, radial engines with valve overlaps of 62° and 40° and the results are reported in references 1 and 2, respectively. By use of the data for the 40° valve overlap engine, an analysis was made for a composite power plant (reference 3) consisting of a reciprocating engine from which the exhaust gas was discharged through a collector ring into a steady-flow turbine mounted on a common shaft with a supercharger and geared to the engine crankshaft. The results of this analysis showed that appreciable gains in power and decreases in specific fuel consumption were obtainable. In order to show the effect on fuel consumption and power that would be obtained with a composite engine having a larger valve overlap (62°), the present analysis, which is similar to that of reference 3, was made.

The effect of various engine operating conditions and altitudes on performance at constant component efficiencies was determined using the data for the 62°-valve-overlap engine. Representative curves using the data of the 40°-valve-overlap engine are shown for comparison. Calculations were also made to show the effect on performance of various constant component efficiencies as well as the effect of using a given turbine, the efficiency of which varied in the conventional manner with blade-to-jet speed ratio, which, in turn, varied with engine operating conditions.

The effect on net power and efficiency of a composite system operating at rich fuel-air ratios with afterburning (burning to completion of unburned products of exhaust gas) is also presented. The system employs the addition of sufficient supercharged altitude air to the engine exhaust gas ahead of the turbine for afterburning and cooling of the gases to allowable turbine-inlet temperatures.

This analysis is based on the results of an investigation of a conventional reciprocating engine and therefore does not necessarily represent the best possible performance obtainable by this method of compounding; the analysis gives, however, an indication of what can be expected from current engines if used in composite power-plant installations.

METHODS

Calculations were made for a system consisting of an 18-cylinder, air-cooled, radial engine with a steady-flow turbine and an auxiliary supercharger so mounted on a common shaft and geared to the engine crankshaft that the turbine power in excess of that necessary for supercharging is available to the engine crankshaft. The net brake horsepower and the net brake specific fuel consumption of the system were computed for ranges of engine speed, inlet-manifold pressure, exhaust pressure, fuel-air ratio, and altitude.

If the turbine horsepower is greater than the auxiliary supercharger horsepower, the net brake horsepower nbhp is

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

where

bhp reciprocating-engine brake horsepower

shp auxiliary-supercharger horsepower

thp turbine horsepower

η_g gear efficiency

If the auxiliary-supercharger horsepower is greater than the turbine horsepower, the net brake horsepower is

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

The net brake specific fuel consumption was obtained by dividing the engine fuel flow by the net brake horsepower.

The reciprocating-engine data used for the two composite power plants discussed were obtained from references 1 and 2. Each engine has a single-stage, gear-driven supercharger. Fuel was introduced by means of a carburetor for each of these engines. As previously stated, the principal difference between the engines is the valve overlap; however, some of the other pertinent engine specifications are listed for comparison:

	Valve overlap, deg	
	40 (reference 1)	62 (reference 2)
Compression ratio	6.65	6.75
Blower gear ratio	7.6:1	7.29:1
Impeller diameter, in.	11	11.5
Propeller reduction-gear ratio	0.50:1	0.45:1
Spark advance, deg B.T.C.	25	20
Valve timing, deg		
Intake opens, B.T.C.	20	36
Intake closes, A.B.C.	76	60
Exhaust opens, B.B.C.	76	70
Exhaust closes, A.T.C.	20	26

The turbine power was that obtained by expansion of the exhaust gas from engine exhaust pressure and temperature for the specific engine operating condition to altitude pressure. The auxiliary-supercharger power was that necessary to compress the air from altitude pressure to carburetor top-deck pressure with allowances for duct losses. An intercooler having a constant effectiveness of 50 percent was assumed to be located between the auxiliary and the engine-stage superchargers.

In general, the auxiliary supercharger and the turbine were assumed to have constant efficiencies of 80 percent and the gears an efficiency of 95 percent. Additional calculations were made to show the effect of change in the value of these efficiencies on net power and net brake specific fuel consumption.

The foregoing assumption of constant turbine and supercharger efficiencies implies that a different turbine and supercharger are used at each operating point. The use of a turbine and a supercharger designed to meet the specified requirements at one operating point would, of course, mean that any change from that point would cause a change in turbine and supercharger efficiencies. In order to show how the net performance of the composite system using the 62°-valve-overlap engine would be affected when the turbine characteristics are included, a turbine having a fixed nozzle area and a definite efficiency curve was assumed and computations were made for various engine operating conditions. The effective nozzle area (17 sq in.) for this turbine was calculated to give an exhaust-to-inlet-manifold pressure ratio p_e/p_m of 0.8 at the following operating conditions:

Altitude, ft	30,000
Fuel-air ratio	0.063
Engine speed, rpm	2200
Inlet-manifold pressure, in. Hg absolute	40

The gears between the engine and the turbine were assumed to have a constant speed ratio such that at an engine speed of 2600 rpm the turbine would have a pitch-line velocity of 1000 feet per second. The auxiliary supercharger was assumed to have a constant efficiency of 80 percent for these computations.

For operation at the higher power levels where rich fuel-air mixtures are required, a considerable amount of energy can theoretically be made available to the turbine by supplying sufficient air to burn the excess fuel in the engine exhaust gas. In this process, enough extra air can be added to cool the gases to a temperature suitable for the turbine. By use of the charts of reference 4, computations were made that show the effect of afterburning and subsequent cooling of the exhaust gas to 1800° F on net performance. An additional compressor having an efficiency of 80 percent was assumed to compress the secondary air to engine exhaust pressure. All the resultant gas (at 1800° F) was passed through the turbine. As previously, the difference between the turbine and the compressor powers was available to the engine crankshaft.

RESULTS AND DISCUSSION

Reciprocating-Engine Component

The reciprocating-engine brake power is the largest component of composite-engine power. Curves of brake horsepower for the 62°- and 40°-valve-overlap engines are presented in figure 1. At the lower values of p_e/p_m and a fuel-air ratio of 0.085, the 62°-valve-overlap engine develops more brake power than the 40°-valve-overlap engine; however, the 62°-valve-overlap engine is more sensitive to changes in exhaust pressure and provides less power than the 40°-valve-overlap engine at the higher exhaust pressure. The difference between the brake power of the two engines at the lower values of p_e/p_m tends to decrease as the speed is increased. At a fuel-air ratio of 0.063, the 62°-valve-overlap engine yields considerably less power than the 40°-valve-overlap engine over the entire range of p_e/p_m.

Composite Engine

Exhaust pressure. - The performance of the composite system is represented herein by net brake horsepower and net brake specific fuel consumption. The effects of inlet-manifold pressure, engine speed, fuel-air ratio, and altitude on the performance of a composite engine using the 62°-valve-overlap engine are shown in figures 2 to 5. Curves for the 40°-valve-overlap engine are included for comparison. In each of these figures, the dimensionless ratio of p_e/p_m is used as the abscissa; therefore, the effect of exhaust pressure on performance is included with that of each of the other variables.

The effect of exhaust pressure on performance is approximately the same for all inlet-manifold pressures, engine speeds, fuel-air ratios, and altitudes. In general, as can be seen in figures 2 to 5, which will be discussed in greater detail with respect to the other variables, the minimum net brake specific fuel consumption occurs at higher values of p_e/p_m than the maximum net brake horsepower. The net brake horsepower is close to the maximum value when p_e/p_m is 0.8 for the 62°-valve-overlap engine and 1.0 for the 40°-valve-overlap engine. The brake specific fuel consumption is close to its minimum when p_e/p_m is 1.0 for both engines. For values of p_e/p_m greater than 0.8, the net brake horsepower for the 62°-valve-overlap engine decreases faster with increasing p_e/p_m than the net power for the 40°-valve-overlap engine.

Inlet-manifold pressure. - The effect of inlet-manifold pressure on net brake horsepower and specific fuel consumption is shown in figure 2. The curves are for an engine speed of 2200 rpm (shown subsequently to be the most efficient), a constant fuel-air ratio of 0.085, and an NACA standard altitude of 30,000 feet. The net brake horsepower increases and the net brake specific fuel consumption decreases as the inlet-manifold pressure is increased. The fuel consumption is approximately 0.02 pound per horsepower-hour lower for the 40°-valve-overlap engine than for the 62°-valve-overlap engine at a p_e/p_m near 0.8.

Fuel-air ratio. - The effect of fuel-air ratio on performance with an engine speed of 2200 rpm, a constant inlet-manifold pressure of 40 inches of mercury absolute, and an NACA standard altitude of 30,000 feet is shown in figure 3. The lowest fuel consumption is obtained at a fuel-air ratio of approximately 0.063. For the 62°-valve-overlap engine at a value of p_e/p_m of 0.8, a change in fuel-air ratio from 0.063 to 0.069 increases the fuel consumption about 2 percent; however, the brake power increases about 8 percent. As the fuel-air ratio is further increased, the fuel consumption increases quite rapidly. A cross plot of the net power with fuel-air ratio shows that the power reaches a maximum, as would be expected, at a fuel-air ratio of about 0.08. The conclusion may be drawn from inspection of figures 2 and 3, that maximum efficiency of the system will be obtained at the highest permissible manifold pressure at a fuel-air ratio near stoichiometric. The 40°-valve-overlap engine yields as much or more power but at a lower specific fuel consumption than the 62°-valve-overlap engine for the conditions shown.

Engine speed. - The effect of engine speed on performance is shown in figure 4 for an inlet-manifold pressure of 40 inches of mercury absolute, a fuel-air ratio of 0.063, and an NACA standard altitude of 30,000 feet. The net brake horsepower is seen to increase with engine speed; the specific fuel consumption, however, is lowest at an engine speed of approximately 2200 rpm for the 62°-valve-overlap engine. For the conditions shown, the 62°-valve-overlap engine provides less net brake power at higher brake specific fuel consumption than the 40°-valve-overlap engine. The brake specific fuel consumption of the 62°-valve-overlap engine is affected more by changes in speed than that of the 40° engine.

Altitude. - The effect of altitude on performance is shown in figure 5 for the 62°-valve-overlap engine. These curves are for the most efficient engine speed and fuel-air ratio, 2200 rpm and 0.063, respectively, (figs. 3 and 4) and for an inlet-manifold pressure of 40 inches of mercury absolute, which is close to the knock-limited value for these conditions. Included in this figure along with the net brake horsepower for the system are the turbine, auxiliary-supercharger, and engine powers. For altitudes from sea level to 30,000 feet, the net brake horsepower increases as the altitude increases. Above approximately 30,000 feet, the net brake horsepower decreases as the altitude increases. This effect is caused by the condition that exists within the troposphere where cooling air at constant temperature flows through a constant effectiveness intercooler while the charge-air temperature increases as the supercharger pressure ratio increases (that is, altitude increases). The net brake specific fuel consumption decreases as the altitude increases for the entire range considered. As the altitude increases, the value of p_e/p_m at which the minimum brake specific fuel consumption occurs decreases from 1.1 at sea level to 1.0 at 45,000 feet.

The operating points at which turbine power equals supercharger power are shown in figure 5 by the intersection of the turbine-power and auxiliary-supercharger-power curves. At this value of p_e/p_m, the composite power plant operates as a turbosupercharged installation with closed waste gate. This condition is shown by the dashed line on the net brake specific fuel consumption curves and by the cross plots presented in figure 6 where the effect of altitude on the performance of the composite and the turbosupercharged power plants is given. The calculations for the turbosupercharged installation apply to a turbine operating with closed waste gate at a pressure ratio that permits the turbine to supply exactly enough power to do all the necessary auxiliary supercharging. As the altitude increases, the composite power plant yields progressively higher power and lower fuel consumption than the turbosupercharged power plant. At an altitude of 30,000 feet, 21 percent lower net brake specific fuel consumption and about 19 percent higher net brake horsepower can be realized with the composite power plant than with the turbosupercharged installation.

A comparison of composite power plants utilizing the 62°- and the 40°-valve-overlap engine is shown in figure 7 wherein performance at various altitudes is plotted against p_e/p_m. The curves for the 62°-valve-overlap engine were replotted from figure 5. The performance of the 40°-valve-overlap power plant is better at all altitudes; for example, at an altitude of 30,000 feet and at a value of p_e/p_m of 0.8, the net brake horsepower is 8 percent higher and the net brake specific fuel consumption is 11 percent lower for the 40° valve overlap power plant.

The maximum power and minimum fuel consumption for any altitude occur at lower values of p_e/p_m for the 62°-valve-overlap engine than for the 40°-valve-overlap engine.

Component efficiencies. - The effect of component efficiencies (turbine, auxiliary supercharger, and gears) on the performance of the 62°-valve-overlap composite engine is shown in figure 8. At a value of p_e/p_m of 0.8, a reduction in turbine efficiency of 10 percentage points causes a decrease in net brake power and an increase in net brake specific fuel consumption of about 4 percent; whereas a reduction of 10 points in auxiliary-supercharger efficiency causes an increase of about 2 percent in net brake specific fuel consumption and a decrease of 4 percent in net brake horsepower. A reduction of 10 points in gear efficiency causes a loss in net brake horsepower and an increase in net brake specific fuel consumption of about 2.5 percent.

Effect of Turbine Characteristics

The variation of turbine efficiency with blade-to-jet speed ratio shown in figure 9 was used in the calculations of the performance of the composite engine having a turbine with fixed nozzle area and gear ratio. The resulting variation of turbine efficiency and power (and attendant change in composite-engine performance) with engine speed, inlet-manifold pressure, fuel-air ratio, altitude, and an assumed temperature drop of the exhaust gas in the ducting before the turbine is shown in figure 10. Within the practical range of engine operating conditions, the turbine efficiency varied less than 10 percentage points from the maximum value, except with altitude, in which case the turbine efficiency varied from 60 percent at sea level to about 80 percent at 15,000 feet and then decreased to about 65 percent at 45,000 feet. (See fig. 10(d).) Assumption of a constant turbine efficiency of 80 percent gave 2.5 percent more net brake horsepower but 1.5 percent higher net brake specific fuel consumption at sea level because of the accompanying change in p_e/p_m. At an altitude of 30,000 feet, however, where a decrease of 7 percentage points in turbine efficiency is indicated with no change in p_e/p_m, a decrease in net brake horsepower and an increase in net brake specific fuel consumption of about 3 percent results.

Performance with Afterburning

The performance of a composite power plant with the 62°-valve-overlap engine operating at the higher power levels and at the necessarily richer (higher than stoichiometric) fuel-air ratios with the addition of enough air to the exhaust gas before the turbine to promote complete afterburning and subsequent cooling to allowable turbine-inlet temperatures (1800° F) is shown in figure 11. For the conditions shown, the additional air, which is heated by the combustion of the excess fuel in the exhaust gas, increases the turbine power far in excess of the amount of compressor power absorbed in compressing the added air. For an engine operating at an engine speed of 2200 rpm, an inlet-manifold pressure of 50 inches of mercury absolute, a fuel-air ratio of 0.100, and an altitude of 30,000 feet, a maximum net brake horsepower of 2940 is indicated with a net brake specific fuel consumption of 0.407 pound per brake horsepower-hour for a value of p_e/p_m of 0.8. Increasing the ratio of p_e/p_m to 1.22 gives a minimum brake specific fuel consumption of 0.387 pound per brake horsepower-hour with a net brake horsepower of 2615.

For the same engine operating conditions, increasing the engine speed to 2600 rpm indicates a maximum net power of 3350 brake horsepower at a p_e/p_m of 0.8 with a net brake specific fuel consumption of 0.410 or an increase of 14 percent in power with an increase of only 0.7 percent in net brake specific fuel consumption.

A comparison of specific fuel consumption and power with and without afterburning at an engine speed of 2200 rpm, an inlet-manifold pressure of 50 inches of mercury absolute, a fuel-air ratio of 0.100, and an altitude of 30,000 feet is shown in figure 12. Included in this figure is the performance of the composite power plant for an inlet-manifold pressure of 40 inches of mercury absolute and a fuel-air ratio of 0.063; this condition gives approximately the lowest net brake specific fuel consumption. For the same engine condition, utilizing the energy of the exhaust gas by afterburning permits an increase of 34 percent in net brake horsepower and a decrease of 25 percent in net brake specific fuel consumption at a value of p_e/p_m of 0.8. Figure 12 also indicates that operation at high power with afterburning provides 81 percent more net power with an increase of only about 7.5 percent in net brake specific fuel consumption as compared with the previously defined most efficient operating condition (engine speed, 2200 rpm; inlet-manifold pressure, 40 in. Hg absolute; fuel-air ratio, 0.063). This increase in net power is caused by the increase in turbine power due to the increased gas flow through the turbine.

SUMMARY OF RESULTS

An analysis based on experimental data for 18-cylinder, radial aircraft engines with different nominal valve overlaps (62° and 40°) and with the fuel introduced by means of a carburetor was made to compare the performance of composite power plants using each of these engines with a steady-flow turbine. The results show that:

1. The performance of the 40°-valve-overlap composite power plant was better at all altitudes than the 62°-valve-overlap power plant. At an NACA standard altitude of 30,000 feet and a ratio of exhaust to inlet-manifold pressure of 0.8, the net brake power was about 8 percent higher and the net brake specific fuel consumption was about 11 percent lower for the 40°-valve-overlap engine as compared with the 62°-valve-overlap engine.

2. The net brake horsepower was close to its maximum value when the exhaust to inlet-manifold pressure ratio was 0.8 for the 62°-valve-overlap composite engine and 1.0 for the 40°-valve-overlap composite engine. The brake specific fuel consumption was close to its minimum when the ratio of exhaust to inlet-manifold pressure was 1.0 for both composite engines.

3. The addition of air to the exhaust gas for afterburning and cooling to a final temperature of 1800° F before expanding through a turbine gave a theoretical increase of 34 percent in net power and a decrease of 25 percent in net brake specific fuel consumption at an engine speed of 2200 rpm, an inlet-manifold pressure of 50 inches of mercury absolute, a fuel-air ratio of 0.100, an altitude of 30,000 feet, and a ratio of exhaust to inlet-manifold pressure of 0.8.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 27, 1947.

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

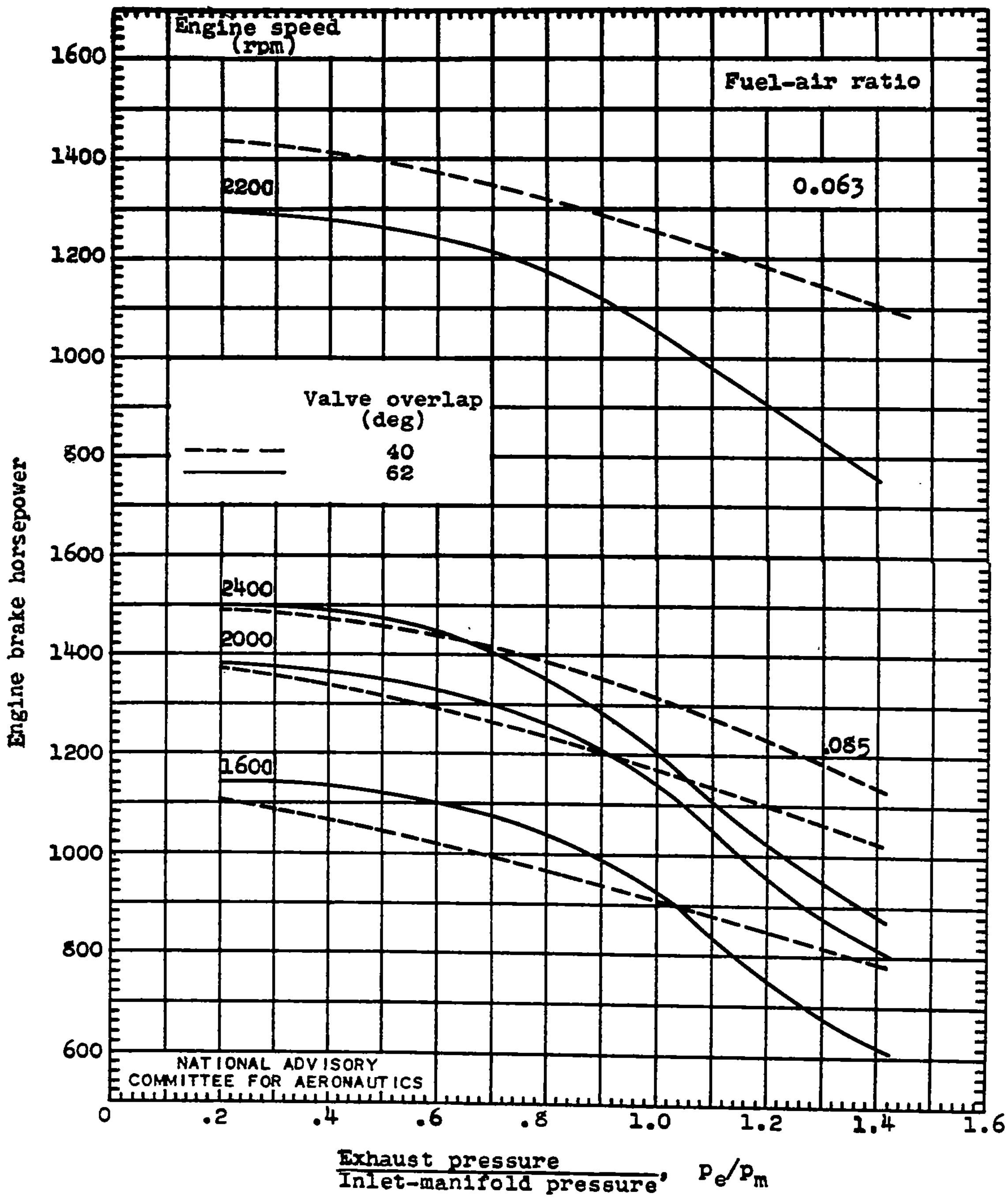


Figure 1. - Effect of p_e/p_m, engine speed, and fuel-air ratio on engine brake horsepower. Manifold pressure, 40 inches mercury absolute.

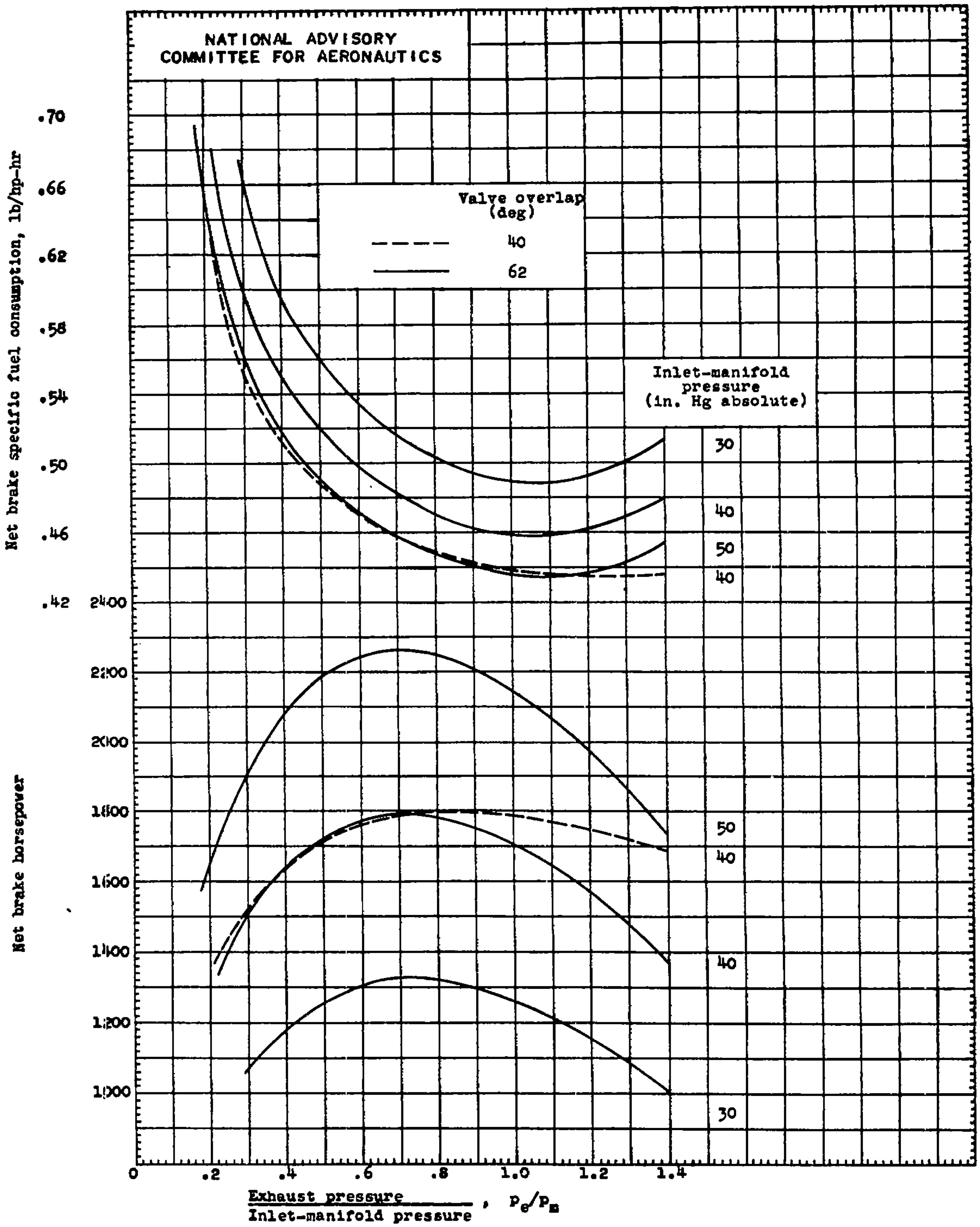


Figure 2. - Effect of p_e/p_m and inlet-manifold pressure on net brake horsepower and brake specific fuel consumption. Engine speed, 2200 rpm; fuel-air ratio, 0.085; NACA standard altitude, 30,000 feet.

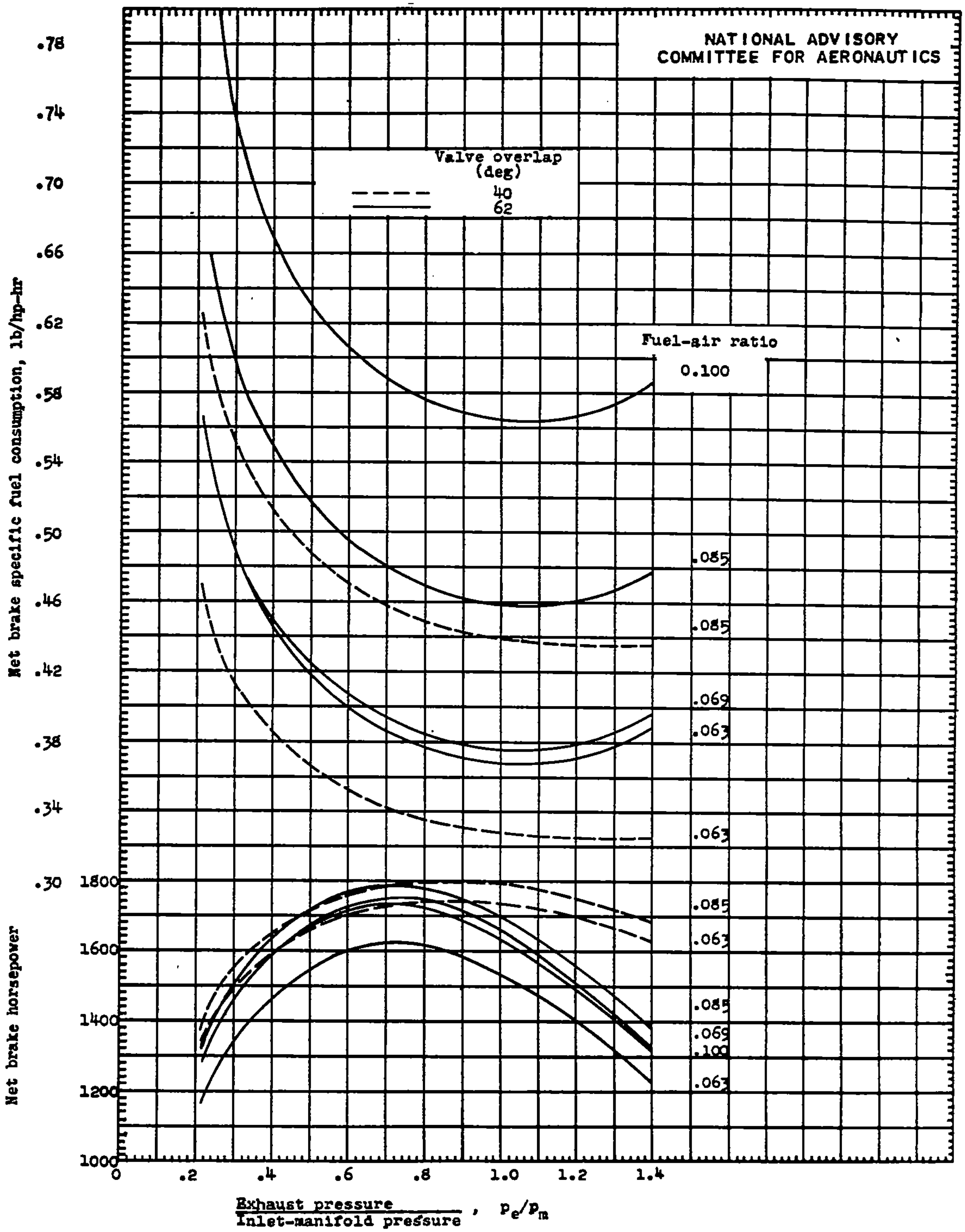


Figure 3. - Effect of p_e/p_m and fuel-air ratio on net brake horsepower and brake specific fuel consumption. Engine speed, 2200 rpm; inlet-manifold pressure, 40 inches mercury absolute; NACA standard altitude, 30,000 feet.

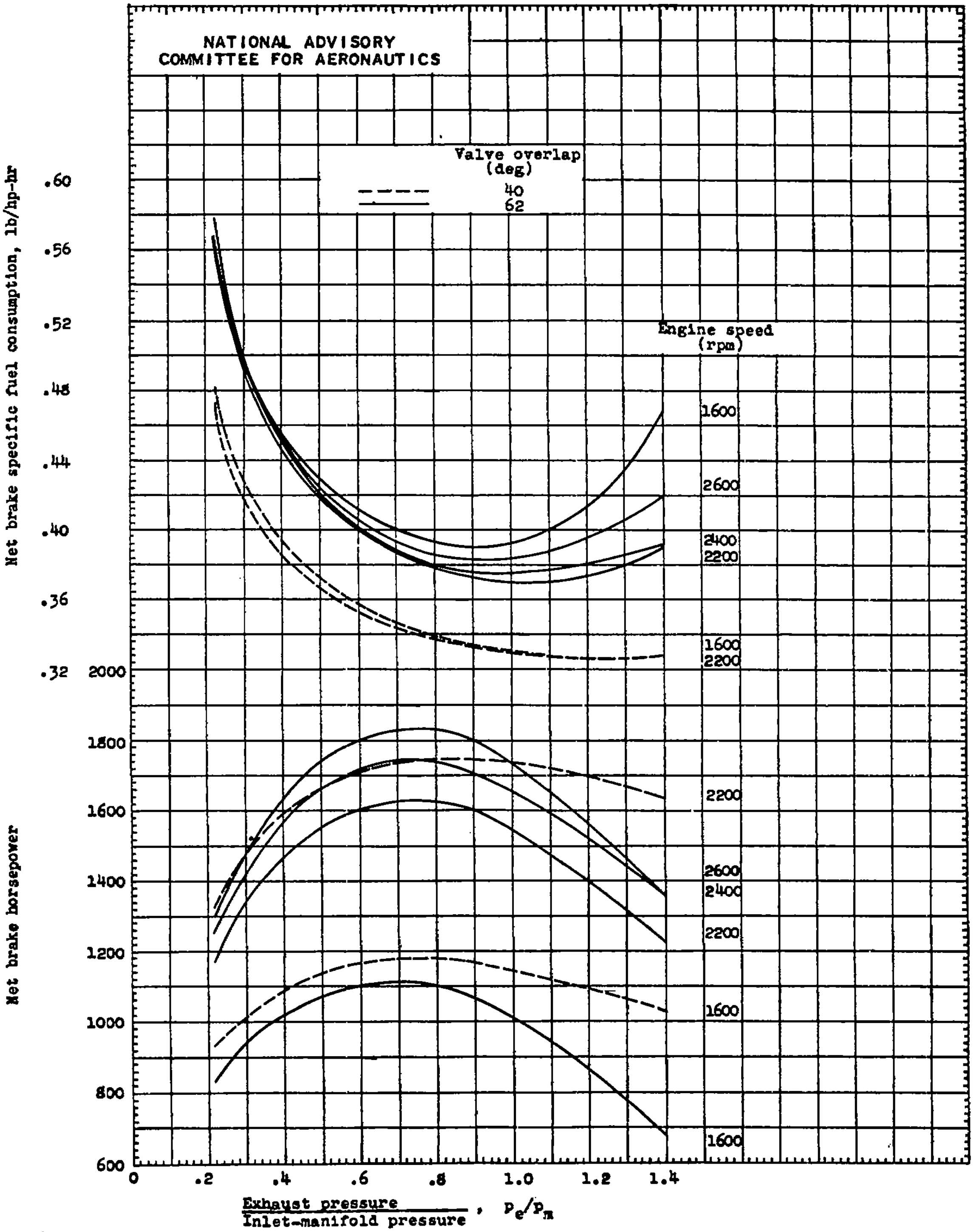


Figure 4. - Effect of p_e/p_m and engine speed on net brake horsepower and brake specific fuel consumption. Inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.063; NACA standard altitude, 30,000 feet.

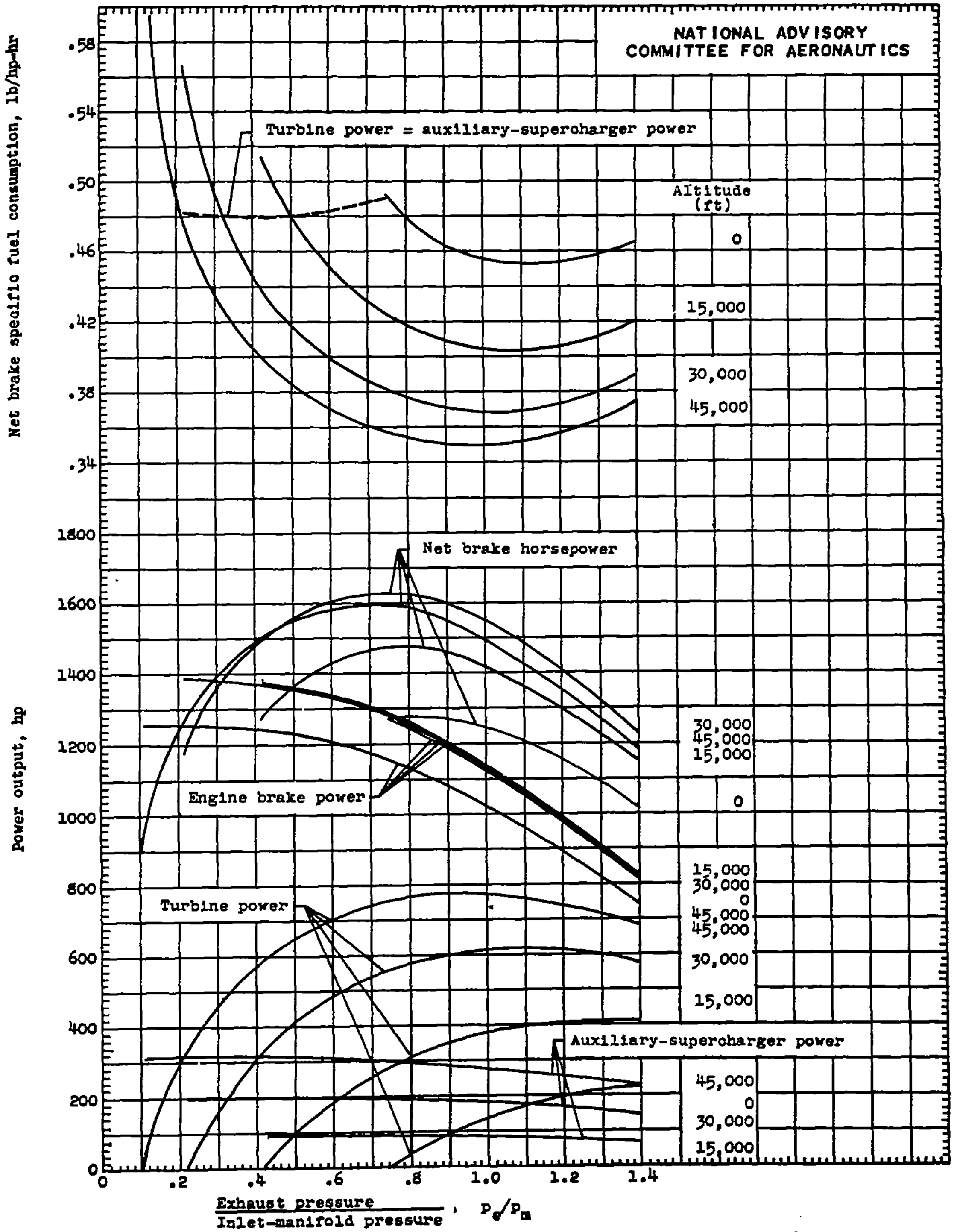


Figure 5. - Effect of p_e/p_m and altitude on performance of the composite engine and components. Valve overlap, 62°; engine speed, 2200 rpm; inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.063.

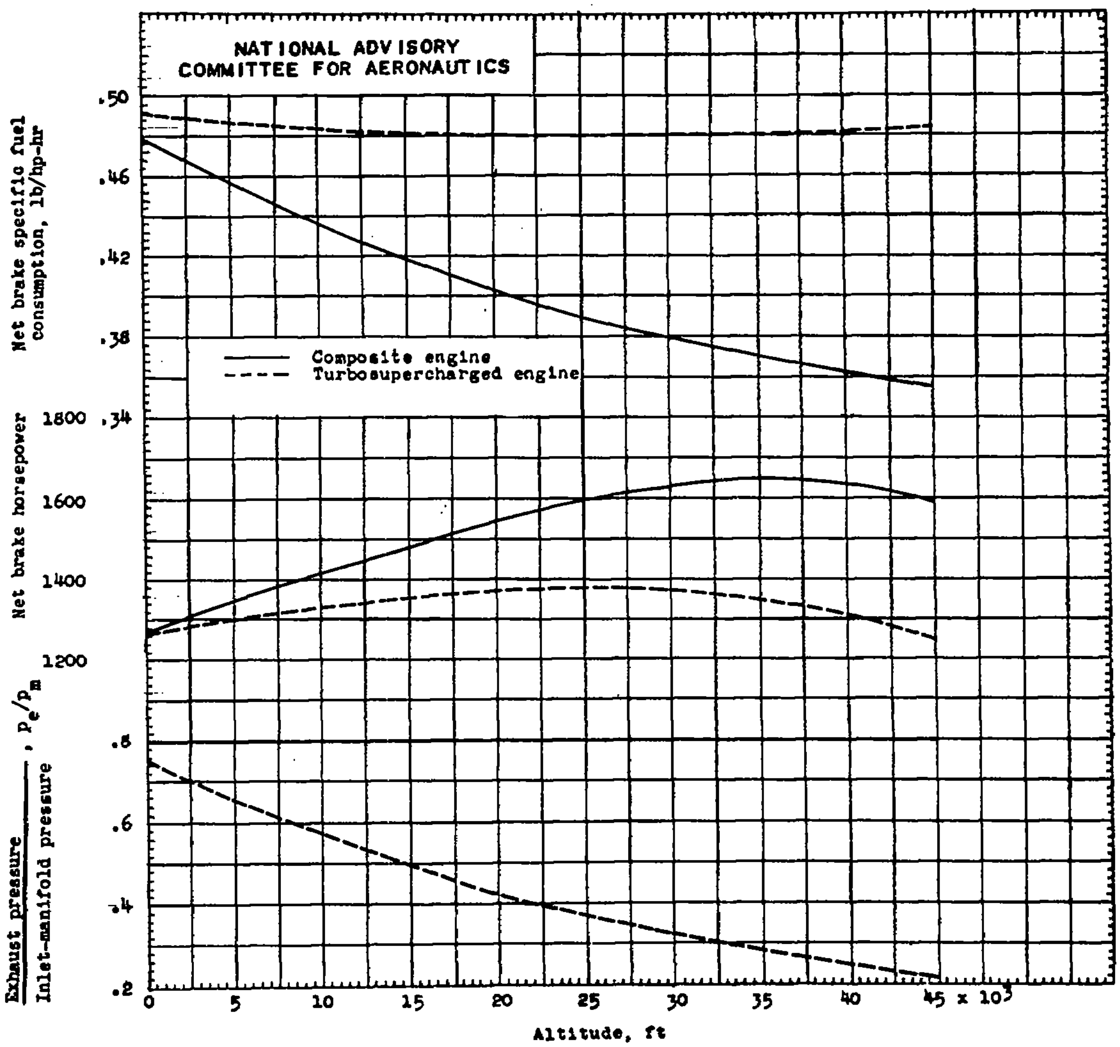


Figure 6. - Effect of altitude on performance of the composite engine and the turbosupercharged engine. Valve overlap, 62°; engine speed, 2200 rpm; inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.063. (Cross plot of fig. 5.)

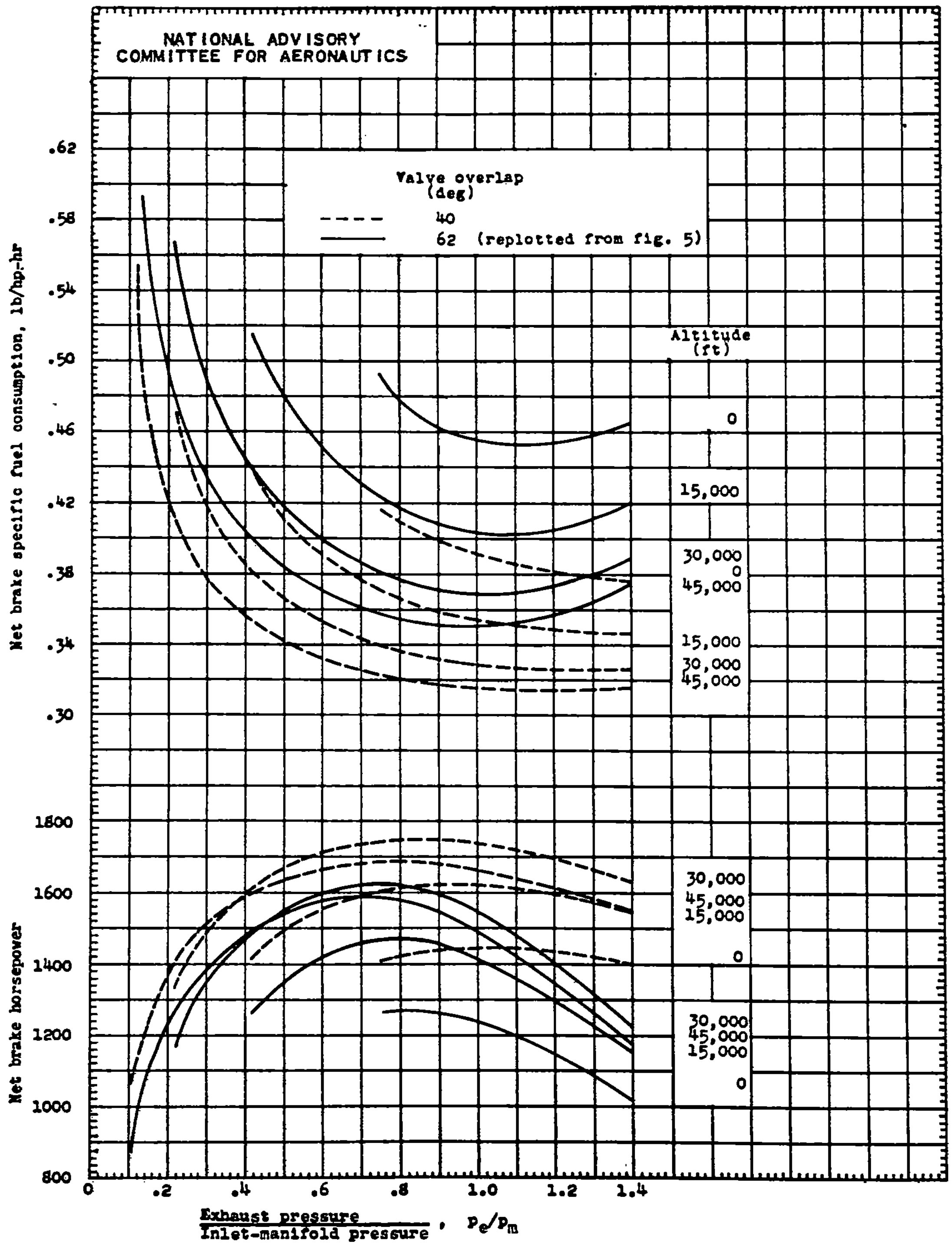


Figure 7. - Comparison of effect of p_e/p_m and altitude on net brake horsepower and brake specific fuel consumption for composite engine. Valve overlap, 40° and 62°; engine speed, 2200 rpm; inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.063.

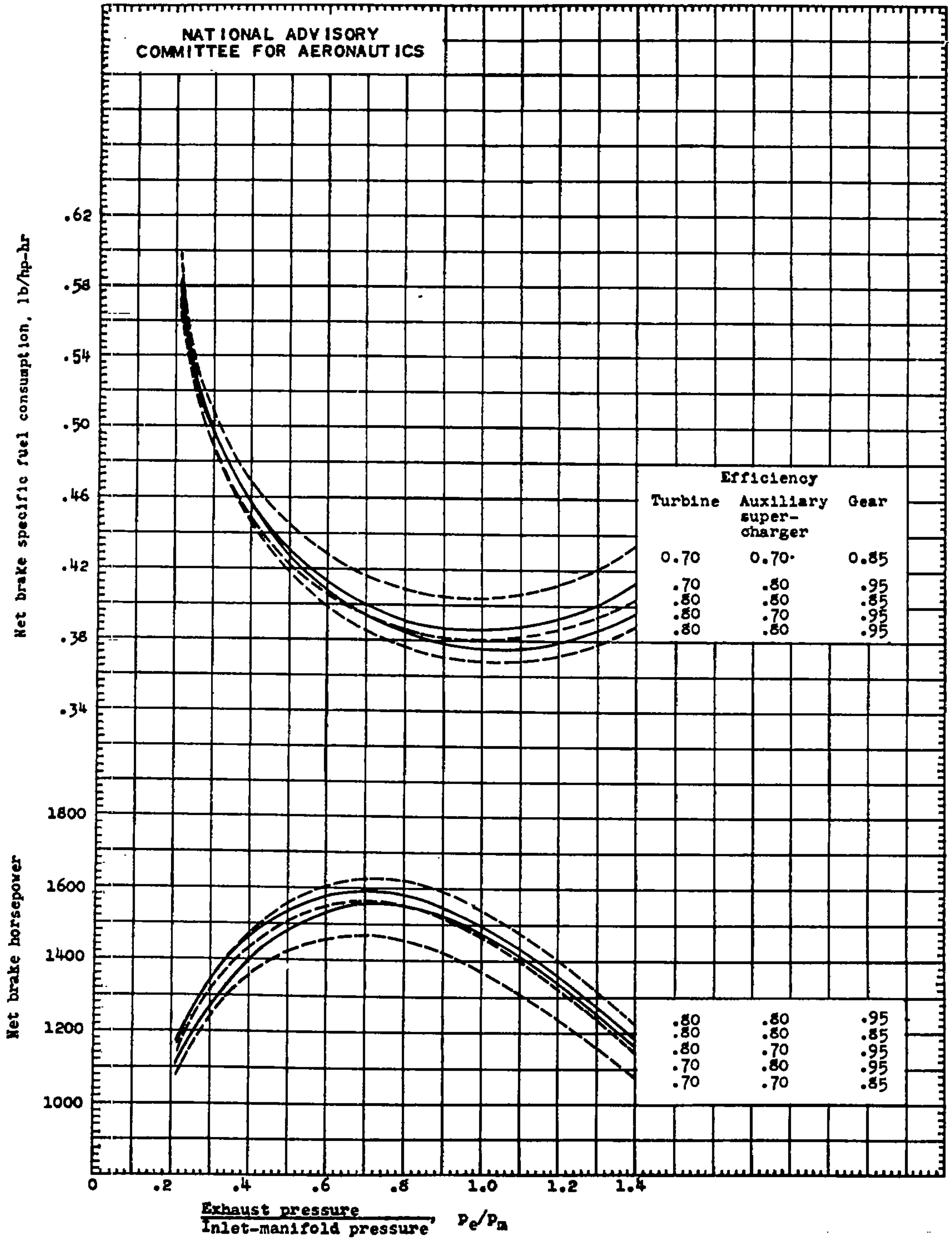


Figure 8. - Effect of p_e/p_m and component efficiencies on net brake horsepower and brake specific fuel consumption. Valve overlap, 62°; engine speed, 2200 rpm; inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.063; NACA standard altitude, 30,000 feet.

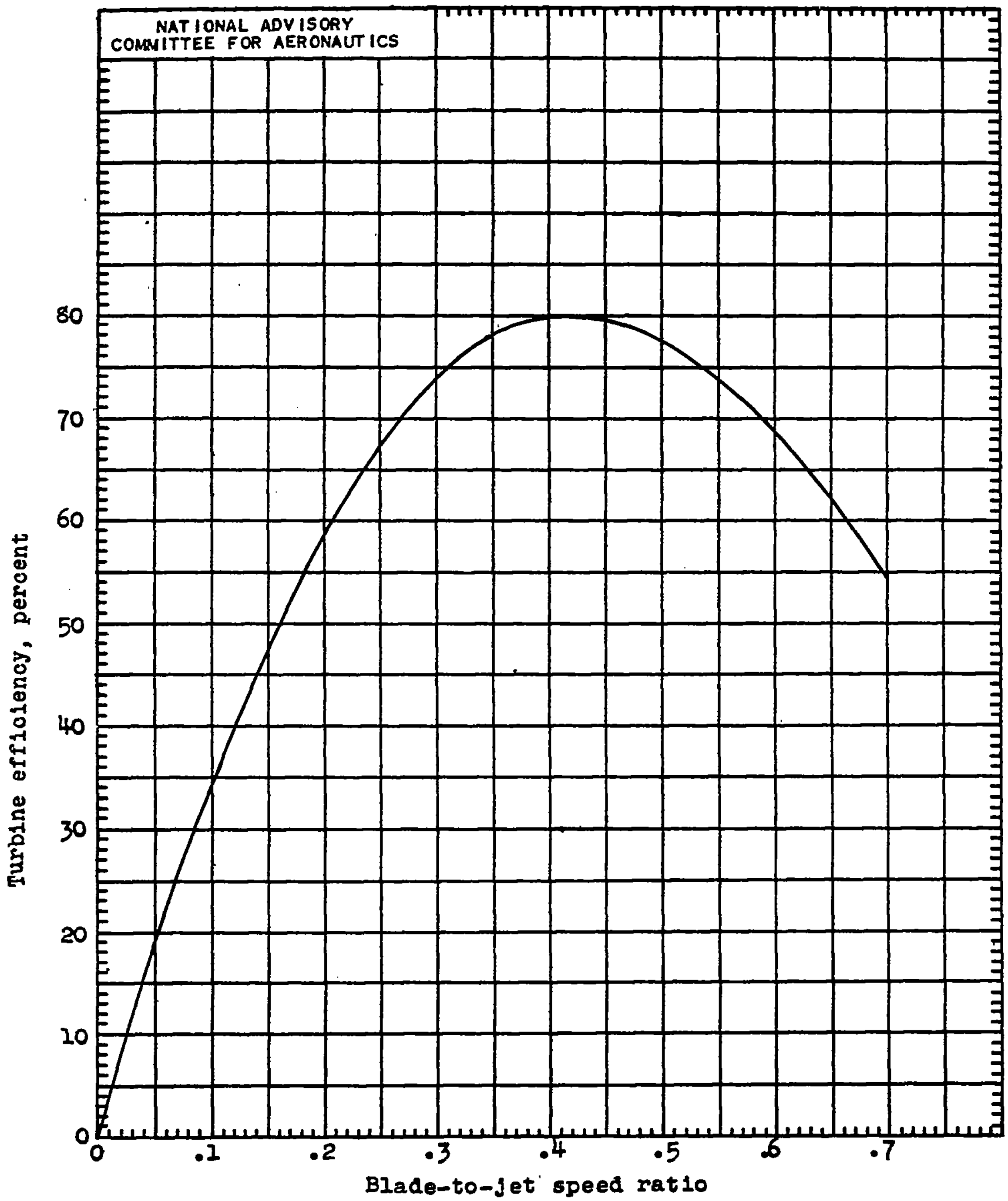
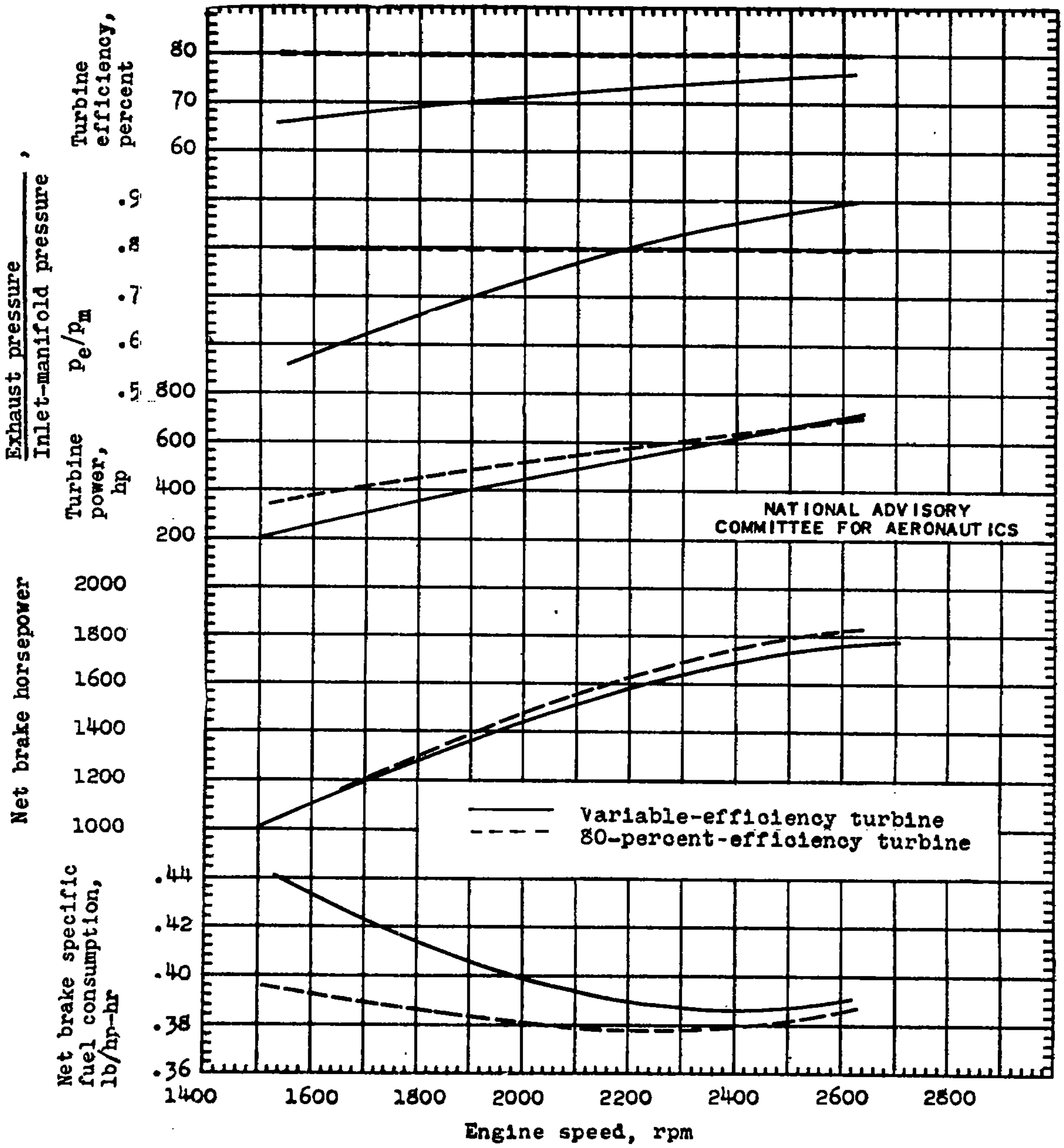
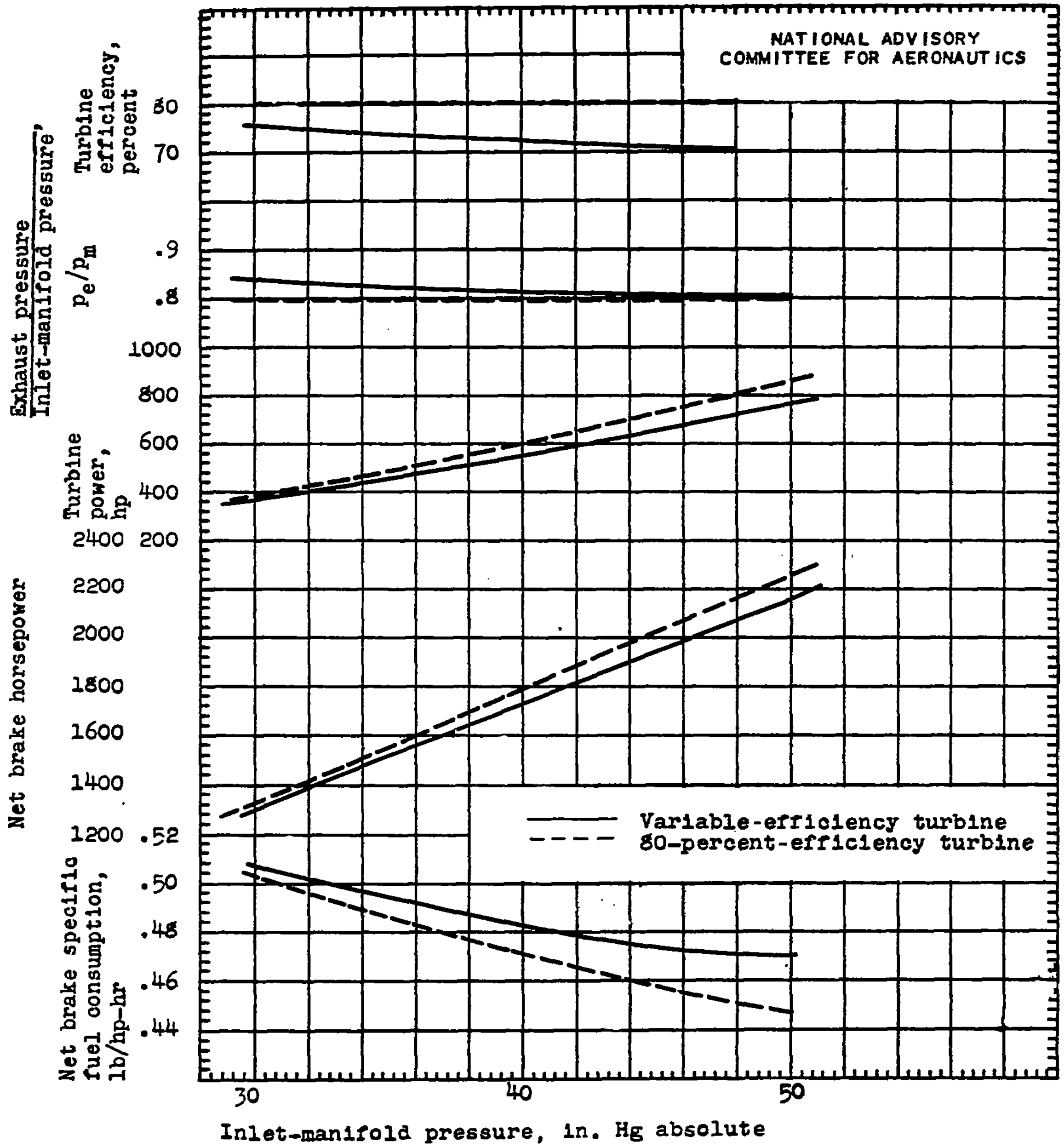


Figure 9. - Variation of turbine efficiency with blade-to-jet speed ratio.



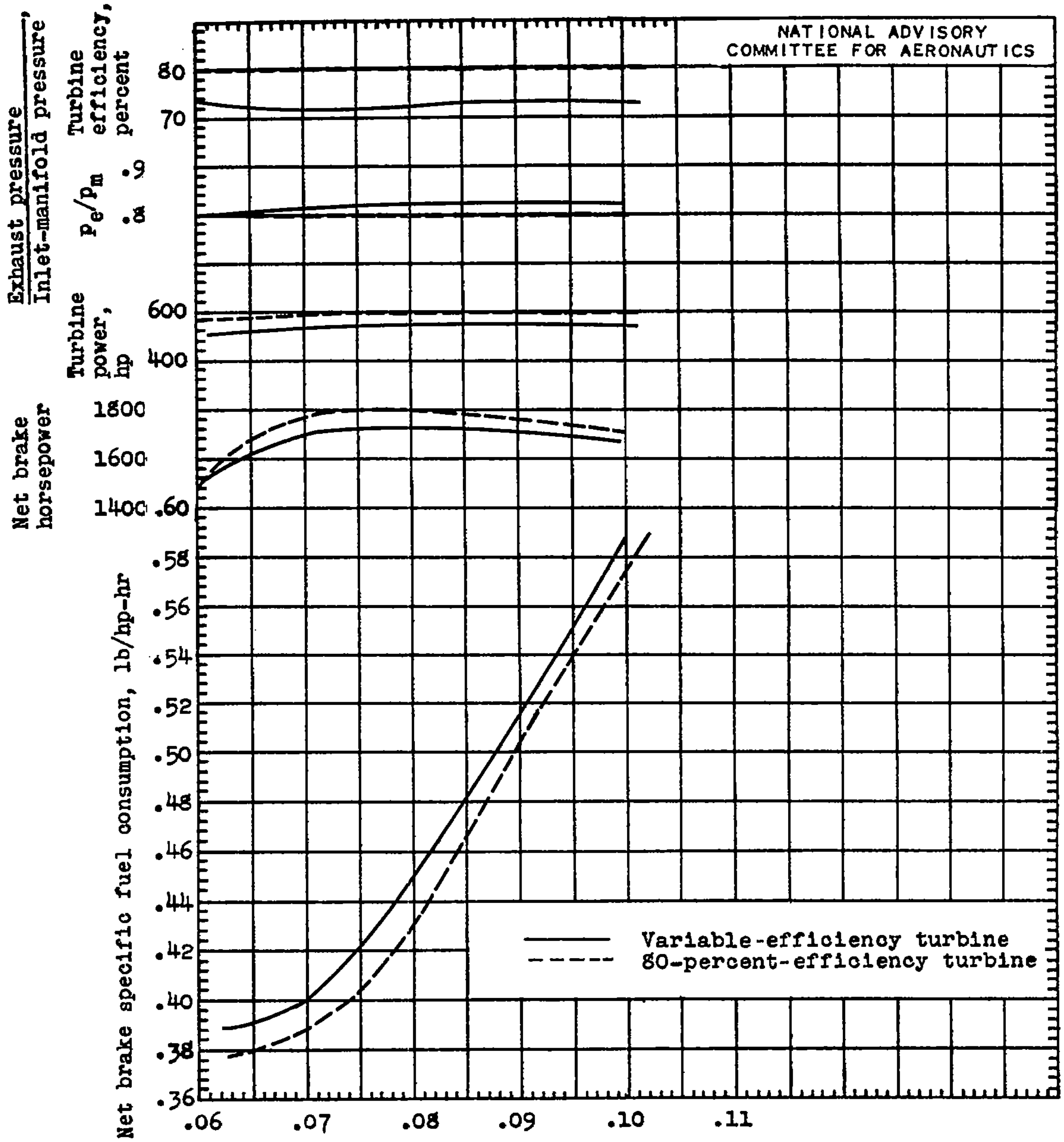
(a) Inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.063; NACA standard altitude, 30,000 feet.

Figure 10. - Comparison between composite engine using variable-efficiency turbine and composite engine using constant-efficiency turbine. Valve overlap, 62°.



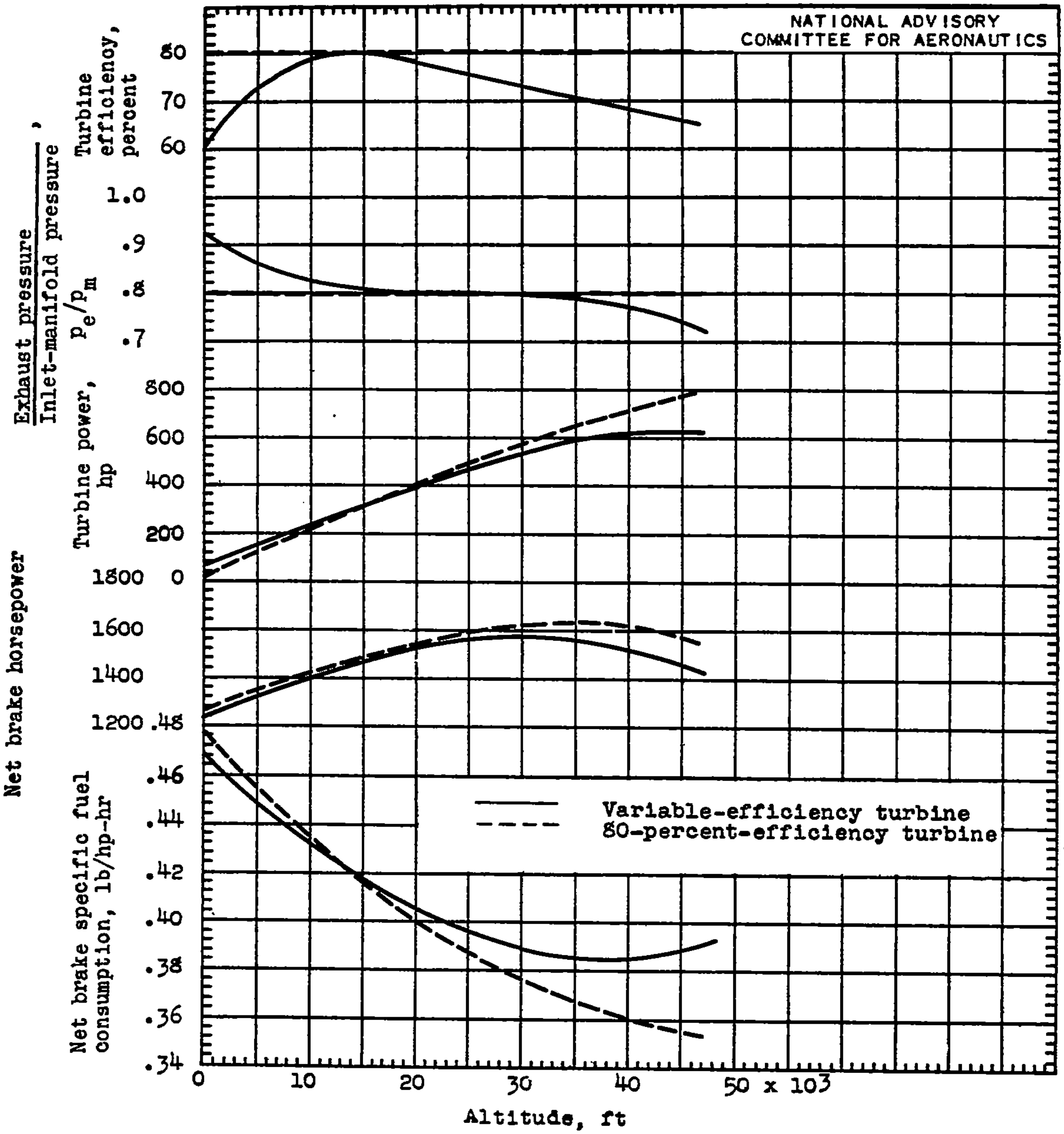
(b) Engine speed, 2200 rpm; fuel-air ratio, 0.085; NACA standard altitude, 30,000 feet.

Figure 10. - Continued. Comparison between composite engine using variable-efficiency turbine and composite engine using constant-efficiency turbine. Valve overlap, 62°.



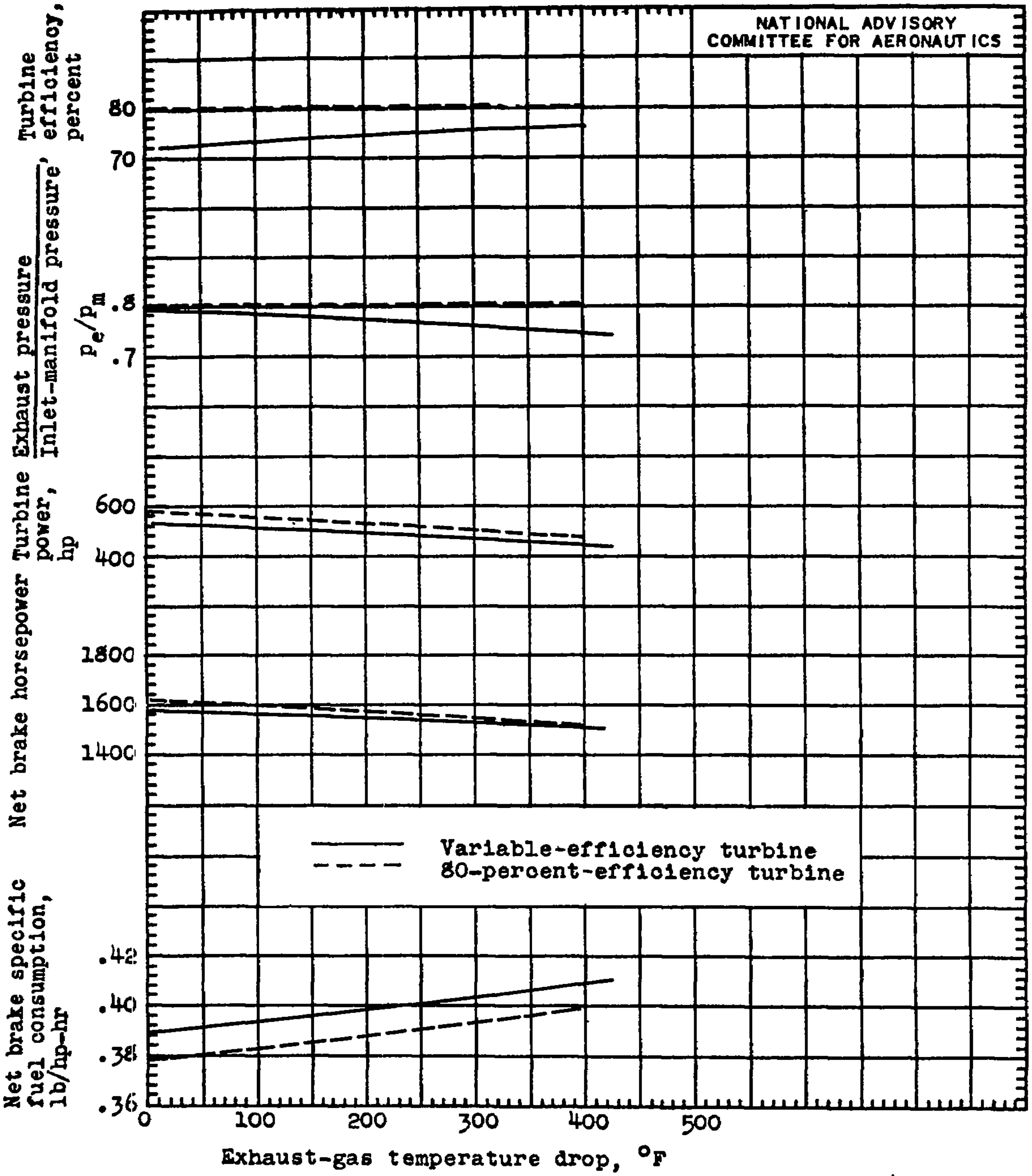
(c) Engine speed, 2200 rpm; inlet-manifold pressure, 40 inches mercury absolute; NACA standard altitude, 30,000 feet.

Figure 10. - Continued. Comparison between composite engine using variable-efficiency turbine and composite engine using constant-efficiency turbine. Valve overlap, 62°.



(d) Engine speed, 2200 rpm; inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.063.

Figure 10. - Continued. Comparison between composite engine using variable-efficiency turbine and composite engine using constant-efficiency turbine. Valve overlap, 62°.



(e) Engine speed, 2200 rpm; inlet-manifold pressure, 40 inches mercury absolute; fuel-air ratio, 0.063; NACA standard altitude, 30,000 feet.

Figure 10. - Concluded. Comparison between composite engine using variable-efficiency turbine and composite engine using constant-efficiency turbine. Valve overlap, 62°.

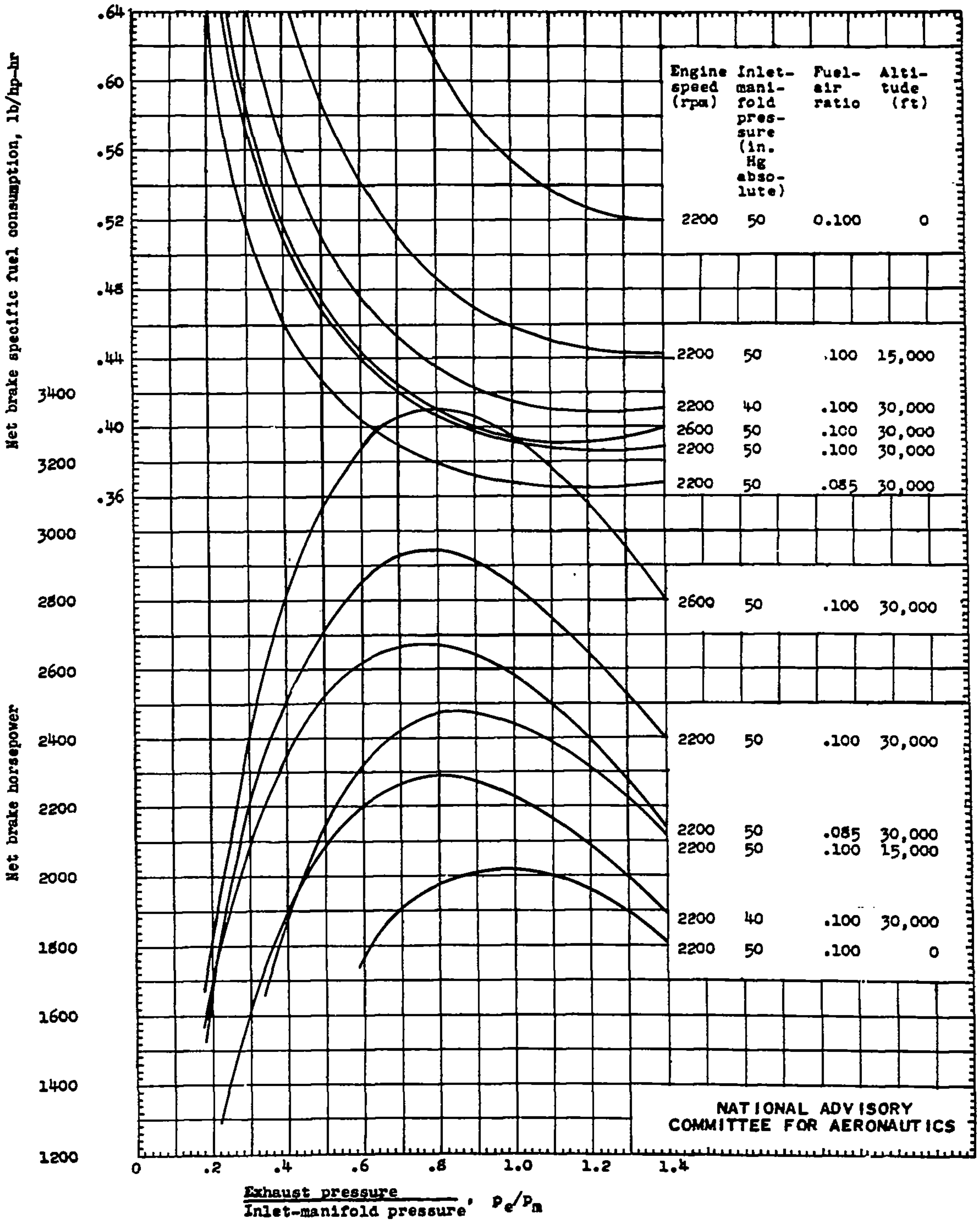


Figure 11. - Effect of p_e/p_m on net brake horsepower and brake specific fuel consumption at various engine conditions with afterburning. Valve overlap, 62°.

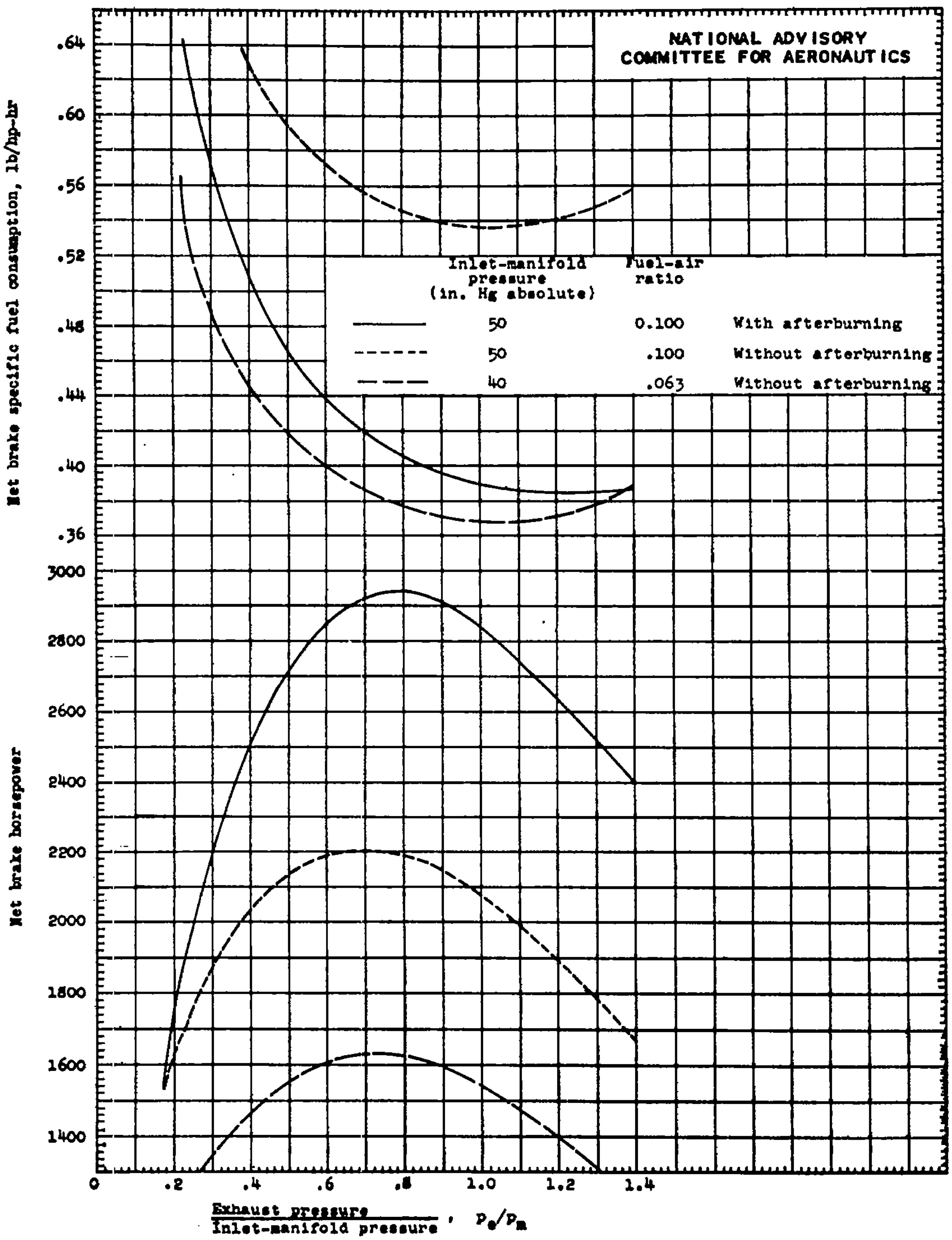


Figure 12. - Comparison of effect of p_e/p_m on net brake horsepower and brake specific fuel consumption with and without afterburning at several engine conditions. Valve overlap, 62°; engine speed, 2200 rpm; NACA standard altitude, 30,000 feet.