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STUDY OF JET-PROPULSION SYSTEM COMPRISING BLOWER BURNER, AND NOZZLE

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ADVANCE CONFIDENTIAL REPORT

STUDY OF JET-PROPULSION SYSTEM COMPRISING BLOWER, BURNER, AND NOZZLE

By Benjamin Pinkel and Eldon W. Hall

SUMMARY

A study was made of the performance of a jet-propulsion system composed of an engine-driven blower, a combustion chamber, and a discharge nozzle. A simplified analysis is made of this system for the purpose of showing in concise form the effect of the important design variables and operating conditions on jet thrust, thrust horsepower, and fuel consumption. Curves are presented that permit a rapid evaluation of the performance of this system for a range of operating conditions. The performance for an illustrative case of a power plant of the type under consideration is discussed in detail.

It is shown that for a given airplane velocity the jet thrust horsepower depends mainly on the blower power and the amount of fuel burned in the jet; the higher the thrust horsepower is for a given blower power, the higher the fuel consumption per thrust horsepower.

Within limits the amount of air pumped has only a secondary effect on the thrust horsepower and efficiency. A lower limit on air flow for a given fuel flow occurs where the combustion-chamber temperature becomes excessive on the basis of the strength of the structure. As the air-flow rate is increased, an upper limit is reached where, for a given blower power, fuel-flow rate, and combustion-chamber size, further increase in air flow causes a decrease in power and efficiency. This decrease in power is caused by excessive velocity through the combustion chamber, attended by an excessive pressure drop caused by momentum changes occurring during combustion.

INTRODUCTION

The performance of a jet-propulsion system depends on a large number of variables, and an exact analysis results in complicated equations that tend to obscure the effects of the important variables.

In the analysis in the present report a number of simplifying assumptions are made that lead to concise equations with only a small sacrifice of accuracy. These equations may be represented by a relatively small number of curves that permit a rapid evaluation of the performance of a jet-propulsion system for any given set of conditions and show clearly the effect on performance of changes in any of the important design variables or operating conditions.

The jet-propulsion device under consideration lends itself well to interceptor and pursuit aircraft because of the good economy for cruising and the very high maximum power and thrust obtainable for short durations. An illustrative example of such an application is discussed and the performance in take-off, cruise, and high-speed operation is given.

SYMBOLS

A_D area of duct cross section at combustion chamber, (sq ft)

B engine brake specific fuel consumption, (lb)/(bhp-hr)

c_p average specific heat of air at constant pressure, (Btu)/(slug)(°F)

C_V velocity coefficient of nozzle

f_t correction factor for jet specific fuel consumption for changes in T_{2a} and airplane velocity

f_c correction factor for jet specific fuel consumption for changes in $C_V{}^2\epsilon$

F net thrust, (lb)

h lower heat value of fuel, (Btu)/(lb)

J mechanical equivalent of heat 778, (ft-lb)/(Btu)

M mass rate of air flow through duct, (slug)/(sec)

p pressure, (lb)/(sq ft)

Δp_{2-3} pressure drop across burner due to burner drag, (lb)/(sq ft)

Δp_{3-4} pressure drop in combustion chamber due to the heating of the air, (lb)/(sq ft)

P_e engine brake horsepower

q_2 dynamic pressure due to velocity at combustion-chamber entrance, (lb)/(sq ft)

R gas constant 1716.3, (ft-lb)/(slug)(°F)

T temperature, (°F absolute)

T_{2a} ideal total temperature after blower on the assumption that the heat resulting from friction and turbulence is removed as it is generated, (°F absolute)

T_4 total temperature after combustion, (°F absolute)

thp jet thrust horsepower

V velocity, (fps)

V_o airplane velocity, (fps) (also air-entrance velocity to system)

V_{5a} jet velocity leaving nozzle without combustion for the same initial conditions that give V_5 with combustion, (fps)

W_f total fuel consumption, (lb)/(hr)

W_{fe} engine fuel consumption, (lb)/(hr)

W_{fj} jet fuel consumption, (lb)/(hr)

X ratio of net added power to initial kinetic energy of air

$$\alpha = \left(\frac{V_5}{V_{5a}}\right)^2 \quad \text{or} \quad \alpha = \epsilon\frac{T_4}{T_{2a}}$$

γ ratio of specific heat at constant pressure to specific heat at constant volume, 1.4

ϵ correction factor for pressure drop due to change in momentum during combustion

η_b blower efficiency based on total temperature and pressure at blower entrance and exit

η_c combustion efficiency

η_d diffuser efficiency, $\frac{T_o}{T_1 - T_o}\left[\left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$

$\eta_d' = \eta_d + \left(\frac{V_2}{V_o}\right)^2 \left(1 - \eta_d - \frac{\Delta p_{2-3}}{q_2}\right)$

ρ gas density, (slug)/(cu ft)

Subscripts:

o free air

1 out of diffuser before blower

2 at combustion-chamber entrance ahead of burner

3 at combustion-chamber entrance after burner

4 at combustion-chamber exit before nozzle

5 at nozzle exit

a conditions corresponding to the case in which no jet fuel is burned

ANALYSIS

The jet-propulsion system under consideration is shown diagrammatically in figure 1. It consists of a diffuser in which a part of the velocity head of the entering air is converted into pressure head, a blower for further compressing the air, a burner for introducing fuel into the combustion chamber, a combustion chamber in which the fuel is burned, and a nozzle through which the jet issues into the atmosphere. The blower may be driven by a conventional engine or by any other suitable prime mover. Although the blower is shown operating in the low-velocity zone of the duct, it may be placed in any convenient location with diffusers placed before and after the blower without appreciably altering the accuracy of the analysis.

It is assumed that all the burning occurs between sections 3 and 4 of figure 1 and that the pressure drop across the burner Δp_{2-3} is equal to that for the unburned air.

The analysis is given in detail in appendixes A, B, and C. The following equations summarize the results and are used for plotting the curves: jet thrust horsepower per initial kinetic power

$$\frac{550\ \text{thp}}{\frac{1}{2}MV_o^2} = 2\left[\sqrt{C_V^2\epsilon\,\frac{T_4}{T_{2a}}\,(1 + X)} - 1\right] \tag{18}$$

where

$$X = \frac{550\eta_d P_e}{\frac{1}{2}MV_o^2} - (1 - \eta_d') \tag{9}$$

in which

$$1 - \eta_d' = (1 - \eta_d)\left[1 - \left(\frac{V_2}{V_o}\right)^2\right] + \frac{\Delta p_{2-3}}{q_2}\left(\frac{V_2}{V_o}\right)^2 \tag{8}$$

or

$$X = \frac{550\eta_b P_e}{\frac{1}{2}MV_o^2} - (1 - \eta_d)\left[1 - \left(\frac{V_2}{V_o}\right)^2\right] - \frac{\Delta p_{2-3}}{q_2}\left(\frac{V_2}{V_o}\right)^2 \tag{6}$$

and

$$\epsilon = 1 - \frac{\left(\frac{V_2}{V_o}\right)^2\left(\frac{T_4}{T_{2a}} - 1\right)}{1 + X} \tag{17}$$

jet thrust per unit mass air flow,

$$F/M = \sqrt{C_V^2\epsilon\,\frac{T_4}{T_{2a}}\,(V_o^2 + V_o^2\,X)} - V_o\ \text{(lb)/(slug)/(sec)} \tag{19}$$

blower-power magnification,

$$\frac{\text{thp}}{\eta_b P_e} = \frac{2\left[\sqrt{C_V^2\epsilon\,\frac{T_4}{T_{2a}}\,(1 + X)} - 1\right]}{X + 1 - \eta_d'} \tag{20}$$

fuel-consumption factor of the jet,

$$\frac{\eta_c W_{f,j}}{thp} = \frac{c_p\ 3600\ T_{2a}\left(\frac{T_4}{T_{2a}} - 1\right) 550}{hV_o^2\left[\sqrt{C_V^2\epsilon\frac{T_4}{T_{2a}}(1 + X)} - 1\right]}\ (lb)/(thp\text{-}hr) \tag{21}$$

and engine fuel consumption,

$$W_{fe} = BP_e\ (lb)/(hr) \tag{22}$$

or

$$\frac{\eta_b W_{fe}}{thp} = \frac{B\left[X + (1 - \eta_d')\right]}{2\left[\sqrt{C_V^2\epsilon\frac{T_4}{T_{2a}}(1 + X)} - 1\right]} = \frac{B}{thp/\eta_b P_e}\ (lb)/(thp\text{-}hr) \tag{24}$$

The value of T_{2a} may be computed from

$$T_{2a} = T_o + \frac{V_o^2\eta_d}{2Jc_p} + \frac{550\eta_b P_e}{MJc_p} \tag{12}$$

The value of the combustion-chamber-approach velocity V_2, required for the computation of X and ϵ, is in many cases known because the maximum value of V_2, at which combustion can be maintained, is often a design limitation. If, however, the mass rate of flow of air M and the combustion-chamber cross-sectional area A_D are given, then, when V_2 is small, a value of sufficient accuracy for determining X and ϵ can be obtained from

$$V_2 = \frac{M}{A_D\rho_2}$$

on the assumption that ρ_2 is nearly equal to atmospheric density. Where V_2 is large and the blower-pressure ratio is considerably greater than unity, it may be necessary to make a more accurate computation of V_2 by means of the equations in appendix C. In most cases an approximate value for V_2 is adequate.

It is noted in equation (18) that, as $\epsilon T_4/T_{2a}$ is increased, the jet thrust horsepower increases (all other conditions remaining constant). The term ϵ represents the effect of the momentum pressure drop in the combustion chamber associated with the increase in

velocity caused by combustion. For a constant value of X and V_2/V_o, the larger the combustion-chamber temperature, the smaller is the value of ϵ (equation (17)) and the greater is the adverse effect of the momentum pressure drop on jet thrust horsepower. Thus an optimum value of T_4/T_{2a} exists at which $\epsilon T_4/T_{2a}$ and also thp are a maximum. This optimum value of T_4/T_{2a} is found by the usual method of calculus, which involves setting the derivative of $\epsilon T_4/T_{2a}$ with respect to T_4/T_{2a} equal to zero and solving for T_4/T_{2a}. This procedure results in the following expression for the optimum value of T_4/T_{2a}:

$$\left(\frac{T_4}{T_{2a}}\right)_{opt} = \frac{1 + X + \left(\frac{V_2}{V_o}\right)^2}{2\left(\frac{V_2}{V_o}\right)^2}$$

Increase in combustion temperature above this optimum value will result in a reduction in thrust horsepower.

DISCUSSION

Performance Charts

Figure 2(a) shows the thrust horsepower in terms of the nondimensional quantity

$$\frac{550 \text{ thp}}{\frac{1}{2}MV_o^2}$$

plotted against X for various values of $C_V^2 \epsilon T_4/T_{2a}$. The quantity

$$\frac{550 \text{ thp}}{\frac{1}{2}MV_o^2}$$

represents the jet thrust horsepower as a ratio of the initial kinetic power of the air involved in the jet-propulsion cycle. From these curves the thrust power for a given set of conditions can be readily evaluated. The term X in figure 2(a) represents the ratio of the net mechanical-power input into the air to the initial kinetic power of the air. The first term of X represents the blower-power output,

the second term represents the power loss in the diffuser, and the third term represents the power loss as burner drag, each as a ratio of the initial kinetic energy of the air. In an efficient design the second and third terms of the quantity X are negligible. The power loss at the discharge nozzle is handled by assigning the appropriate value to the nozzle-velocity coefficient C_V in the term $C_V^2 \epsilon T_4/T_{2a}$. The same term, by assigning an appropriate value of ϵ, takes care of the loss in power resulting from the pressure drop caused by the momentum change that occurs during combustion. The value of ϵ is 1 when the momentum pressure drop is negligible and decreases as the momentum pressure drop increases. A chart for determining ϵ will be described later.

The quantity $C_V^2 \epsilon T_4/T_{2a}$ was chosen as one of the parameters in the graphs because of the resulting reduction in the number of curves required to present the jet thrust horsepower and because the important trends are readily apparent from the curves. In many cases the value of the combustion temperature T_4 is one of the known design limitations. The value of T_{2a} can be computed by means of equation (12) and, over a large part of the operating range of interest, it differs from atmospheric temperature by less than 20 percent. Thus, the value of $C_V^2 \epsilon T_4/T_{2a}$ can be quickly computed or estimated, depending on the accuracy desired.

Figure 2(b), which can be computed from figure 2(a) (or equation (20)), shows the variation of $thp/\eta_b P_e$ with X for various values of $C_V^2 \epsilon T_4/T_{2a}$ and η_d' and is presented for the purpose of graphically illustrating the trend of the magnification of the blower power by the jet-propulsion system.

The fuel consumptions per thrust horsepower-hour of the jet and the engine may be obtained from figure 3, which is a plot of equations (21) and (24). The total specific fuel consumption is the sum of these two values. The engine fuel consumption is plotted against the same variables as the jet fuel consumption for the purpose of comparing their relative magnitudes. The engine fuel consumption can be calculated more readily by merely taking the product of the engine power and the engine brake specific fuel consumption.

Figure 4 shows an alternative method of presenting the fuel-consumption curves. The curves of jet fuel consumption were obtained by cross-plotting figures 2(b) and 3(a). The curves of engine fuel consumption were computed from equation (24) (see Analysis) for three values of engine brake specific fuel consumption B. The values of c_p of 7.728 Btu per slug °F (air at 80° F) and the heating value of

the fuel h of 19,000 Btu per pound were chosen in the computations of the jet fuel consumption in this report. It is noted in equation (21) that the jet specific fuel consumption is directly proportional to c_p and inversely proportional to h. The values of specific fuel consumption can be corrected for other values of c_p and h than those which are used in this report by making use of these proportionalities. The values of c_p vary somewhat with the type of fuel used and the temperature range during combustion. The values of c_p for combustion gas in the combustion-temperature range are usually about 10 percent higher than the value used in this report, and the jet fuel consumptions given should be increased by 10 percent. The value of the jet fuel rate obtained from figures 3 and 4 and equation (21) should be reduced by an amount equivalent in combustion heat to the heat generated by turbulence. (See appendix B.) This correction in the usual case is small and may be neglected.

Figure 5 is a plot of equation (17) and provides a means of obtaining the value of ϵ from the values of X, V_2/V_o, and T_4/T_{2a} for use in computing the term $C_V{}^2\ \epsilon T_4/T_{2a}$ in figures 2, 3, and 4. The factor ϵ takes care of the pressure drop in the combustion chamber caused by the increase in momentum of the gases in the process of heating.

In figure 6 are plotted values of thrust per unit mass F/M from equation (19) for take-off conditions of V_o equal to 0 and 150 feet per second. The term $(1 - \eta_d)\ (V_o{}^2 - V_2{}^2)$ in $V_o{}^2X$ must be omitted when V_2 is greater than V_o, as discussed in detail in appendix A.

Figures 7 to 10 show the performance for an illustrative case and will be discussed in detail later. Figure 11 gives values of the adiabatic temperature equivalent of velocity for aiding in the computation of T_{2a} and T_2. (See equations (12) and (32).) Figure 12 shows the ratio of the blower total exit pressure to total inlet pressure.

Maximum economy is obtained by burning no fuel in the jet. The system then reduces to the equivalent of a ducted propeller that is capable of high efficiency. The quantity $thp/\eta_b P_e$ is, in this case, less than unity and can theoretically be made to approach unity by increasing the quantity of air pumped and by improving the efficiencies of the diffuser and nozzle.

Burning fuel in the jet provides a means of obtaining a thrust horsepower many times the engine power. This procedure is wasteful of fuel but in maneuvers of brief duration, such as take-off and combat, high power is more important than low specific fuel consumption.

Of the figures shown, figure 4 possibly provides the clearest picture of the performance that may be obtained for this type of operation and shows that considerable magnification of the blower power can be achieved at the cost of increased fuel consumption per thrust horsepower-hour. For an effective duct efficiency that can reasonably be expected, namely, $\eta_d' = 0.90$, the specific fuel consumption for a given power magnification is nearly independent of the combustion-chamber temperatures up to a power magnification of 6. Thus, the power magnification in this range depends mainly on the amount of fuel burned in the jet and only slightly on the amount of air pumped. As the air rate is reduced for a given fuel rate, the combustion temperature is increased. An upper limit of combustion-chamber temperature exists and is determined by the strength-temperature properties of the structure and the amount of surface cooling provided. As the air rate is increased for a given fuel rate, the combustion temperature decreases. Increase in air rate, however, increases the velocity V_2 at the burner (for a given unit size) and a point is reached where this velocity becomes excessive and causes a reduction in ϵ (see fig. 5) and an increase in specific fuel rate (see plot of f_c in fig. 4). This condition establishes a lower limit on the combustion-chamber temperature and an upper limit on air rate for a given fuel-flow rate. The proper air rate lies between this upper limit and the lower limit imposed by maximum allowable combustion temperature. The higher the power magnification, the closer are the low and the high air-flow rate limits. In a choice of the air rate, consideration should be given to the characteristics of the blower. The lower the air rate, the higher is the pressure rise across the blower for a given engine power.

Above a power magnification of 6, inspection of figure 4 for $\eta_d' = 0.90$ appears to indicate an advantage in operating at low combustion-chamber temperatures. An increase in power magnification and a reduction in combustion-chamber temperatures, however, both tend to increase the required air rate. In a duct of practical size this high air rate may lead to excessive velocities at the combustion chamber and to a reduction in ϵ, the effect of which may increase the specific fuel consumption for low combustion-chamber temperatures with respect to that for high combustion-chamber temperatures. This effect will be illustrated in a later section when a specific design will be discussed in detail. It will be further

shown that the effect under discussion places an upper limit on the magnification of the blower power that can be obtained for a given combustion-chamber temperature; the higher the combustion-chamber temperature, the higher is the maximum power magnification for a given blower power and duct size.

The maximum thrust horsepower for a given duct diameter and engine power is developed when the maximum amount of fuel is burned in the jet (fig. 4), consistent with a number of practical limitations. The amount of fuel that may be burned is limited by the permissible maximum combustion-chamber temperature. The larger the air-flow rate through the combustion chamber, the larger is the permissible fuel-flow rate for a given limiting combustion temperature. The maximum air-flow rate depends on the maximum velocity of approach to the burners V_2 at which combustion can be maintained or at which ϵ is not appreciably less than unity. This air-flow rate can be roughly estimated by taking the product of the maximum V_2, the combustion-chamber cross-sectional area, and the atmospheric density. Further increase in thrust horsepower for the given duct size requires an increase in the engine power.

Inspection of the ordinate of figure 4 reveals that the jet specific fuel consumption decreases rapidly with increase in airplane velocity, decrease in atmospheric temperature, and increase in combustion efficiency. The curves for f_c indicate the loss in efficiency accompanying a reduction in discharge-nozzle-velocity coefficient and in the value of ϵ.

It is noted that, for $\eta_d' = 0.70$, the jet fuel consumption increases with reduction in combustion-chamber temperature. This increase is the result of higher losses in the duct with the higher air rates required to maintain the lower combustion-chamber temperatures. The same effect is noted for $\eta_d' = 0.90$ at low power magnifications but to a much lesser degree than for $\eta_d' = 0.70$ because of the greater value of η_d'. Comparison of the curves for η_d' of 0.70 and 0.90 indicates the importance of a high diffuser efficiency and a low burner drag. With good design, values of η_d' of 0.90 or greater can reasonably be expected.

The equations and curves neglect the usually small contribution to the thrust provided by the rearward motion of the fuel. The thrust horsepower corrected for this contribution is

$$\text{Corrected thrust horsepower} = \left(1 + \frac{W_{fj}}{3600\ Mg}\right)\text{thp} + \frac{W_{fj}V_o^2\ 10^{-6}}{1.98\ g}$$

The jet-propulsive effect of the engine exhaust was also neglected. If individual jet stacks are used, the engine exhaust thrust may be computed by means of the data in reference 1. In this computation the cost of taking on board the engine air should be included.

The following example illustrates an application of the curves in figures 2, 3, and 5:

The given design and flight conditions are:

Altitude, feet	30,000
Atmospheric temperature, °F absolute	412
Airplane velocity V_o, miles per hour	500
or feet per second	733
Velocity of approach to burners V_2, feet per second	200
Temperature after combustion T_4, °F absolute	2260
Jet air flow M, slugs per second	4
Engine power P_e, brake horsepower	1200
Blower efficiency η_b	0.90
Combustion efficiency η_c	0.85
Diffuser efficiency η_d	0.90
Nozzle-velocity coefficient C_V	0.98
Pressure drop across burner Δp_{2-3}, pounds per square foot	10
Engine brake specific fuel consumption B, pounds per brake horsepower-hour	0.5

The value of T_{2a} may be computed from equation (12) and the foregoing data and is 475° F absolute.

The following quantities may then be computed:

$$\frac{T_4}{T_{2a}} = \frac{2260}{475} = 4.76$$

$$\frac{V_2}{V_o} = \frac{200}{733} = 0.273$$

$$\frac{\frac{1}{2}MV_o^2}{550} = \frac{1}{2} \times 4 \times \frac{733^2}{550} = 1950 \text{ hp}$$

From equation (6)

$$X = \frac{0.9 \times 1200}{1950} - (1 - 0.9)\ (1 - 0.273^2) - \frac{10 \times 0.273^2 \times 16.4}{\frac{1}{2} \times 4 \times 200}$$

$$= 0.554 - 0.093 - 0.031 = 0.430$$

where the duct area A_D is 16.4 square feet.

From figure 5

$$\epsilon = 0.80$$

Thus

$$C_V^2\ \epsilon T_4/T_{2a} = 0.98^2 \times 0.80 \times 4.76 = 3.65$$

From figure 2(a)

$$\frac{550\ \text{thp}}{\frac{1}{2}MV_o^2} = 2.56$$

or

$$\text{thp} = 2.56 \times 1950 = 5000$$

From figure 3(a)

$$\eta_c W_{fj}/\text{thp}\ f_t = 2.20$$

and

$$f_t = 0.91$$

or the jet specific fuel consumption is

$$\frac{W_{fj}}{\text{thp}} = \frac{2.20 \times 0.91}{0.85} = 2.36\ (\text{lb})/(\text{thp-hr})$$

The engine fuel consumption is

$$0.5 \times 1200 = 600\ (\text{lb})/(\text{hr})$$

or, in terms of specific fuel consumption,

$$\frac{600}{5000} = 0.12\ (\text{lb})/(\text{thp-hr})$$

The total specific fuel consumption is

$$W_f/thp = 2.36 + 0.12 = 2.48 \text{ (lb)/(thp-hr)}$$

The magnification of the blower power is

$$\frac{thp}{\eta_b P_e} = \frac{5000}{0.9 \times 1200} = 4.63$$

The duct area A_D can be found by the equations given in appendix C and is 16.4 square feet.

Illustrative Example of Application of the Jet-Propulsion System

The application of the jet-propulsion system to pursuit and interceptor fighters has been suggested. In the cruising condition the system may be operated without burning fuel in the combustion chamber, in which case the system reduces in action to a mechanically actuated jet device that is capable of high efficiency. In take-off and during combat extremely high power can be obtained at the expense of high fuel consumption by burning fuel in the combustion chamber. These operations are of relatively short duration and high thrust power is more important than high efficiency.

An illustrative case of such an application will be discussed in detail as it brings out some of the characteristics and limitations of the system. A jet-propulsion system, which is provided with a combustion chamber 5 feet in diameter, housed within a fuselage or nacelle and a variable-area discharge nozzle will be considered. At each point the correct blower to handle the required amount of air at the specified power and efficiency of the problem is assumed. The following are the assumed performance characteristics of the components of the system:

Blower efficiency η_b	0.90
Combustion efficiency η_c	0.90
Diffuser efficiency η_d	0.90
Nozzle-velocity coefficient C_V	1.00
Pressure drop across burner Δp_{2-3}, pounds per square foot	0

The combustion-chamber temperature is assumed to be limited to 2260° F absolute. Air conditions are based on NACA standard atmosphere (reference 2).

Figure 7 shows the jet thrust horsepower that can be obtained at sea level and at 30,000 feet for engine powers of 800 and 1200 horsepower for various rates of air flow. The curves indicate that a thrust horsepower of 10,000 can be obtained at sea level with a 1200-horsepower engine at an air-flow rate of about 13 slugs per second. The reduction in thrust horsepower at higher values of M is mainly caused by excessive pressure drop in the combustion chamber associated with the large momentum changes resulting from combustion at the high values of V_2. The energy loss in the diffuser is a contributing factor to the loss in thrust at high values of air flow.

It is noted in figure 7 that, for the two sea-level cases, the specific fuel consumption begins to increase rapidly at an air flow of about 9 slugs per second. In the vicinity of 9 slugs per second the thrust-horsepower curves begin to level off in approaching the peak value and it appears to be good judgment to accept a small reduction in thrust horsepower to avoid extremely high specific fuel consumptions. In the case of operation at 30,000 feet, a similar compromise air flow appears at 4 slugs per second. The velocities of approach to the burner corresponding to these compromise air flows are between 150 and 170 feet per second for both sea level and 30,000 feet.

Figure 8 shows the thrust horsepower obtained for the conditions tabulated when cruising at an airplane velocity of 200 and 300 feet per second and when no fuel is burned in the combustion chamber. The over-all propulsive efficiency is the ratio of the thrust horsepower thp to the engine horsepower P_e. For example, at an air flow of 14.5 slugs per second and an airplane velocity of 300 feet per second at sea level and at 1200 engine horsepower, the net propulsive efficiency is 0.75. The curves of thrust horsepower against air flow in figure 8 have not reached their peak values for the range of air flows shown. Comparison of figures 7 and 8 indicates that a given jet-propulsion system should be designed to handle considerably more air in the cruise condition with cold jet than in the high-power condition when fuel is burned in the jet. This requirement would necessitate a blower with variable-pitch blades in addition to a discharge nozzle with a variable-area control.

The thrust that may be developed by the system under consideration for take-off operation is shown in figure 9. Curves (a) show the case where sufficient fuel is burned to maintain a combustion-chamber gas temperature of 1800° F (2260° F absolute). Curves (b) show the case where the gas temperatures are held at the optimum values for maximum thrust. At values of M greater than those at the points of tangency of curves (a) and their associated curves (b), the optimum gas temperatures are less than 1800° F and decrease

rapidly as M is increased; at smaller values of M the optimum values of combustion temperature are greater than 1800° F and are not usable under the present assumption of maximum permissible temperature. It appears that, at take-off with mass-air-flow rates close to those required for high-speed operation at sea level, thrusts somewhat less than the maximum values of curves (a) are obtained. The combustion-chamber gas temperature at these higher mass-air-flow rates will also be reduced with respect to the value of 1800° F.

Figure 10 shows the variation of specific fuel consumption per thrust horsepower-hour with jet thrust horsepower for combustion-chamber gas temperatures of 1860°, 2260°, and 2660° F absolute at sea level and at 30,000 feet. Inspection of the curves reveals that, if the thrust horsepower is to be reduced below the maximum value for a given maximum allowable combustion temperature, the fuel and air flow should first be reduced keeping the maximum allowable temperature in the combustion chamber in order to obtain the maximum reduction in fuel consumption. Below a certain point the specific fuel consumption for a given power appears to be independent, within limits, of combustion temperature. From strength considerations, it is advantageous to operate at the lowest temperature that will give efficient performance.

The design of a jet-propulsion system for a specific application requires a detailed analysis of the characteristics and operating requirements of the airplane in which the system is to be installed. It is not the purpose of the present report to recommend any set of operating conditions but rather to show the trends and illustrate some of the considerations involved in a jet-propulsion system of the type under discussion.

CONCLUSIONS

The following conclusions are made on the jet-propulsion system comprising an engine, a compressor, a burner, and a discharge nozzle:

1. At a given airplane speed the power magnification, that is, the ratio of the thrust horsepower to the blower power, is a function mainly of the specific fuel consumption in the jet. The greater the power magnification, the greater is the required jet fuel consumption per thrust horsepower-hour.

2. Over a large part of the practical operating range for a given fuel flow, the amount of air handled has a secondary effect on the net efficiency or thrust horsepower. For a given fuel rate

and blower power, at very low air-flow rates, the combustion temperature becomes excessive and results in structural failure; whereas at very high air-flow rates, if the combustion-chamber size is limited, the velocity in the combustion chamber becomes very large accompanied by an excessive pressure drop caused by momentum change during the combustion process and results in a sharp drop in net efficiency. The satisfactory air-flow rate lies between these limits. Practical consideration may place it closer to the high flow-rate limit because of the lower combustion-chamber temperature and the lower pressure rise that is required from the blower.

3. The higher the power magnification, the closer are the low and the high air-flow limits and the smaller is the range of permissible air-flow rates. At very high power magnifications, the maintenance of safe gas temperature is the limiting factor and excessive air-flow rates may be required, attended by sharply decreasing efficiency. The power magnification approaches a maximum and then falls off as the air and fuel rate is increased.

4. The maximum possible power magnification for a given combustion-chamber temperature and size decreases with increase in altitude because the mass-air-flow rate, at which excessive velocities in the combustion chamber occur, decreases with increase in altitude as a result of the decreased air density.

5. When maximum efficiency is the primary consideration, no fuel should be burned in the combustion chamber and the system reduces in operation to a mechanically actuated jet.

6. For a given airplane speed, engine power, and air velocity entering the combustion chamber, because of the pressure drop in the combustion chamber associated with the increase in the momentum of the gas during combustion, an optimum gas temperature exists above which any further increase in temperature results in a decrease in thrust.

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APPENDIX A

THRUST HORSEPOWER OF JET

In the following analysis, terms having a negligible effect on the result were omitted from the equations.

The thrust horsepower of the jet-propulsion device is given by application of the familiar momentum equation

$$\text{thp} = \frac{MV_o}{550}\left(V_5 - V_o\right) \tag{1}$$

It is expedient in the analysis to make use of a fictitious jet velocity defined as follows: Let V_{5a} be the jet velocity for the case where no fuel is burned in the combustion chamber but where the blower power, mass flow, pressure at the combustion-chamber entrance, and the diffuser and blower efficiencies remain the same as for the case where fuel is burned. This condition is mechanically achieved by adjusting the discharge-nozzle opening. It is further required in the definition of V_{5a} that heat generated by turbulence resulting from energy losses in the diffuser, the blower, and the burner is removed from the gas as it is formed and therefore does not contribute to the exit velocity V_{5a}. Let α be defined by the relation

$$V_5 = V_{5a}\sqrt{\alpha} \tag{2}$$

Then

$$\frac{550\ \text{thp}}{\frac{1}{2}MV_o^2} = 2\left(\frac{V_{5a}}{V_o}\sqrt{\alpha} - 1\right) \tag{3}$$

When the theoretical gain in kinetic energy of the air for the cold condition is equated to the difference between mechanical power added by the blower and the power losses at the diffuser and at the constriction in the combustion chamber caused by the burner, there is obtained

$$\frac{1}{2}M\left[\left(\frac{V_{5a}}{C_V}\right)^2 - V_o^2\right] = 550\ \eta_b P_e - \left(1 - \eta_d\right)\left(\frac{1}{2}MV_o^2 - \frac{1}{2}MV_2^2\right) - M\frac{\Delta p_{2-3}}{\rho_2} \tag{4}$$

An approximation is apparent in equation (4) where the diffuser efficiency is assumed to apply to the change in velocity from V_o to V_2. The complication of a more exact relation is not considered warranted because of the smallness of the error involved.

Solution for V_{5a}/V_o from equation (4) gives

$$V_{5a}/V_o = C_V \sqrt{1 + X} \tag{5}$$

where

$$X = \frac{550\eta_b P_e}{\frac{1}{2}MV_o^2} - \left(1 - \eta_d\right)\left[1 - \left(\frac{V_2}{V_o}\right)^2\right] - \frac{\Delta p_{2-3}}{q_2}\left(\frac{V_2}{V_o}\right)^2 \tag{6}$$

or

$$V_o^2 X = \frac{550\eta_b P_e}{\frac{1}{2}M} - \left(1 - \eta_d\right)\left(V_o^2 - V_2^2\right) - \frac{\Delta p_{2-3}}{q_2} V_2^2 \tag{7}$$

and

$$q_2 = \frac{1}{2} \rho_2 V_2^2$$

Let η_d' be defined by

$$1 - \eta_d' = 1 - \eta_d \left[1 - \left(\frac{V_2}{V_o}\right)^2\right] + \frac{\Delta p_{2-3}}{q_2}\left(\frac{V_2}{V_o}\right)^2 \tag{8}$$

Equation (6) becomes

$$X = \frac{550\eta_b P_e}{\frac{1}{2}MV_o^2} - (1 - \eta_d') \tag{9}$$

Part of the diffusing action takes place in the free-air stream ahead of the nacelle. The diffuser efficiency includes losses in this region as well as those occurring in the diffuser proper. When the velocity at the combustion chamber V_2 becomes greater than the free-air velocity V_o, a nozzle rather than a diffuser is required. In such cases the sign ahead of the terms

$$\left(1 - \eta_d\right)\left[1 - \left(\frac{V_2}{V_o}\right)^2\right]$$

and

$$\left(1 - \eta_d\right)\left(V_o^2 - V_2^2\right)$$

should be changed in order that these terms again appear as a loss in energy. In all cases the efficiency η_d is defined as the ratio of the true change in kinetic energy to the ideal change in kinetic energy for the same entrance condition and pressure change. Therefore, conditions where $V_2 > V_o$ should be treated as special cases where, depending on the over-all efficiency of the venturi, the second term on the right-hand side of equations (4), (6), and (7) can be either corrected or omitted.

Combining equations (3) and (5)

$$\frac{550 \text{ thp}}{\frac{1}{2}MV_o^2} = 2\left[C_V \sqrt{\alpha\,(1 + X)} - 1\right] \tag{10}$$

The equation for the jet thrust per unit mass flow is

$$F/M = C_V \sqrt{\alpha\left(V_o^2 + V_o^2 X\right)} - V_o \tag{11}$$

The quantity α may be derived in the following manner. The discharge velocity of the jet is given by the equation

$$V_5 = C_V \sqrt{2Jc_p T_4 \left[1 - \left(\frac{p_o}{p_4}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where T_4 and p_4 are the total temperature and pressure, respectively.

For the cold condition a similar expression for V_{5a} may be obtained with T_4 replaced by T_{2a}, where T_{2a} is a theoretical total temperature at the burner entrance corresponding to the case where the jet discharge velocity is V_{5a}. The value of T_{2a} obtained from the conditions given in the definition of V_{5a} is substantially

$$T_{2a} = T_o + \frac{\frac{1}{2}V_o^2\eta_d}{Jc_p} + \frac{550\eta_b P_e}{MJc_p} \tag{12}$$

The remark that follows equation (4) applies also in the case of equation (12).

The jet velocity for the cold condition is then given by

$$V_{5a} = C_V\sqrt{2Jc_p\,T_{2a}\left[1 - \left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{13}$$

where p_3 is the total pressure

Let $\Delta p_{3-4} = p_3 - p_4$

Then

$$V_5 = C_V\sqrt{2Jc_p\,T_4\left[1 - \left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}}\left(1 - \frac{\Delta p_{3-4}}{p_3}\right)^{-\frac{\gamma-1}{\gamma}}\right]}$$

When the first two terms of the series expansion for the term $\left(1 - \frac{\Delta p_{3-4}}{p_3}\right)^{-\frac{\gamma-1}{\gamma}}$ are taken

$$V_5 = C_V\sqrt{2Jc_p\,T_4\left[1 - \left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}}\frac{\Delta p_{3-4}}{p_3}\,\frac{\gamma-1}{\gamma}\right]}$$

$$V_5 = C_V\sqrt{2Jc_p\,T_{2a}\left[1 - \left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}} - \left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}}\frac{\Delta p_{3-4}}{\rho_3 T_3\,Jc_p}\right]\frac{T_4}{T_{2a}}}$$

$$V_5 = \sqrt{\left[V_{5a}^2 - 2\left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}} \frac{\Delta p_{3-4} C_V^2}{\rho_3}\right] \frac{T_4}{T_{2a}}}$$

Where the assumption is made that T_{2a}/T_3 may be taken equal to unity in the term containing Δp_{3-4}.

Then

$$V_5 = V_{5a} \sqrt{\epsilon \frac{T_4}{T_{2a}}} \tag{14}$$

where

$$\epsilon = 1 - 2\left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}} \frac{\Delta p_{3-4}}{\rho_3} \frac{C_V^2}{V_{5a}^2} \tag{15}$$

Thus

$$\alpha = \frac{T_4}{T_{2a}} \epsilon \tag{16}$$

But

$$\Delta p_{3-4} = \frac{1}{2}\rho_3 V_3^2 + \rho_3 V_3 (V_4 - V_3) - \frac{1}{2}\rho_4 V_4^2$$

$$\Delta p_{3-4} = \frac{1}{2}\rho_3 V_3^2 \left(\frac{V_4}{V_3} - 1\right)$$

If the approximations are made that $V_4/V_3 = T_4/T_{2a}$ and $V_3 = V_2$, then

$$\epsilon = 1 - \frac{C_V^2 V_2^2}{V_{5a}^2}\left(\frac{T_4}{T_{2a}} - 1\right)\left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}}$$

When V_{5a} is eliminated from the equation for ϵ by means of equation (5), there results

$$\epsilon = 1 - \frac{\left(\frac{V_2}{V_o}\right)^2 \left(\frac{T_4}{T_{2a}} - 1\right)\left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}}}{1 + X}$$

For the type of system under discussion, the term $\left(\frac{p_o}{p_3}\right)^{\frac{\gamma-1}{\gamma}}$ in the equation for ϵ may be replaced by unity without introducing appreciable error in the practical range of operation. Thus

$$\epsilon = 1 - \frac{\left(\frac{V_2}{V_o}\right)^2 \left(\frac{T_4}{T_{2a}} - 1\right)}{1 + X} \tag{17}$$

Combination of equations (10) and (16) gives the thrust horsepower equation as

$$\frac{550 \text{ thp}}{\frac{1}{2}MV_o^2} = 2\left[\sqrt{C_V^2 \, \epsilon \, \frac{T_4}{T_{2a}} (1 + X)} - 1\right] \tag{18}$$

Equations (11) and (16) give the thrust equation as

$$F/M = \sqrt{C_V^2 \, \epsilon \, \frac{T_4}{T_{2a}} \left(V_o^2 + V_o^2 X\right)} - V_o \tag{19}$$

The ratio of thp $\eta_b P_e$ can be derived from equations (6) and (18)

$$\frac{\text{thp}}{\eta_b P_e} = \frac{2\left[\sqrt{C_V^2 \, \epsilon \, \frac{T_4}{T_{2a}} (1 + X)} - 1\right]}{X + (1 - \eta_d)\left[1 - \left(\frac{V_2}{V_o}\right)^2\right] + \frac{\Delta p_{2-3}}{q_2}\left(\frac{V_2}{V_o}\right)^2}$$

or from equations (9) and (18)

$$\frac{thp}{\eta_b P_e} = \frac{2\left[\sqrt{C_V^{\,2}\,\epsilon\,\frac{T_4}{T_{2a}}\,(1 + X)} - 1\right]}{X + 1 - \eta_d'} \tag{20}$$

In this analysis the thrust obtained from the rearward motion of the fuel was neglected. The following relation will correct for this contribution to the thrust:

$$\text{Corrected thrust horsepower} = thp\left(1 + \frac{W_{fj}}{3600\ M_G}\right) + \frac{W_{fj}V_o^{\,2}10^{-6}}{1.98_G}$$

The thrust of the engine exhaust was also neglected.

APPENDIX B

FUEL CONSUMPTION

Combustion of the jet fuel occurs at substantially constant pressure; therefore

$$\eta_c h W_{fj} = Mc_p\ (T_4 - T_2)\ 3600$$

or

$$\eta_c h W_{fj} = Mc_p\ (T_4 - T_{2a})\ 3600 - Mc_p\ (T_2 - T_{2a})\ 3600$$

The term $Mc_p\ (T_2 - T_{2a})\ 3600$ represents the heat generated by turbulence in the diffuser and at the blower. This heat is usually small compared with the heat generated by combustion and in most cases can be neglected. It will be neglected in the subsequent equations. For low efficiencies, to correct for this approximation, it is merely necessary to subtract from the fuel rate obtained from the ensuing equations a value equivalent to the heat generated by turbulence. Then from equation (18)

$$\frac{\eta_c W_{fj}}{thp} = \frac{c_p\ 3600\ T_{2a}\left(\frac{T_4}{T_{2a}} - 1\right) 550}{hV_o^2\left[\sqrt{C_V^2\,\epsilon\,\frac{T_4}{T_{2a}}\,(1 + X)} - 1\right]}\ \text{(lb)/(thp-hr)} \qquad (21)$$

If

$$c_p = 7.728\ \text{(Btu)/(slug)(}^\circ\text{F)}$$

and

$$h = 19{,}000\ \text{(Btu)/(lb fuel)}$$

$$\frac{\eta_c W_{fj}}{thp} = \frac{805.3\ T_{2a}\left(\frac{T_4}{T_{2a}} - 1\right)}{V_o^2\left[\sqrt{C_V^2\,\epsilon\,\frac{T_4}{T_{2a}}\,(1 + X)} - 1\right]}\ \text{(lb)/(thp-hr)}$$

The engine fuel consumption can be assumed to be proportional to the engine brake horsepower. Thus,

$$W_{fe} = BP_e \text{ (lb)/(hr)} \tag{22}$$

From equations (18) and (22)

$$\frac{W_{fe}}{thp} = \frac{BP_e\ 550}{\frac{1}{2}MV_o^{\ 2}} \times \frac{1}{2\left[\sqrt{C_V^{\ 2}\ \epsilon\ \frac{T_4}{T_{2a}}\ (1 + X)} - 1\right]} \text{ (lb)/(thp-hr)} \tag{23}$$

From equation (9), equation (23) becomes

$$\frac{\eta_b W_{fe}}{thp} = \frac{B\left[X + (1 - \eta_d')\right]}{2\left[\sqrt{C_V^{\ 2}\ \epsilon\ \frac{T_4}{T_{2a}}\ (1 + X)} - 1\right]} = \frac{B}{thp/\eta_b P_e} \text{ (lb)/(thp-hr)} \tag{24}$$

Assuming

$$\eta_d' = 0.90$$

and

$$B = 0.6 \text{ (lb fuel)/(bhp-hr)}$$

then

$$\frac{\eta_b W_{fe}}{thp} = \frac{0.3\ (X + 0.1)}{\sqrt{C_V^{\ 2}\ \epsilon\ \frac{T_4}{T_{2a}}\ (1 + X)} - 1} \text{ (lb)/(thp-hr)} \tag{25}$$

APPENDIX C

RELATIONS BETWEEN ATMOSPHERIC CONDITIONS AND CONDITIONS AT COMBUSTION-CHAMBER ENTRANCE

Accurate values of V_2 and T_2 may be found by the following method. The conditions after the diffuser and before the blower (V_1, p_1, and T_1) can be obtained from the following three formulas: From the conservation of energy

$$\frac{\frac{1}{2}V_o^2}{Jc_p} + T_o = \frac{\frac{1}{2}V_1^2}{Jc_p} + T_1 \tag{26}$$

From the definition of diffuser efficiency

$$\eta_d\ (T_1 - T_o) = T_o\left[\left(\frac{p_1}{p_o}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{27}$$

and

$$V_1 = \frac{MRT_1}{A_D p_1} \tag{28}$$

The values of V_2, p_2, and T_2 may be found by the following formulas:

$$550\eta_b P_e = Jc_p T_1 M\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] + \frac{1}{2}V_2^2 - \frac{1}{2}V_1^2 \tag{29}$$

$$\frac{\frac{1}{2}V_1^2}{Jc_p} + T_1 + \frac{550P_e}{MJc_p} = \frac{\frac{1}{2}V_2^2}{Jc_p} + T_2 \tag{30}$$

and

$$V_2 = \frac{MRT_2}{A_D p_2} \tag{31}$$

For an approximate value of V_2, values for T_2 and p_2 can be replaced by T_o and p_o in equation (31). Equations (26) and (30) give

$$\frac{\frac{1}{2}V_o^2}{Jc_p} + T_o + \frac{550P_e}{MJc_p} = \frac{\frac{1}{2}V_2^2}{Jc_p} + T_2 \tag{32}$$

which can then be used to find T_2.

If M, P_e, T_o, p_o, and V_o are known and V_2 is assumed to be equal to V_1 as an approximation, then for any value of V_1 the values of T_1 and T_2 can be obtained from equations (26) and (30), respectively. By use of this method the values of p_1 and p_2 can be obtained from equations (27) and (29), respectively, and the value of A_D from equation (31).

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2. Diehl, Walter S.: Standard Atmosphere - Tables and Data. NACA Rep. No. 218, 1925.

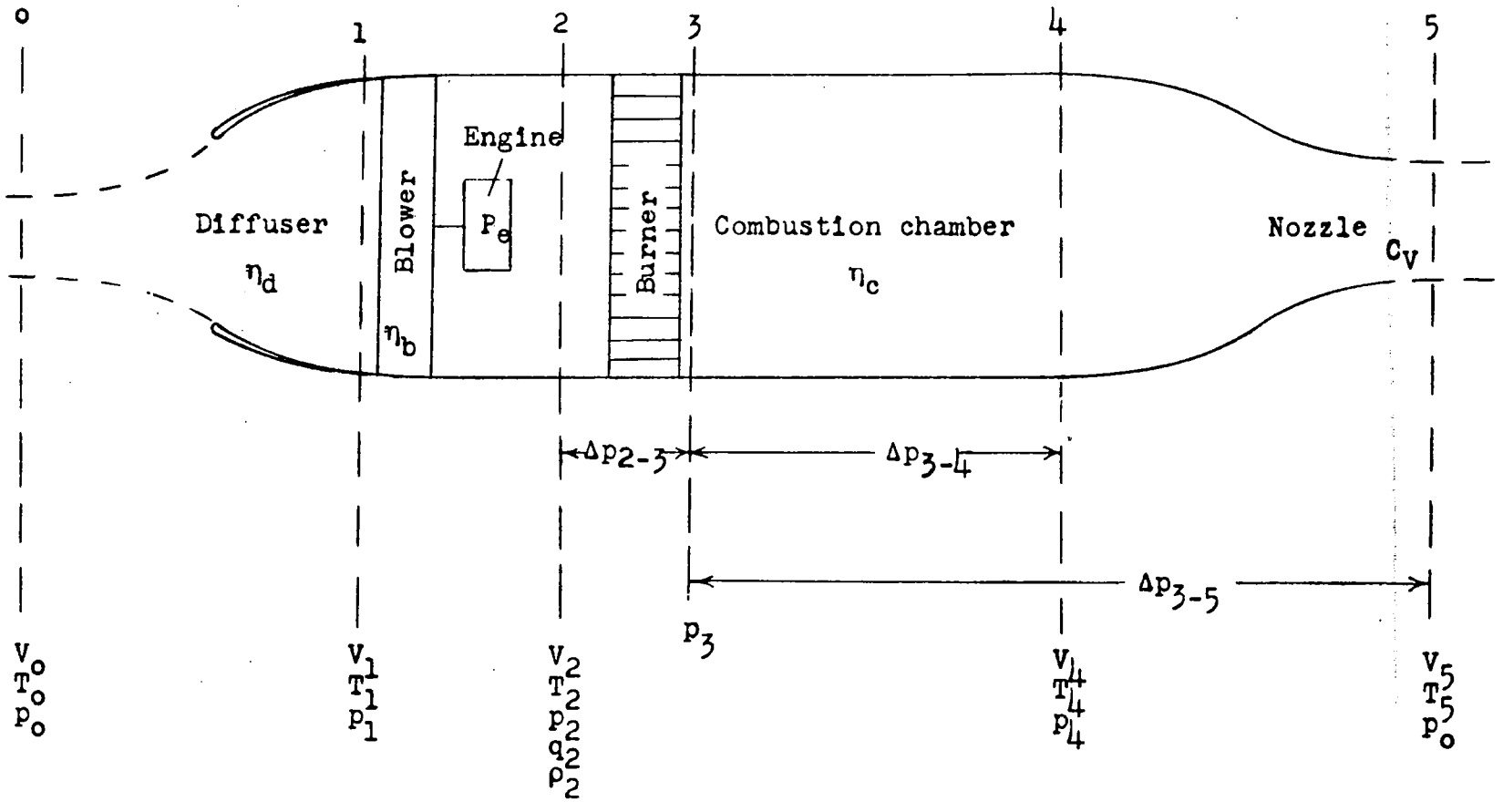

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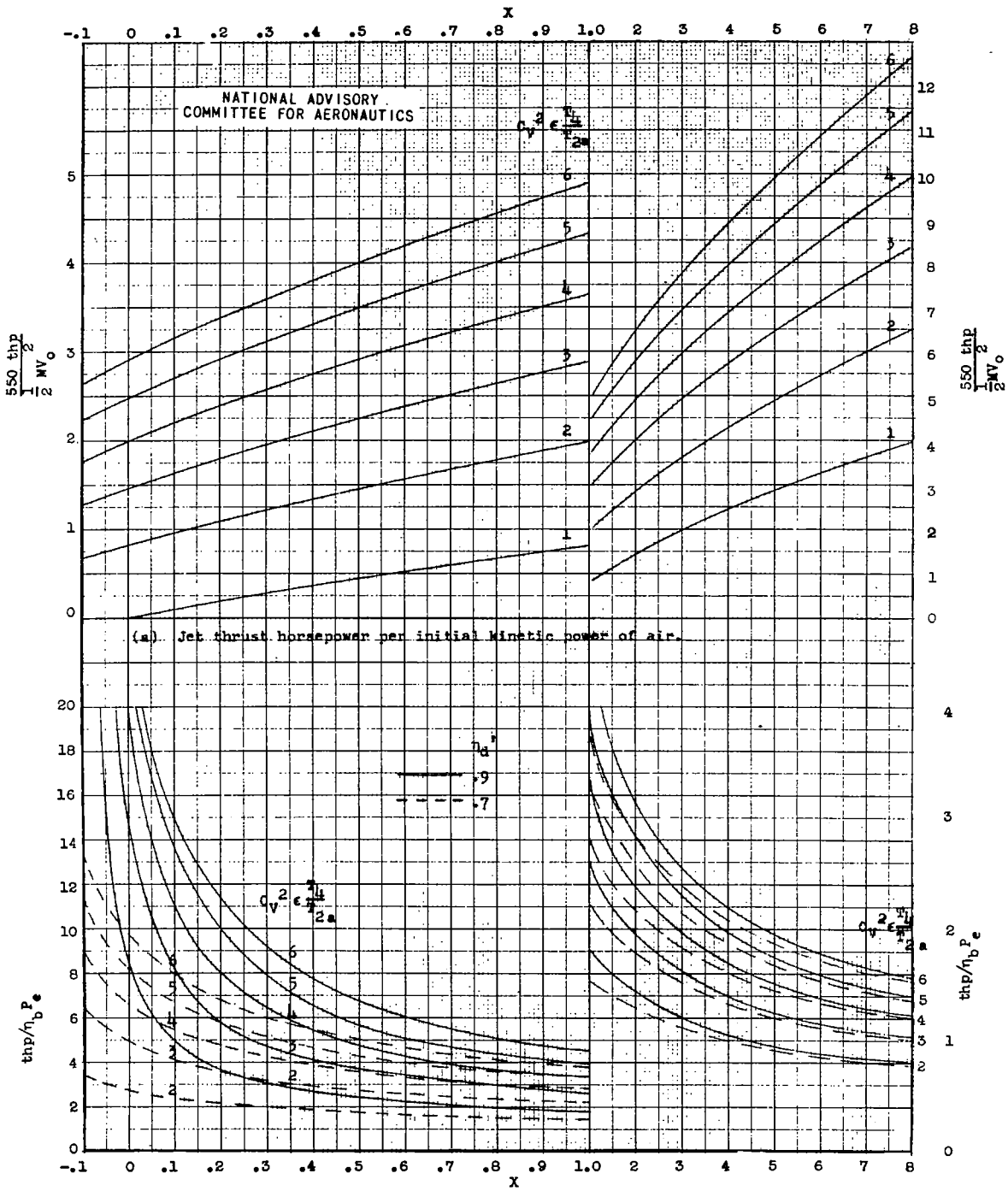
Figure 1. - Diagram of jet-propulsion system.

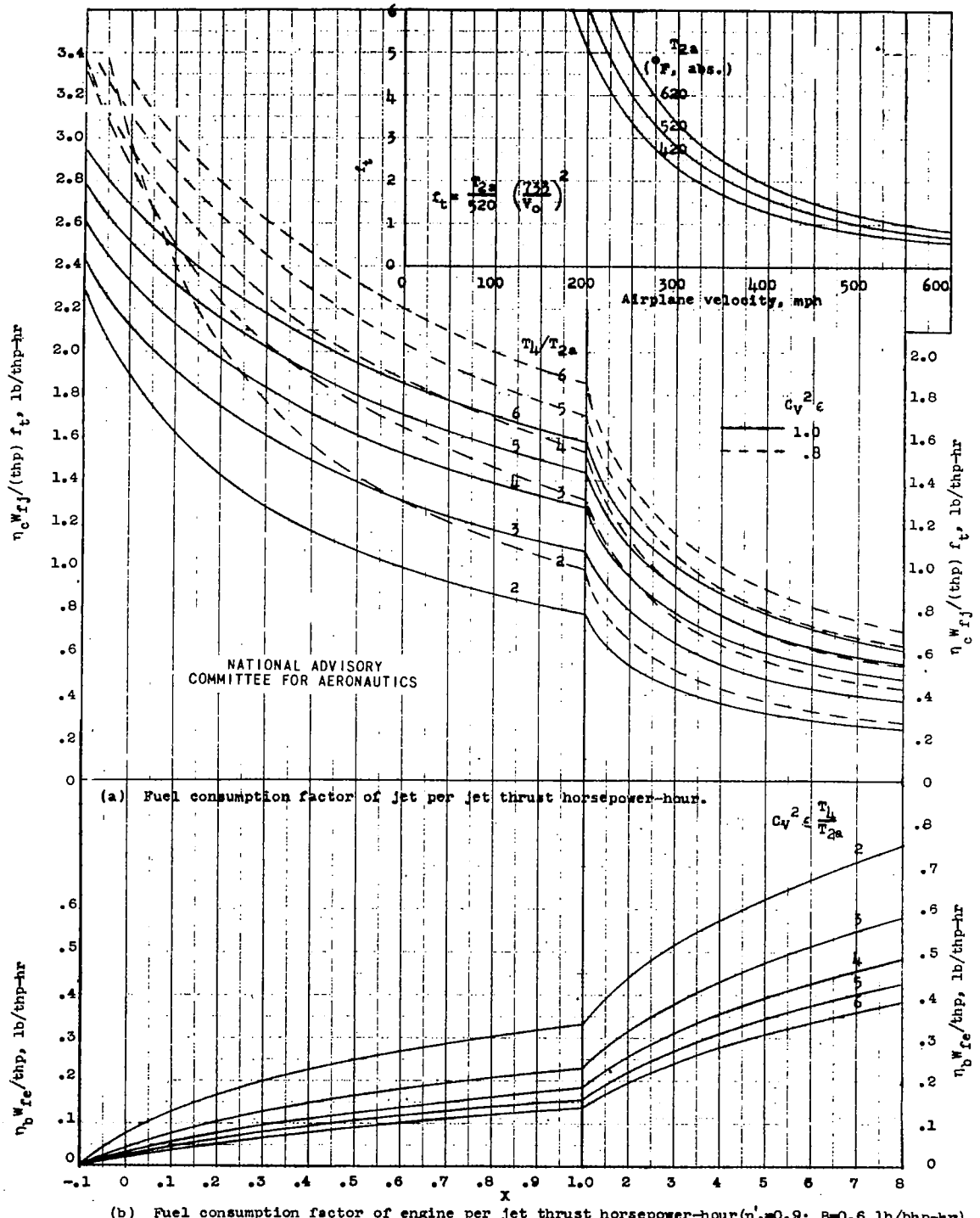


(a) Jet thrust horsepower per initial kinetic power of air.

(b) Jet thrust horsepower per blower power.

Figure 2.- Curves for obtaining jet thrust horsepower.

$$X = \frac{550\eta_b P_e}{\frac{1}{2}MV_o^2} - (1 - \eta_d)\left[1 - (V_2/V_o)^2\right] - \frac{\Delta p_{2-3}}{q_2}(V_2/V_o)^2$$



(b) Fuel consumption factor of engine per jet thrust horsepower-hour(η_d'=0.9; B=0.6 lb/bhp-hr).

Figure 3.- Specific fuel consumption factor of jet-propulsion device.

$$X = \frac{550\eta_b P_e}{\frac{1}{2}MV_o^2} - (1-\eta_d)\left[1 - (V_2/V_o)^2\right] - \frac{\Delta p_{2-3}}{q_2}\ (V_2/V_o)^2$$

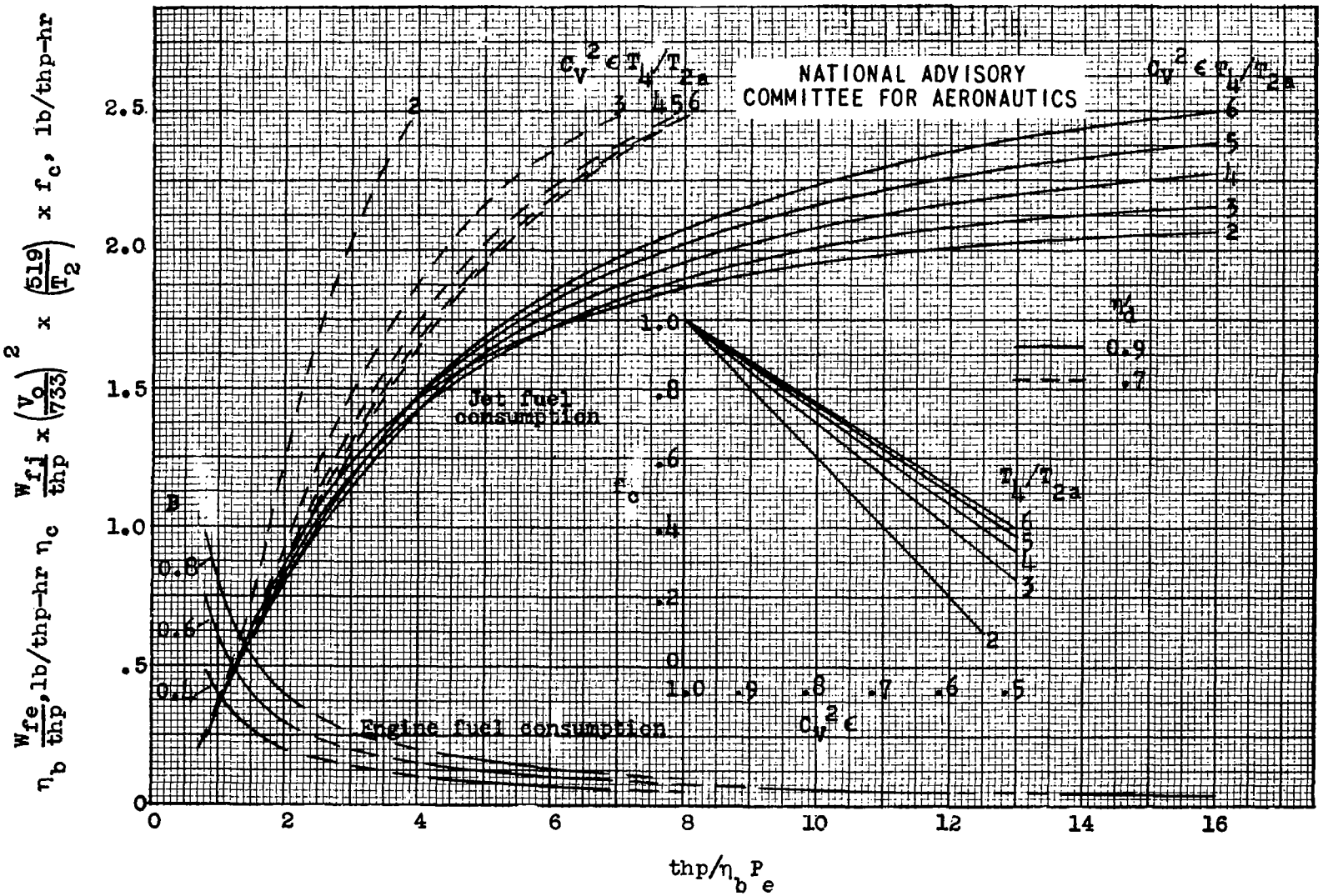


Figure 4.- Specific-fuel-consumption factors of jet-propulsion device.

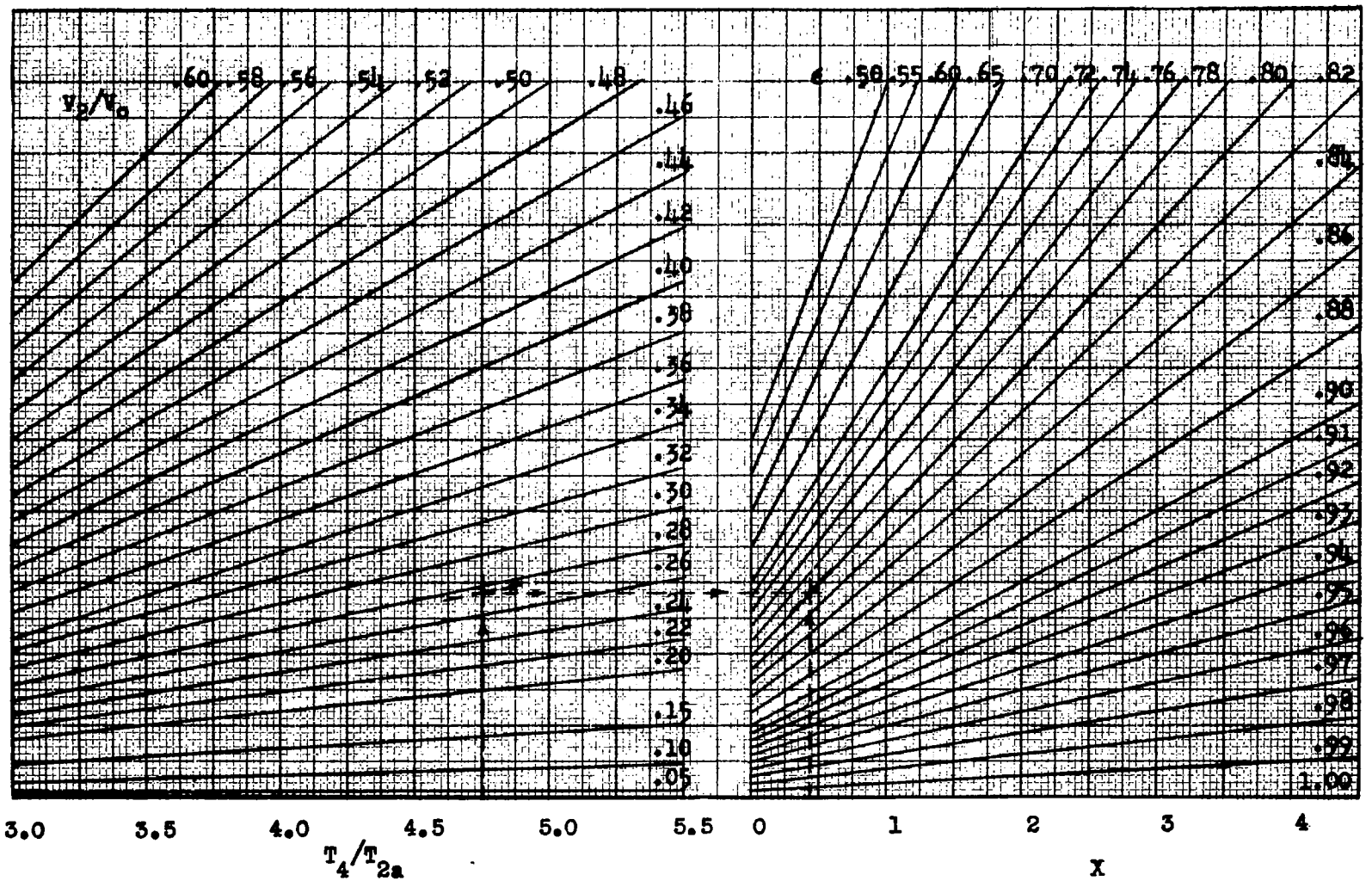


Figure 5.- Correction factor ϵ for momentum pressure drop in combustion chamber.

$$\epsilon = 1 - \frac{(V_2/V_o)^2 \; (T_4/T_{2a} - 1)}{1 + X}$$

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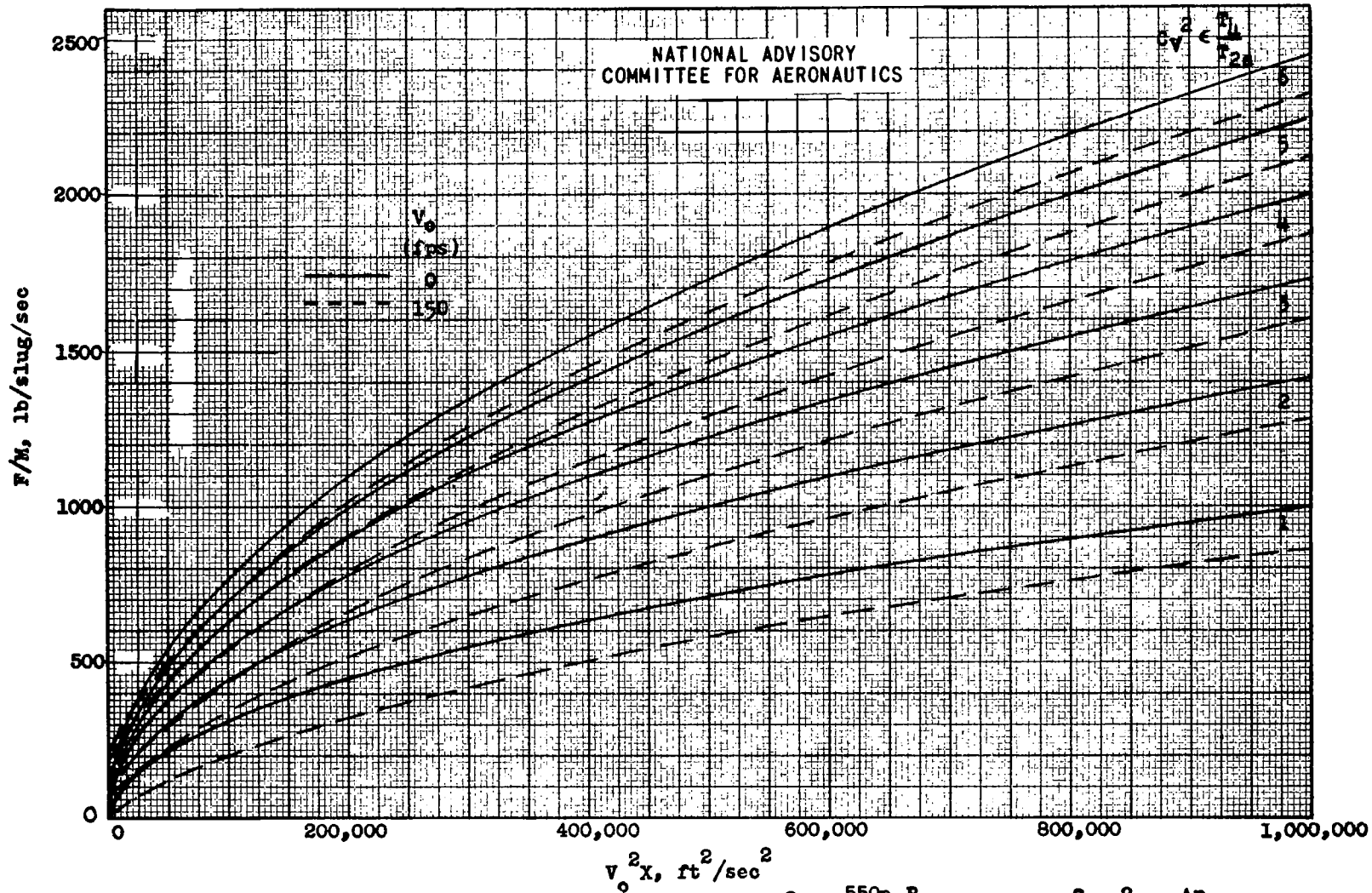

Figure 6.- Jet-thrust factor for take-off operation. $V_o^2X = \frac{550\eta_b P_e}{\frac{1}{2}M} = (1-\eta_d)(V_o^2-V_2^2) - \frac{\Delta p_{2-3}}{q_2}V_2^2$.

Term $(1-\eta_d)(V_o^2-V_2^2)$ should be omitted when $V_2>V_o$.

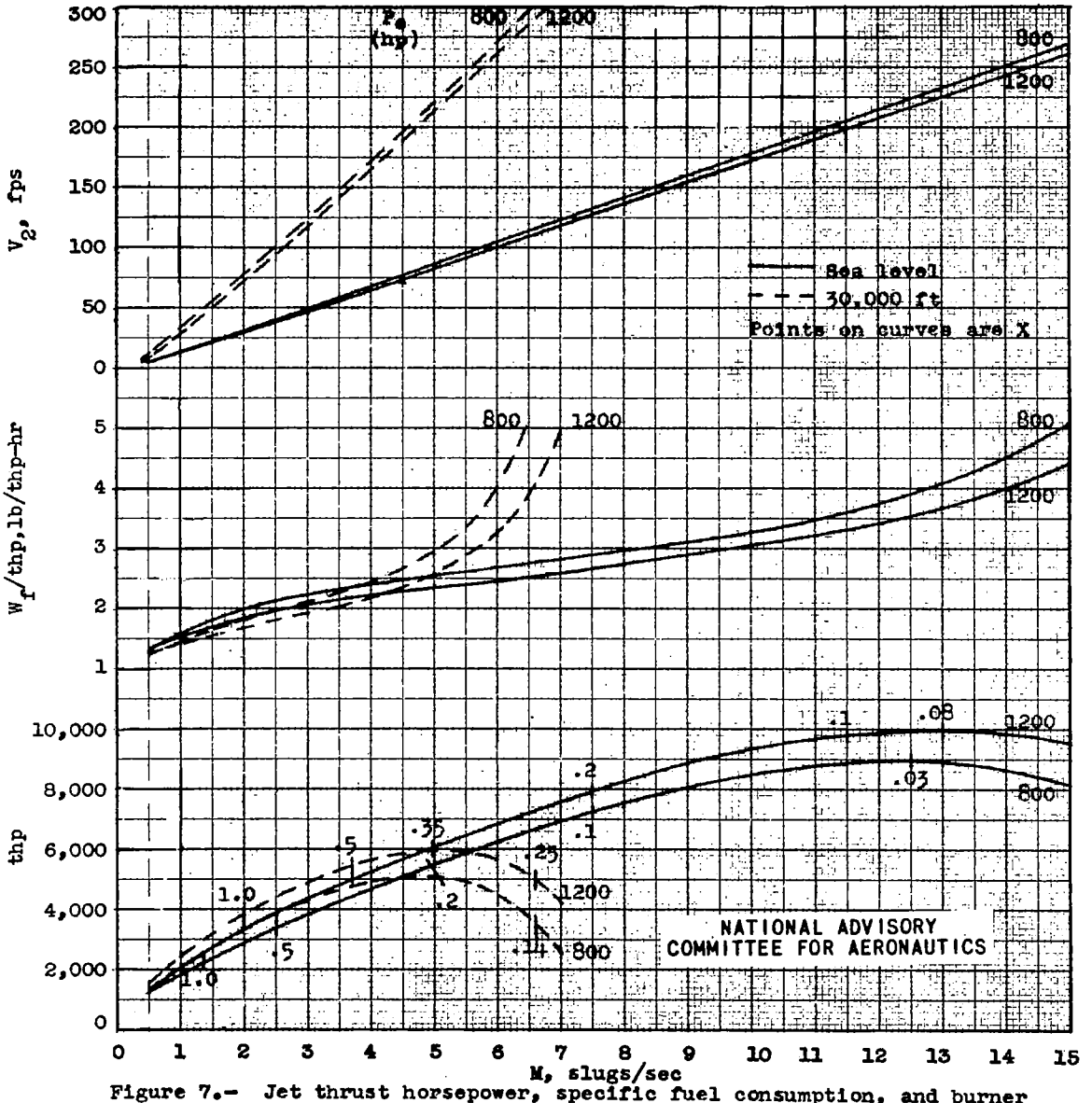

Figure 7.- Jet thrust horsepower, specific fuel consumption, and burner entrance velocity against air flow, for an airplane velocity of 500 miles per hour for the illustrative case ($\eta_b = \eta_c = \eta_d = 0.9$; $C_v = 1$; $\Delta p_{2-3} = 0$; $T_4 = 2260^\circ$ F abs.; combustion-chamber diameter, 5 ft).

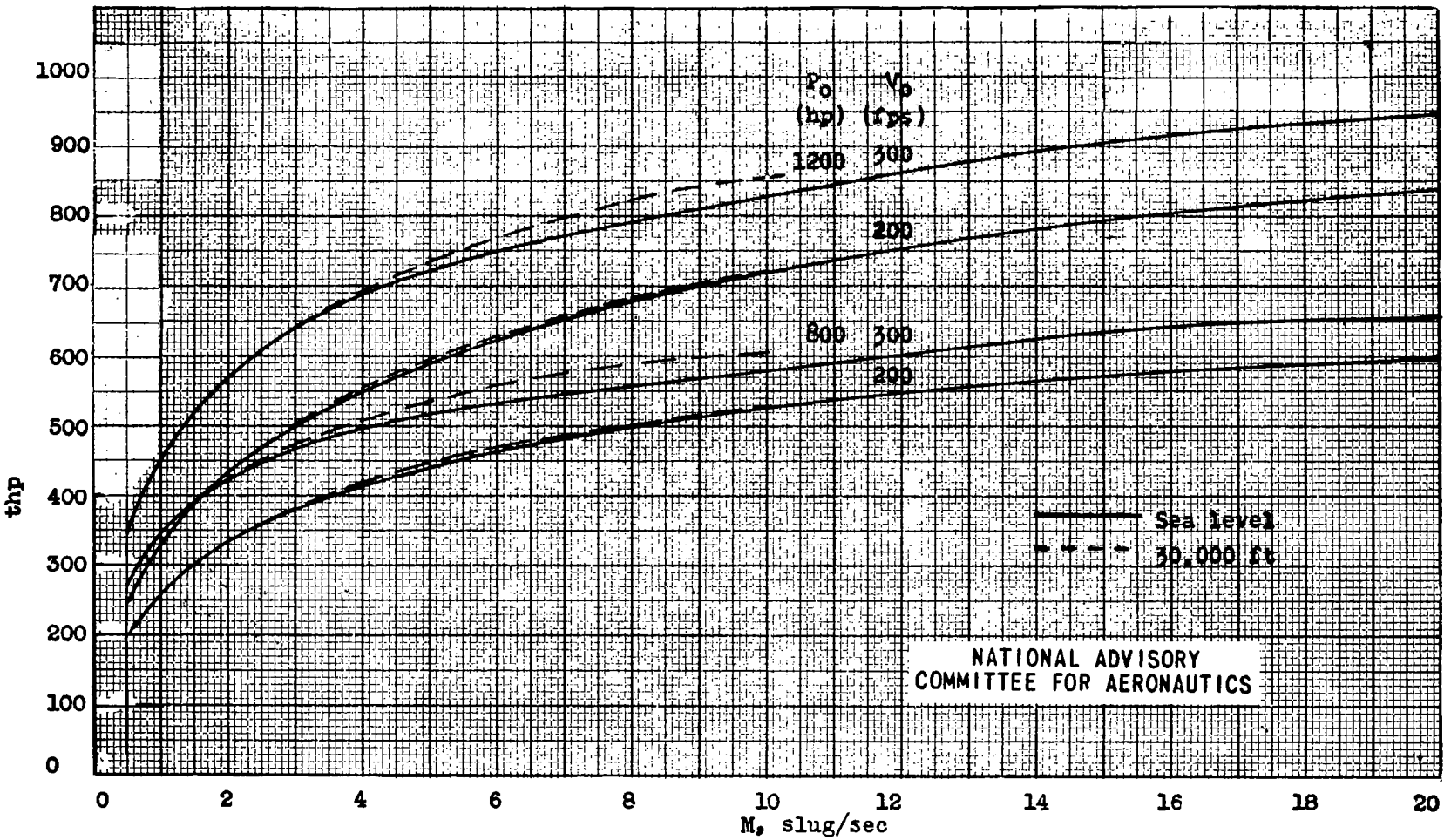

Figure 8.- Thrust horsepower in cruise condition with no fuel burned in jet for the illustrative case ($\eta_b = \eta_d = 0.9$; $\Delta p_{2-3} = 0$; $C_V = 1$; combustion-chamber diameter, 5 ft).

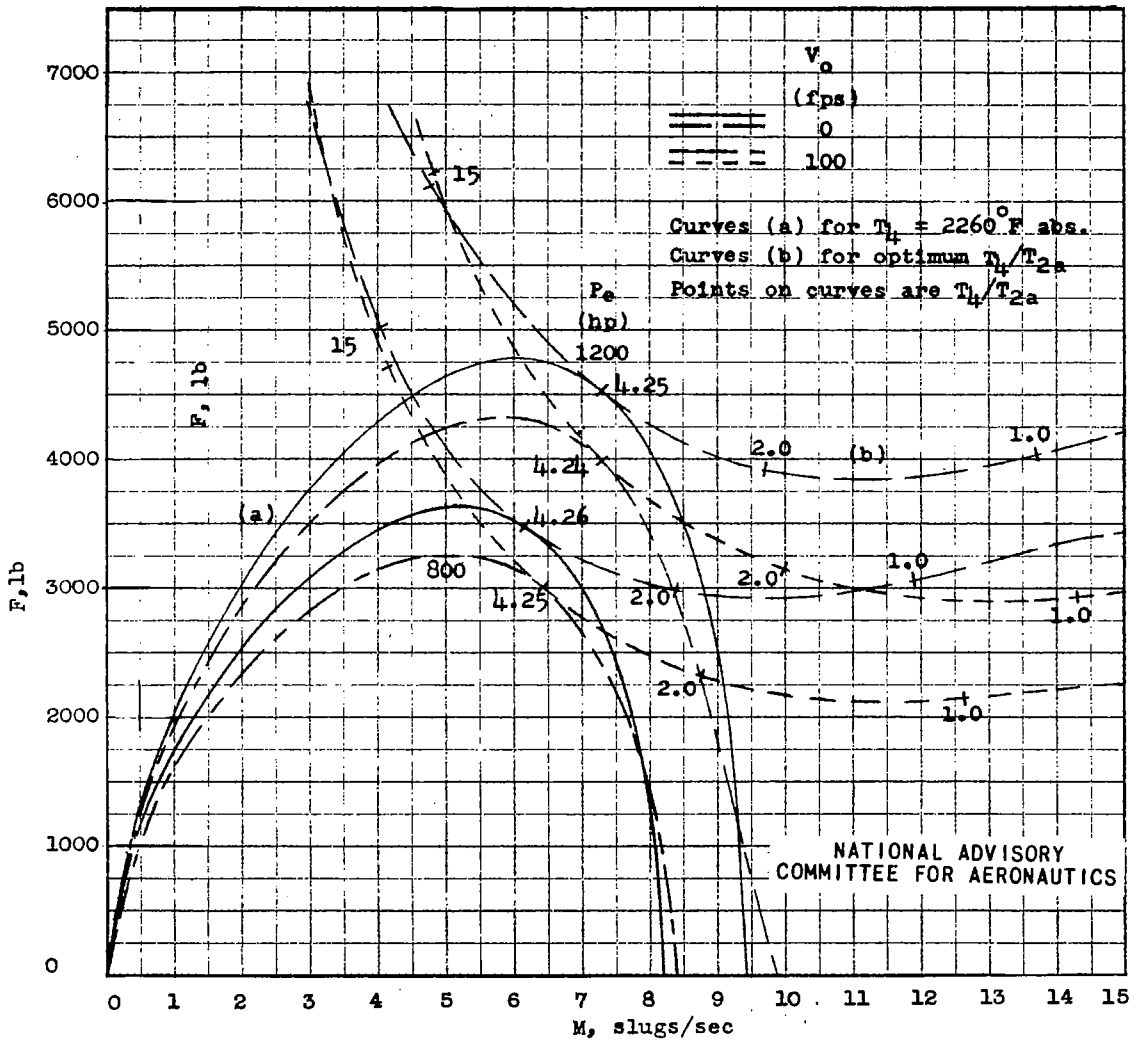

Figure 9.- Thrust during take-off operation for the illustrative case (Maximum T_4 = 1800° F; $\eta_b = \eta_d = 0.9$; $C_V = 1$; $\Delta p_{2-3} = 0$; combustion-chamber diameter, 5 ft).

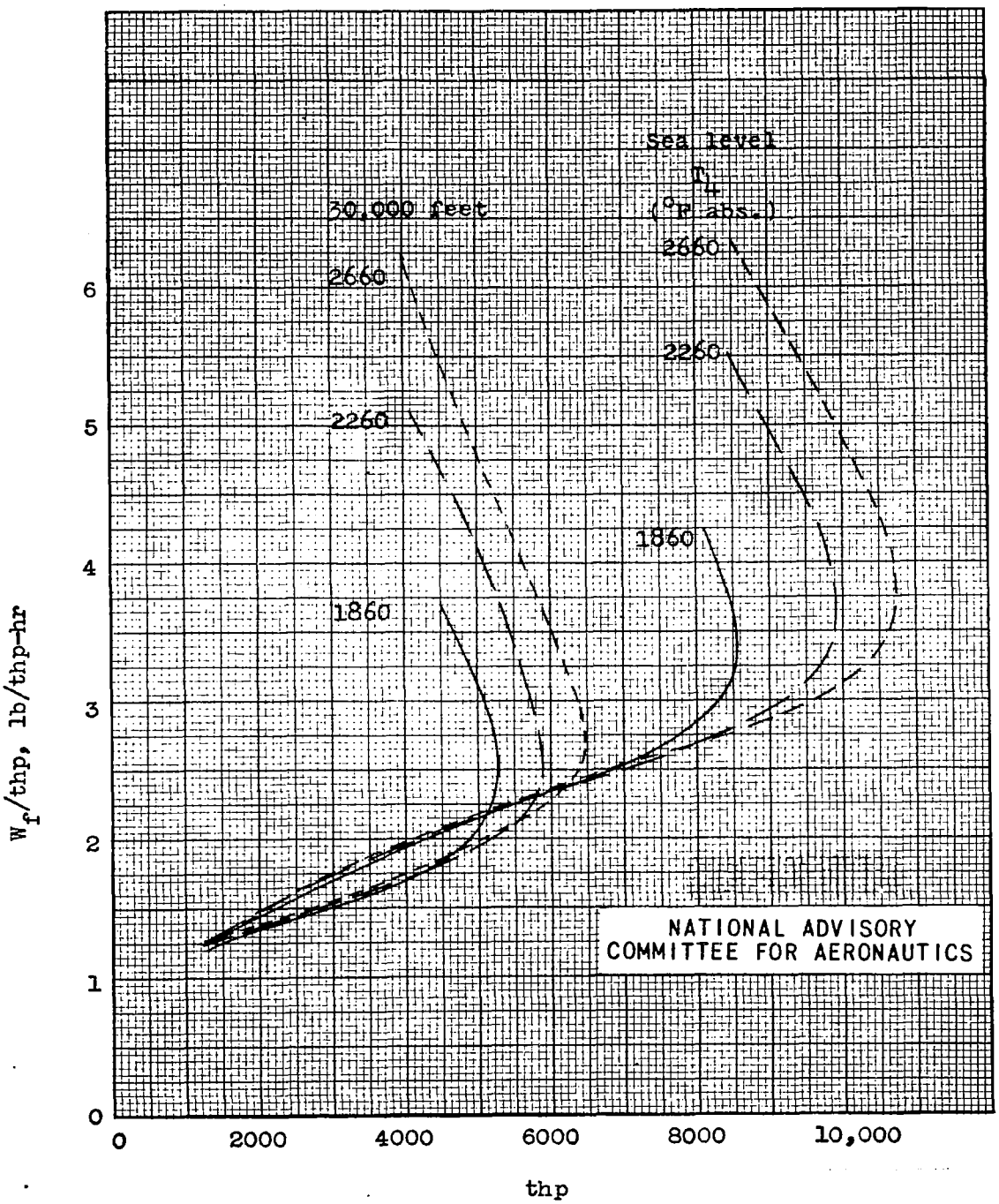

Figure 10.- Variation of specific fuel consumption with jet thrust horsepower for various combustion-chamber temperatures and altitudes (P_e = 1200 hp; $\eta_b = \eta_c = \eta_d = 0.9$; V_o = 733 fps; C_V = 1; Δp_{2-3} = 0; combustion-chamber diameter, 5 ft).

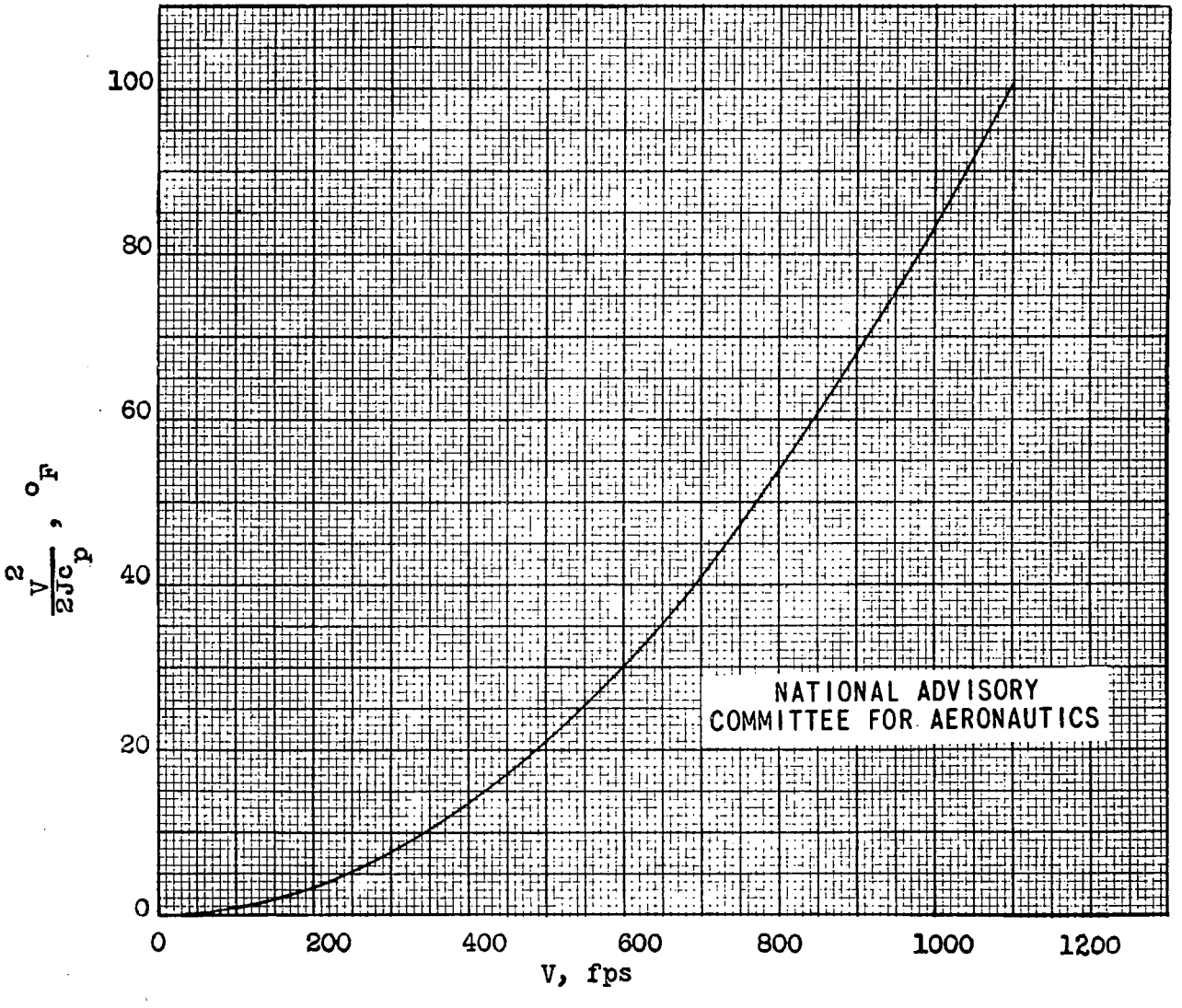

Figure 11.- Adiabatic temperature equivalent of velocity of air.

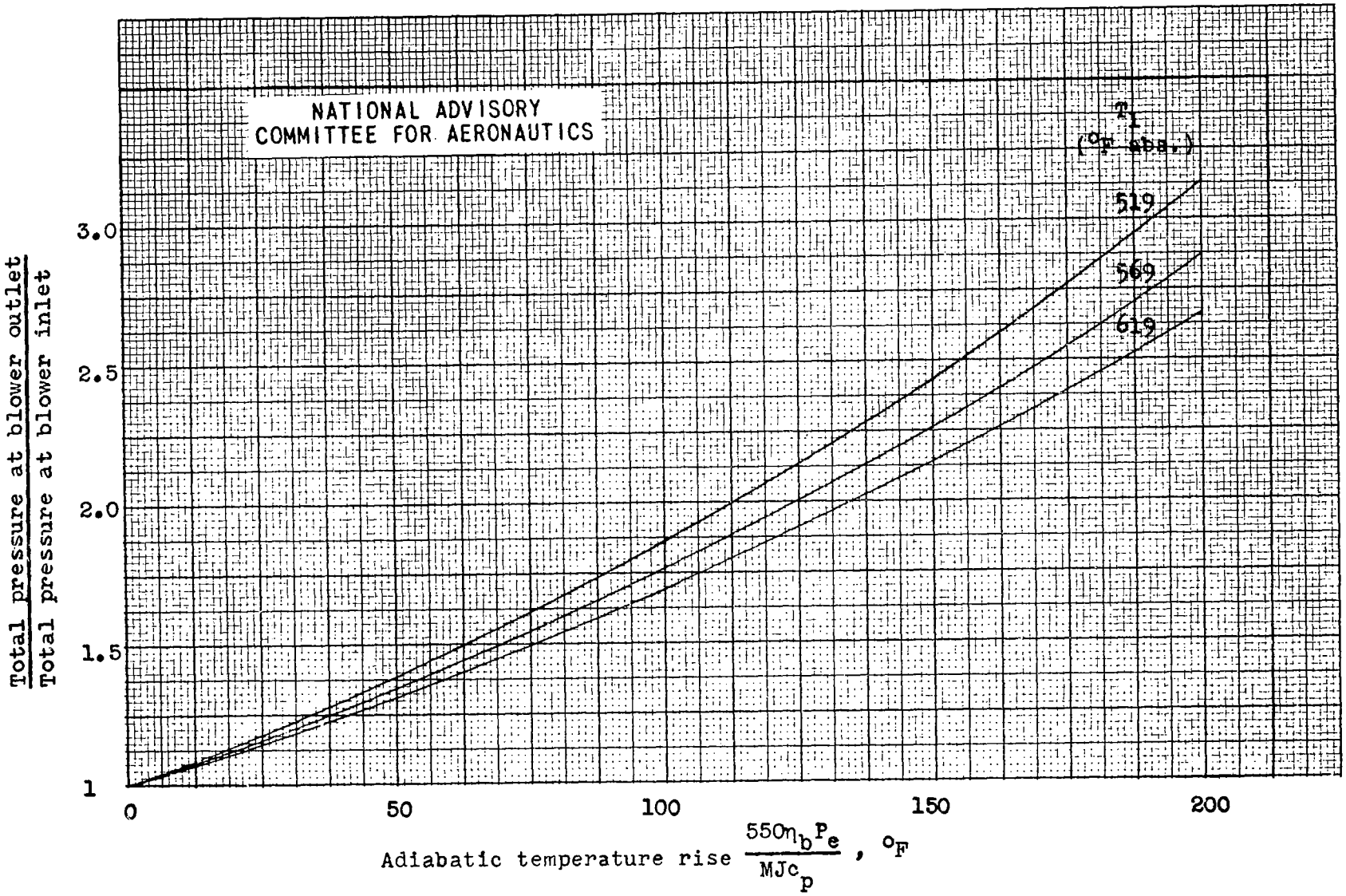

Figure 12.- Total pressure ratio of blower.

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