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A PRELIMINARY STUDY OF A PROPELLER POWERED BY GAS JETS ISSUING FROM THE BLADE TIPS

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SUMMARY

A theoretical analysis is made of a propeller powered by gas jets issuing from the blade tips. In the propeller considered, the air is drawn through the hub and passes through the hollow propeller blades to the tips, where burners heat the air and expel it through the nozzles in the blade tips. The reaction of the jets rotates the propeller.

Computations are made of the performance of a propeller designed to develop 56 thrust horsepower at 100 miles per hour. The fuel consumption of a jet-operated propeller would be considerably higher than that of a reciprocating engine and a propeller. The lighter weight of the jet-operated propeller will result in a lighter weight of engine plus fuel for short-range flights. For long-range flights, the weight of the jet-operated propeller with its fuel would be greater than the weight of a reciprocating engine with its propeller and fuel.

INTRODUCTION

The compactness, the simplicity, and the low cost of operation of jet-propulsion systems for aircraft would make them desirable for use in light aircraft provided that the fuel consumption of the propulsion unit in a slow-speed airplane is low enough to permit a reasonable range. Proposals have been made (reference 1) to locate gas jets in the tips of the blades of a propeller in such a manner that the reaction of these jets would turn the propeller. Air would enter the propeller hub, pass radially through the hollow blades and burners located in the blades, and be ejected from the nozzles at the blade tips. (See fig. 1.) Thus, the proposed installation is essentially a Nernst turbine (reference 2) in the form of a propeller.

The advantages of the jet-operated propeller over other jet-propulsion systems for slow-speed aircraft arise from the high speed at which the burners and nozzles move. Jet propulsion is inefficient at the low speeds of light airplanes but becomes more efficient at the relatively high tip speeds of the propeller blade. This simple engine with only one rotating member and with a fuel pump, an igniter, and a starter as the only auxiliaries would be lighter than a reciprocating engine of comparable power and would probably be easier to repair and maintain.

An analysis of the performance of a propeller powered by jets in the blade tips made by Roy in 1930 (reference 3) showed that this engine would be less efficient than a reciprocating engine; consequently, research on this engine was not recommended. It is interesting to note that a similar lack of interest was shown in the development of the turbojet engine, which is now of outstanding interest.

The possibilities of the jet-operated propeller are re-examined and the computed performance and range of a light airplane powered by a jet-operated propeller are compared with one using a conventional reciprocating engine. An analysis of the operating cycle shows the cycle efficiency and the ideal horsepowers obtainable, with aerodynamic losses neglected. An example of a jet-operated propeller for a light airplane is presented together with calculations of the propulsive efficiency. Estimates are made of the cruising range and the cost of operation of an airplane powered by this propeller and a discussion of safety considerations is presented.

THEORETICAL EFFICIENCY AND POWER

The computations of the theoretical efficiency and power of a jet propeller were made to show the effects of engine speed and burner temperature; aerodynamic and burner losses were neglected. Consideration was given to the possibility of increasing the efficiency and power by supercharging.

Effects of engine speed and burner temperature. - The effect of blade tip speed and temperature rise in the burner on the ideal fuel consumption of an unsupercharged jet-operated propeller is shown in figure 2; a combustion efficiency of 100 percent is assumed and the pressure loss in the burner is neglected. The method of computation is given in appendix A. In the presentation of the specific fuel consumption, the term "jet horsepower" is used to denote the net power delivered to the propeller by the air passing through the combustion chamber and the tip jets. The jet horsepower is therefore the equivalent of the shaft horsepower of a reciprocating engine driving a propeller.

A great reduction in specific fuel consumption results from an increase in the tip speed of the propeller. At a Mach number of 1.0, the specific fuel consumption is between 1.1 and 1.5 pounds per jet horsepower-hour. The use of tip speeds in excess of a Mach number of 1.0 is improbable because the centrifugal stresses in the rotating parts and the windage power loss of the propeller blades increase at high speeds.

The theoretical efficiency and the power of a jet-operated propeller are the same as the theoretical efficiency and the power of a ram jet moving at the same speed as the tips of the propeller. The theoretical advantage of a jet-operated propeller over other types of jet propulsion for low-speed aircraft is therefore clearly shown in the trends of figure 2. At standard sea-level conditions and a forward speed of 100 miles an hour, the equivalent flight Mach number is 0.13. The specific fuel consumption of a ram-jet engine attached rigidly to the airplane traveling at this low Mach number is much higher than that of a similar jet-operated propeller moving with tip Mach numbers above 0.7 (fig. 2).

The ideal jet horsepower per square foot of nozzle area is shown in figure 3. Again the aerodynamic losses and the burner losses have been neglected. The horsepower increases very rapidly with tip Mach number and temperature rise in the burner. The optimum condition is therefore the highest propeller tip speed possible without encountering excessive drag resulting from compressibility effects.

PERFORMANCE ESTIMATES ACCOUNTING FOR BURNER LOSSES AND PROPULSIVE EFFICIENCY OF THE PROPELLER

The performance characteristics shown in figures 2 and 3, obtained from assumptions of an ideal cycle, are useful for illustrating the effects on performance of the two primary factors: tip Mach number and temperature rise. For a reasonable evaluation of the expected performance of the jet propeller, however, the relatively large losses resulting from pressure drop in the burner and drag of the propeller must be considered. A blade of large cross-sectional area for a given nozzle size reduces the burner pressure losses but increases the drag of the blade and thereby reduces the propulsive efficiency. An optimum blade size therefore exists for a specified thrust power.

In a more accurate estimate of the performance of the jet propeller, too many variables must be considered to permit a simple general solution. For this investigation, a propeller was chosen to develop a thrust power equivalent to that produced by a 70-horsepower reciprocating engine and a conventional propeller. If the propulsive efficiency of the propeller used with the reciprocating engine is 0.8, the thrust-horsepower becomes 56.

A tip Mach number of 0.85 was chosen for the jet propeller because figure 2 shows that a high Mach number is desirable. At a higher Mach number, excessive drag losses may result from the compressible action of the air. Other operating conditions and design factors assumed for this propeller were:

Ratio of actual jet power to theoretical jet power	0.8
Combustion efficiency.	0.9
Airfoil.	NACA 0025
Coefficient of profile drag.	0.0143
Velocity of airplane, miles per hour	100
Turbulence pressure loss in burner, percent of dynamic head. . .	50

For a series of ratios of nozzle area to burner area and for a range of burner temperature rise, the fuel consumption and the power per square foot of nozzle area were estimated, accounting for friction and momentum pressure losses. Aerodynamic losses of the propeller were estimated and the propulsive efficiency was calculated for several propeller diameters. The net specific fuel consumption of the jet propeller was then computed. Details of these calculations of the jet specific fuel consumption are shown in appendix A; computations of the propulsive efficiency of the propeller are shown in appendix B. The results of these calculations for a propeller having a diameter of 5 feet are shown in figure 4. Use of a larger ratio of nozzle area to burner area reduces the chord and the cross-sectional area of the propeller blade and increases the propulsive efficiency of the propeller, but the loss in jet efficiency resulting from the greater burner velocity increases the jet specific fuel consumption. This change causes the minimum thrust specific fuel consumption to occur at the relatively low ratio of nozzle area to burner area of 0.35. Similar analyses were made for other propeller diameters and the minimum thrust specific fuel consumption is plotted against propeller diameter in figure 5. The lowest specific fuel consumption calculated was about 3 pounds per thrust horsepower-hour.

These calculations included the primary factors affecting jet-propeller performance with the exceptions of the blade-tip losses and the combustion losses resulting from the burning of the gas before it reaches the tip of the blade. Fuel that is burned closer to the center of rotation will be utilized at a low jet efficiency that corresponds to the local Mach number. Another source of error might be the low turbulence pressure loss assumed for the burner. Estimates of the increase in fuel consumption resulting from the turbulence pressure-loss rise from 50 to 200 percent of the burner dynamic head showed, however, only a 2-percent increase in fuel consumption when the ratio of nozzle area to burner area was 0.35.

RANGE COMPARISON

Calculations were made to compare the range of an airplane powered by a jet-operated propeller with the range of an airplane powered by a reciprocating engine and a conventional propeller. For these calculations, an airplane weighing 1200 pounds and powered by a 70-horsepower engine was chosen. The weights of the power systems, other than fuel tanks, are given in the following table. The fuel tanks were assumed to weigh 0.5 pound per gallon of capacity. The weights of the starters were assumed equal.

Power system	Engine weight (lb)	Propeller weight (lb)	Engine mount and cowling weight (lb)	Total fixed weight (lb)
Reciprocating engine	175	25	19	219
Jet-operated propeller	0	65	7	72

The weights of the power systems, including fuel and tanks, computed for maximum ranges from 0 to 500 miles, are shown in figure 6. In these computations the specific fuel consumption was assumed to be 0.70 and 3.0 pounds per thrust horsepower-hour for the reciprocating engine and jet-operated propeller, respectively. For maximum ranges of less than 150 miles the power system using the jet-operated propeller is the lighter but, for greater maximum ranges, the system using the reciprocating engine is the lighter. Use of the jet-operated propeller may thus result in a lighter aircraft for short-range flights, but the required fuel load will make such an aircraft heavier for long-range flights.

The airplane for which the calculations were made would have a range of about 300 miles. If the jet-operated propeller were used and the take-off weight of the power system plus fuel were maintained constant, the range would be reduced to about 185 miles, or about 38 percent less than the range obtainable with the reciprocating engine. Use of additional fuel tanks on the original airplane to increase its range to 500 miles makes the comparison even more unfavorable to the jet propeller.

OTHER CONSIDERATIONS

In addition to range and performance, other considerations are involved in the evaluation of a power system. Important among these considerations are cost and safety. Neither experience nor analysis provides accurate information on these considerations. Discussions of cost and safety are therefore given in general terms.

Cost. - A simple unsupercharged jet propeller with very few machined parts will be less expensive to manufacture than the conventional reciprocating engine, although the use of heat-resistant materials in the propeller blades will be a costly item. Only approximate estimates can be made of the final production cost of the jet propeller, but estimates of its cost and consideration of the cheap fuel that may be used indicate that the first cost and the total operating cost of the jet propeller may be less than that of the conventional reciprocating engine.

Safety. - Engine failure may result from excessive heating of one of the propeller blades. The resulting unbalance of the propeller rotating at high speed would increase the danger to the occupants, but the possibility of achieving better efficiency with low temperatures renders such a mishap unlikely. Flames or unburned fuel issuing from the nozzles would also constitute a hazard.

On the other hand, the simplicity of a jet propeller would render effective inspection very easy and would make possible frequent examinations of the critical parts without extensive disassembly or removal of the engine. A lubrication system for the jet propeller would not be necessary although circulation of a lubricant to the main thrust bearing would provide a longer trouble-free life. Temporary failure of the lubrication system would not be destructive.

The jet propeller with no pitch control would not accelerate so quickly as the reciprocating engine and consequently make landing maneuvers more difficult because sudden bursts of power could not be obtained. An automatic pitch control would overcome this difficulty but would add greatly to the cost of the engine.

CONCLUSIONS

A theoretical analysis of an airplane powered by a jet-operated propeller led to the following conclusions:

1. A jet-operated propeller of reasonable size could be made for a light airplane.

2. The fuel consumption of an unsupercharged jet-operated propeller would be appreciably greater than that of a reciprocating engine and a propeller.

3. For a representative application of a jet propeller developing 56 thrust horsepower in a light airplane, the weight of the jet propeller and its fuel was less than the weight of a reciprocating engine and its fuel when the range was less than 150 miles. For longer ranges, the jet propeller and its fuel weighed more than the reciprocating engine and its fuel.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, July 15, 1946.

APPENDIX A

ESTIMATE OF JET EFFICIENCY, POWER, AND FUEL CONSUMPTION

The computations of the jet efficiency and the power involve combustion efficiency, turbulence losses, and momentum losses in the burner. Conventional power equations are presented in terms of jet velocity and blade tip velocity. The jet velocity is then derived in terms of blade tip speed, burner pressure loss, and temperature ahead of the nozzle. Methods of estimating the burner pressure losses are given. The net power is then computed by simultaneous solution of these equations and the efficiency is calculated, using the power thus obtained.

The conventional equation for power produced by reaction jet is:

$$P_j = \frac{m}{550}\left(V_j V_t - V_t^2\right)$$

where

m mass rate of air flow, slugs/(sec)

P_j net rotative power produced by jets; corresponds to shaft horsepower of reciprocating engine, (hp)

V_j velocity of gas issuing from nozzle relative to nozzle, (ft)/(sec)

V_t velocity of tip of propeller blade relative to undisturbed atmosphere, (ft)/(sec)

The mass rate of air flow is given by the equation:

$$m = V_j \rho_j A_j$$

where

A_j effective area of jet nozzle, (sq ft)

ρ_j density of gas issuing from nozzle, slugs/(cu ft)

Therefore

$$P_j = \frac{V_j \rho_j A_j}{550}\left(V_j V_t - V_t^2\right)$$

and

$$\frac{P_j}{A_j} = \frac{V_j \rho_j}{550} (V_j V_t - V_t^2)$$

The density of the gas issuing from the nozzle is:

$$\rho_j = \frac{p_o}{Rt_j}$$

where

p_o ambient air pressure, (lb)/(sq ft)

R gas constant, 1716 (ft-lb)/(lb)(^oR)

t_j static temperature of gas issuing from nozzle, (^oR)

and the static temperature of the gas issuing from the nozzle is:

$$t_j = T_t \left(\frac{p_o}{p_t}\right)^{\frac{\gamma-1}{\gamma}}$$

where

p_t total pressure of gas in tip of blade before nozzle entrance, (lb)/(sq ft)

T_t total temperature of gas in tip of blade before nozzle entrance, (^oR)

γ ratio of specific heats

Hence

$$\rho_j = \frac{p_o}{RT_t}\left(\frac{p_t}{p_o}\right)^{\frac{\gamma-1}{\gamma}}$$

The total pressure in the tip of the blade is:

$$p_t = p_b - \Delta p_b$$

where

p_b total pressure of air at burner entrance, (lb)/(sq ft)

Δp_b total pressure loss in flow through burner, (lb)/(sq ft)

The total pressure at the entrance to the burner is

$$p_b = p_o \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

where

M Mach number of tip of propeller blade relative to undisturbed atmosphere

Therefore

$$p_t = p_o \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} - \Delta p_b$$

and

$$\rho_j = \frac{p_o}{RT_t} \left[\frac{p_o \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} - \Delta p_b}{p_o}\right]^{\frac{\gamma-1}{\gamma}}$$

$$\frac{P_j}{A_j} = \frac{p_o}{550\ RT_t} \left[\frac{p_o \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} - \Delta p_b}{p_o}\right]^{\frac{\gamma-1}{\gamma}} V_j \left(V_j V_t - V_t^2\right) \qquad (1)$$

The equation for jet velocity is:

$$V_j = 223.7 \sqrt{c_p\ T_t \left[1 - \left(\frac{p_o}{p_t}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where

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

When the expression for p_t is used, the equation for V_j becomes:

$$V_j = 223.7 \sqrt{c_p T_t \left\{ 1 - \left[\frac{p_o}{p_o \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} - \Delta p_b} \right]^{\frac{\gamma-1}{\gamma}} \right\}} \qquad (2)$$

The total pressure loss through the burner is computed from the turbulence pressure loss in the mixing of the fuel and the air and from a momentum pressure loss that results from reduction of the air density during heating. The turbulence pressure loss was assumed to be 50 percent of the dynamic pressure entering the burner and was computed from the equation

$$\Delta p_f = 0.25 \rho_b V_j^2 \left(\frac{A_j}{A_b}\right)^2 \left(\frac{\rho_j}{\rho_b}\right)^2$$

where

A_b cross-sectional area of burner, (sq ft)

ρ_b density of air entering burner, slugs/(cu ft)

Δp_f pressure loss in burner resulting from turbulence, (lb)/(sq ft)

The total loss in pressure of the fluid flowing through the burner is:

$$\Delta p_b = 0.25 \rho_b V_j^2 \left(\frac{A_j}{A_b}\right)^2 \left(\frac{\rho_j}{\rho_b}\right)^2 + \text{momentum pressure loss} \qquad (3)$$

The fluid densities before the burner and in the jet, respectively, are

$$\rho_b = \rho_o \left(\frac{p_{bs}}{p_o}\right)^{\frac{1}{\gamma}}$$

where

p_{be} static pressure of air at burner entrance

ρ_o density of ambient air, slugs/(cu ft)

and

$$\rho_j = \frac{p_o}{RT_t}\left[\frac{p_o\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} - \Delta p_b}{p_o}\right]^{\frac{\gamma-1}{\gamma}}$$

The momentum pressure loss was computed in the manner described on page 231 of reference 4.

The power output was determined by the simultaneous solution of equations (1), (2), and (3). The solution was achieved by trial and error.

The jet efficiency was computed from the equation:

$$\eta_j = \left[\frac{550 \dfrac{P_j}{\rho_j V_j A_j}}{Jg\ c_p\ (t_t - t_b)}\right]\eta_b \qquad (4)$$

where

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

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

t_b static temperature of air at burner entrance, (°R)

t_t static temperature of gas in tip of blade before nozzle entrance, (°R)

η_b combustion efficiency of burner

The static temperature of the air at the burner entrance was obtained from the following equation:

$$t_b = T_o \frac{\left(1 + \frac{\gamma - 1}{2} M^2\right)}{\left(1 + \frac{\gamma - 1}{2} M_b{}^2\right)}$$

where

M_b Mach number of air entering burner relative to burner

T_0 temperature of ambient air, (°R)

The jet specific fuel consumption was computed from the following equation:

$$f = \frac{2545}{19{,}000\ \eta_j}$$

where

f specific fuel consumption, (lb)/(hp-hr)

η_j jet efficiency

APPENDIX B

ESTIMATE OF PROPULSIVE EFFICIENCY

The propulsive efficiency was computed by adding the energy loss in the slipstream computed by the momentum theory of propellers to the profile drag of the propeller blades. Computation of the chord of the airfoil was required to provide the required internal passage area.

The cross-sectional area of an airfoil of symmetrical series NACA 00xx was determined by measurement to be:

$$A_a = 0.688\ y\ b^2 \tag{5}$$

where

A_a cross-sectional area of blade, (sq ft)

b chord of propeller blade, (ft)

y ratio of thickness to chord of airfoil

The area of the burner was assumed to be 75 percent of the airfoil area, and y for the NACA 0025 airfoil is 0.25.

The profile drag loss for a 2-blade propeller was computed from the equation:

$$P_D = \frac{2\ C_{D_o}\ \rho_o\ b\ V_t^3}{4400} \left(\frac{r_2^4 - r_1^4}{r_2^3}\right) \tag{6}$$

where

C_{D_o} coefficient of profile drag, 0.0143

P_D power lost as profile drag of propeller blades, (hp)

r_1 radius of propeller hub, (ft)

r_2 radius of propeller from center of rotation to blade tips, (ft)

The power lost in the slipstream was computed by the equation:

$$P_i = \frac{550\ P_F^{\,2}}{2\ \rho_o V_o^{\,3}\left(r_2^{\,2} - r_1^{\,2}\right)} \tag{7}$$

where

P_F thrust horsepower, (hp)

P_i power lost as residual energy of slipstream, (hp)

V_o forward velocity of airplane, (ft)/(sec)

The propulsive efficiency was than computed as follows:

$$\eta_P = \frac{P_F}{P_F + P_D + P_i} \tag{8}$$

where

η_P propulsive efficiency of propeller

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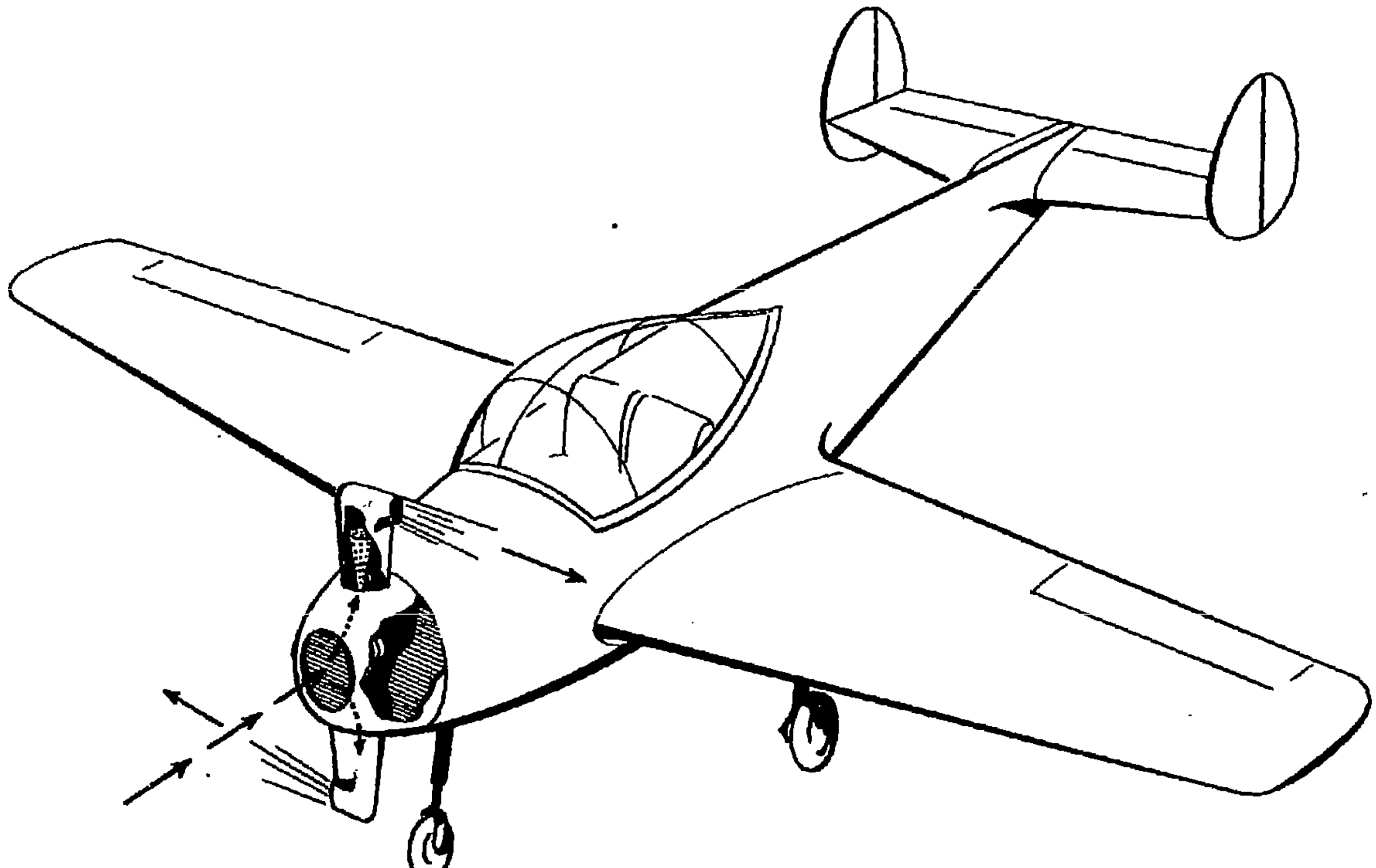

Figure 1. - Artist's conception of an airplane powered by a jet-operated propeller.

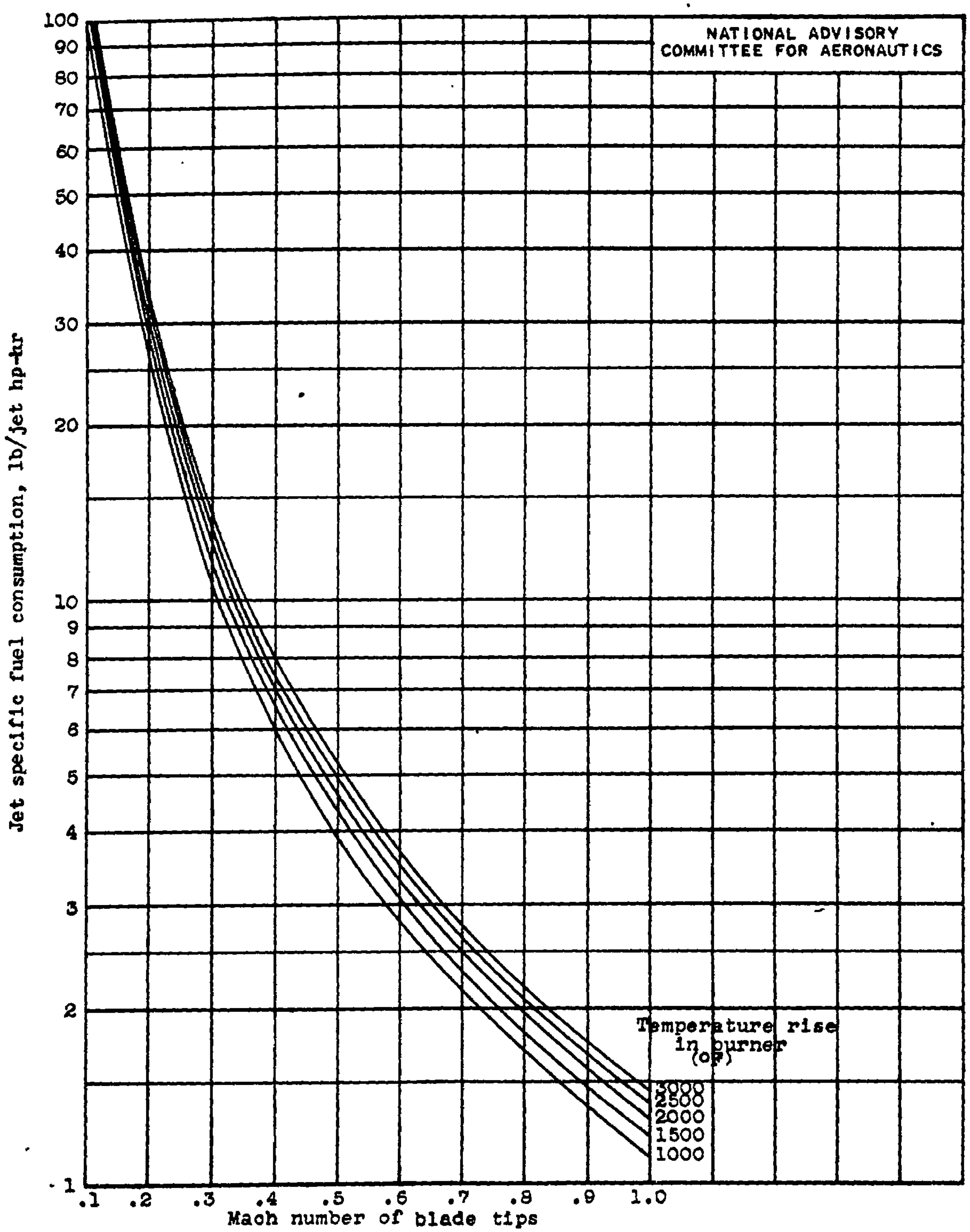

Figure 2. - Ideal fuel consumption of a jet-operated propeller at NACA standard sea-level conditions. Combustion and aerodynamic losses are neglected.

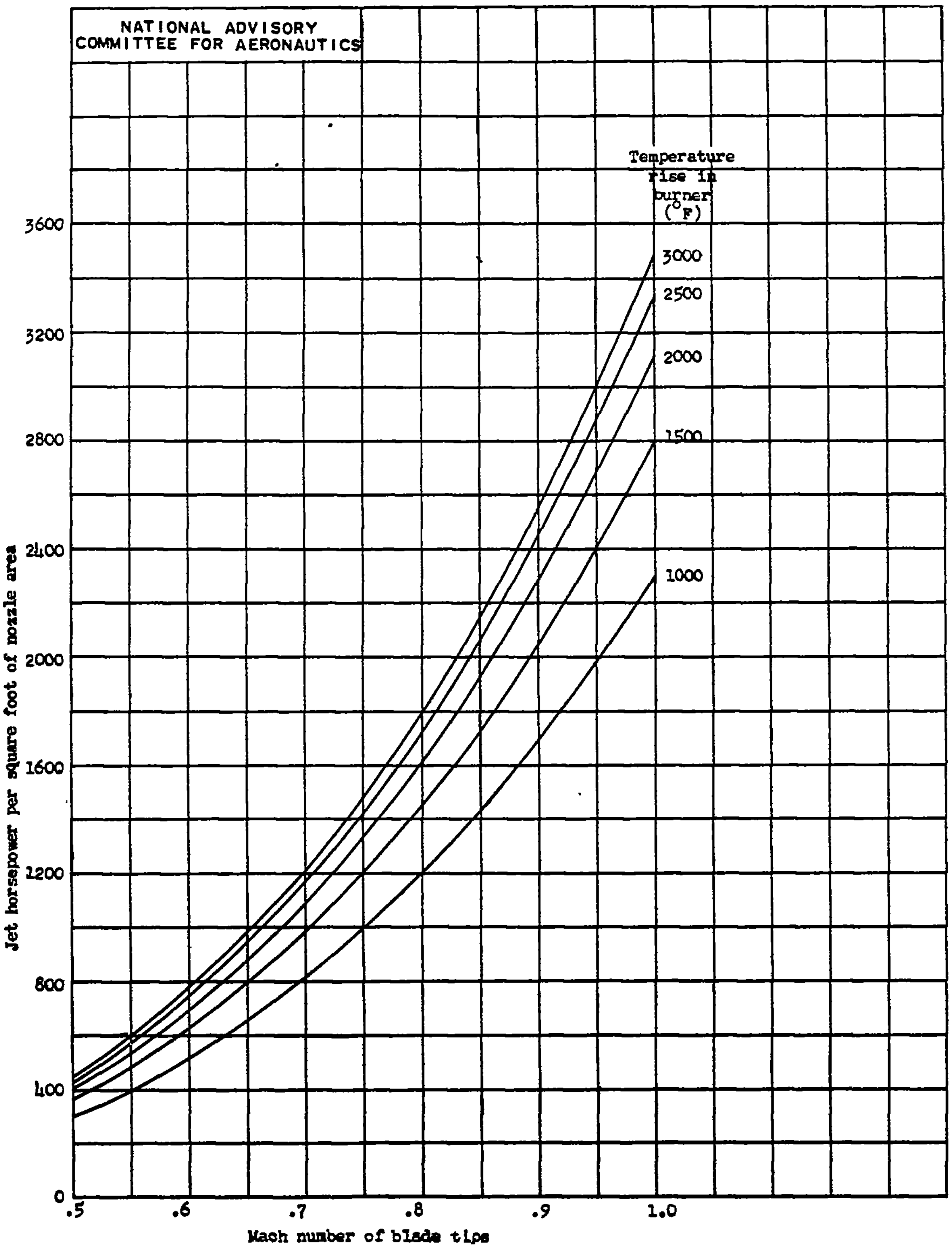

Figure 3. - Ideal power output of an unsupercharged jet-operated propeller at NACA standard sea-level conditions. Combustion and aerodynamic losses are neglected.

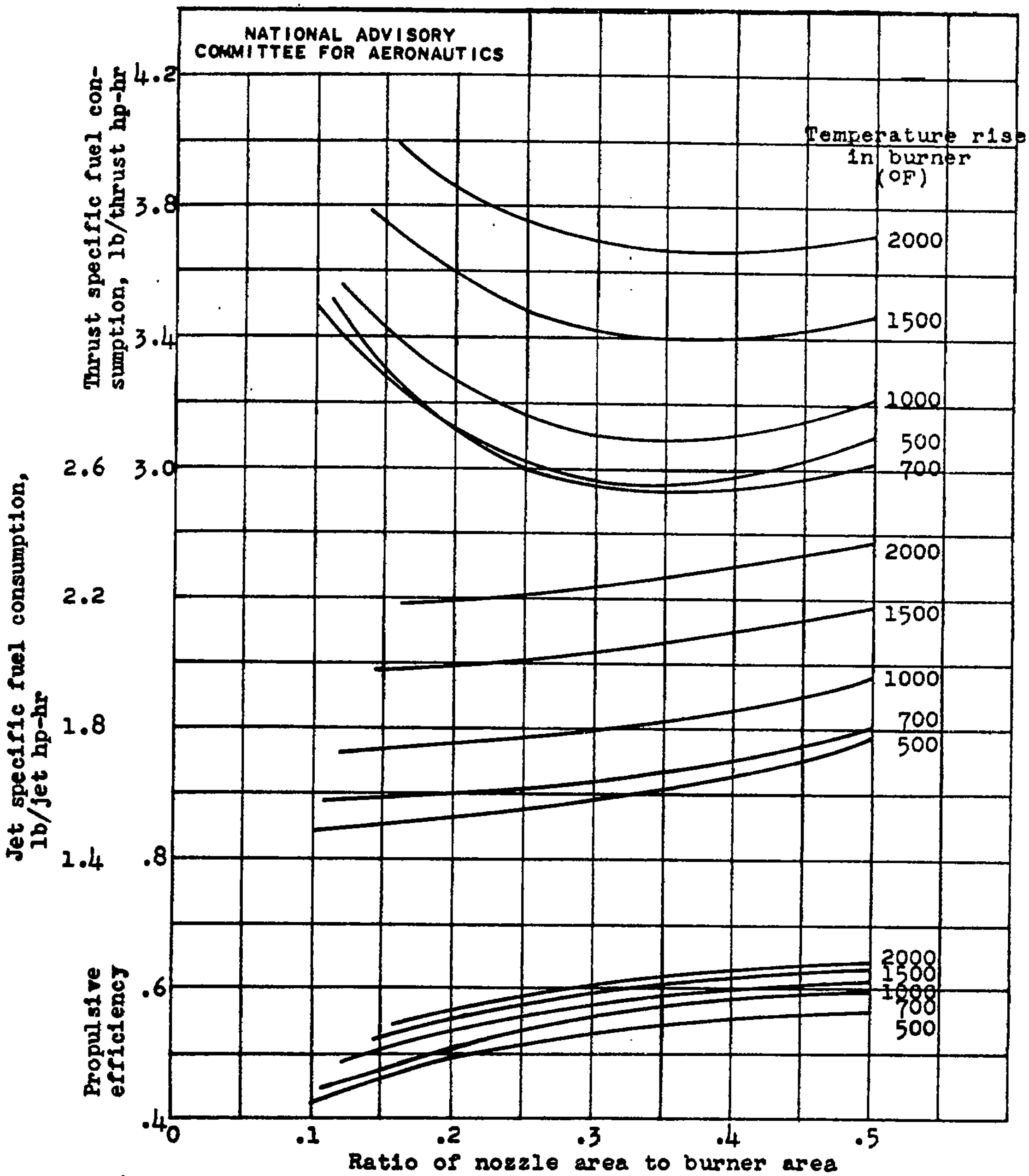

Figure 4. - Effect of ratio of nozzle area to burner area on the specific fuel consumption of a jet propeller, taking into account burner losses and propulsive efficiency. Diameter of propeller, 5 feet; tip Mach number, 0.85; airplane speed, 100 miles per hour; altitude, NACA standard sea level; combustion efficiency, 0.9; thrust horsepower, 56.

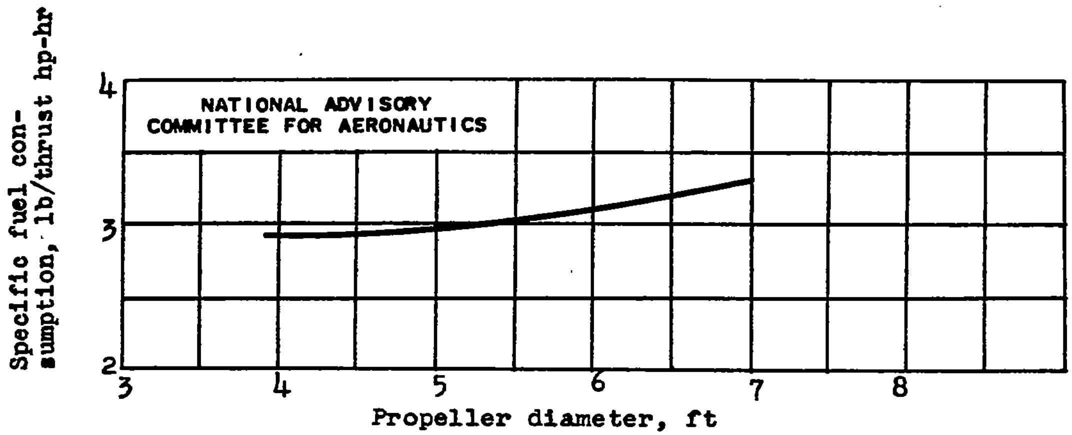

Figure 5. - Effect of propeller diameter on the minimum specific fuel consumption of a jet-operated propeller. Tip Mach number, 0.85; airplane speed, 100 miles per hour; altitude, NACA standard sea level; combustion efficiency, 0.9; thrust horsepower, 56; pressure loss in burner, 50 percent of dynamic head.

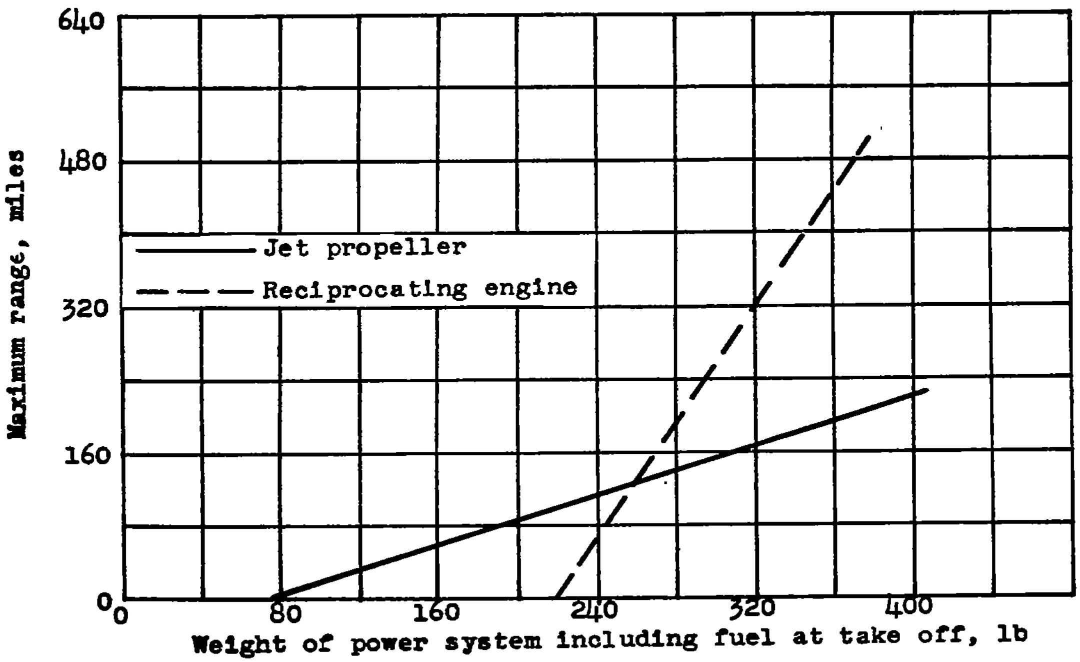

Figure 6. - Range-weight comparison of an airplane powered by a jet-operated propeller and one using a propeller driven by a reciprocating engine. Weight of airplane, 1200 pounds; cruising airspeed, 100 miles per hour; fuel consumption of jet-operated propeller, 3.0 pounds per thrust horsepower-hour; fuel consumption of reciprocating engine, 0.70 pound per thrust horsepower-hour; weight of fuel tanks, 0.5 pound per gallon of capacity; Mach number of tips of jet-operated propeller blades, 0.85.