NACA

RESEARCH MEMORANDUM

EFFECT OF AMBIENT CONDITIONS ON THE PERFORMANCE OF A PRESSURE-JET POWERPLANT FOR A HELICOPTER

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NATIONAL ADVISORY COMMITTEE
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RESEARCH MEMORANDUM

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SUMMARY

A generalized analysis of a pressure-jet powerplant has been made. The effect of changes in ambient conditions on the powerplant performance is provided in a series of charts using parameters containing temperatures and pressures.

Calculations were also made to show the effect of changes in ambient conditions on the performance of a typical 30,000-pound helicopter powered by a pressure jet. If the helicopter can hover in the standard atmosphere at sea level with a jet temperature just under 2100° R, a jet temperature of 4000° R is required to hover at Denver on a hot day (altitude, 6000 ft; temperature, 95° F). For this same helicopter, the rate of climb at a pressure altitude of 9000 feet is about 45 percent less than at sea level. At sea level an increase in ambient temperature from 20° to 95° F decreases the rate of climb about 30 percent. The engine for a pressure-jet helicopter should be sized so that the most demanding power condition is met with the maximum permissible jet temperature.

For the magnitude of changes in ambient conditions investigated, the maximum change in hovering time was 13 percent and in range was 12 percent.

INTRODUCTION

As a part of a study on powerplants suitable for helicopters, the Lewis laboratory has made a preliminary investigation of the pressure-jet system (ref. 1). In this system compressed air is ducted through the helicopter rotor blades and is discharged tangentially at the blade tips. The reaction of the escaping air on the blade tips drives the helicopter rotor. Additional power is obtained by burning fuel with the air in the tip before the gas mixture is ejected. A typical pressure-jet powerplant installed in a helicopter is shown in figure 1. For this analysis the compressed air was assumed to come from an auxilliary compressor driven by a gas-turbine engine.

The pressure-jet powerplant, or system, has certain advantages when adapted to a helicopter. The powerplant is lightweight for the rotor power it furnishes, and both the rotor reduction gear and the antitorque rotor may be eliminated.

The analytical investigation reported in reference 1 is limited in scope in several respects. The pressure-jet-system performance curves are valid only for standard sea-level ambient conditions. The helicopter performance calculations are limited to hovering in the standard atmosphere at sea level and to forward flight at a pressure altitude of 5000 feet at standard sea-level temperature (59° F). No indication is given as to the effect of changes in ambient conditions on the performance of the pressure-jet system or on the flight performance of the helicopter.

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Changes in ambient pressure and temperature have a considerable effect on the performance of a pressure-jet system. It was considered important to determine the magnitude of these changes and their effect on the performance of a helicopter powered with a pressure jet. The variation in pressure-jet performance with changes in ambient conditions might be of considerable importance in selecting design values for the pressure-jet system and in determining the size system required to power the helicopter.

The analysis of reference 1 is extended in this report to give an evaluation of the change in performance of both the pressure-jet powerplant and the helicopter as a whole induced by changes in ambient pressure and temperature. An indication is given of the effect of ambient-temperature changes on the choice of design auxiliary-compressor pressure ratio and design jet temperature. Calculations are included to show the effect of ambient changes on hovering time, range, and rate of climb of the pressure-jet helicopter. Ambient pressures corresponding to altitudes from sea level to 9000 feet and ambient temperatures from 20° to 95° F were investigated.

ANALYSIS

The pressure-jet powerplant performance characteristics were determined by a cycle analysis in which the state of the gas was computed at successive stations in the system indicated in figure 2. Component values held fixed throughout the analysis are given as follows:

Diffuser-inlet total-pressure recovery, P_2/P_0 . . . . 0.95
Duct friction factor, k_f 2.5
Burner efficiency, η_b 0.90
Jet velocity coefficient, $C_{v,j}$ 0.95
Ratio of duct area to burner area, A_x/A_4 . . . . 0.667

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The auxiliary-compressor characteristics are shown in figure 3. Momentum pressure losses in the burner were evaluated as functions of the burner-inlet Mach number M_4 and the burner temperature ratio T_5/T_4 by means of the chart of figure 4. The symbols used in this report are defined in appendix A, and details of the cycle analysis are presented in appendix B.

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The results of the cycle analysis are presented in terms of generalized parameters. These parameters have been extensively used in the analysis of gas-turbine engines. The basis of their generalization is given in references 2 and 3. The same principles have been applied to the pressure-jet system. As a result of the generalization, the tip speed of reference 1 generalizes to a tip Mach number M_t, and the jet temperature to a jet temperature ratio T_6/T_2. Thrust per unit duct area is generalized to $F/A_x\delta_0$, and thrust per unit air flow to $\frac{F/\delta_0}{w\sqrt{\theta_2}/\delta_2}$. The total temperatures at stations 0, 1, and 2 are assumed equal.

Auxiliary-Compressor Characteristics and Operation

The compressor characteristics shown in figure 3 are similar to those used in reference 1. The assumed design has been modified somewhat so that there is a more nearly linear relation between compressor speed and air flow along the operating line near rated conditions. The ordinate and abscissa of the compressor map have been generalized so as to be independent of design pressure ratio and rated air flow.

The mechanical speed of the gas turbine and auxiliary compressor was kept at the rated value for the entire analysis. For those flight conditions that required burning fuel in the tips, the jet-exhaust-nozzle areas at the rotor tips were adjusted to keep the compressor operating point on the operating line shown in figure 3. When the rotor power requirements were sufficiently small so that no tip burning was required, power was modulated by the jet exhaust nozzles at the rotor tips. To reduce power, the nozzles were opened and the compressor operated away from the operating line along a constant-equivalent-speed line at reduced compressor pressure ratio.

Helicopter Design

The helicopter assumed for this analysis is identical to the one used in reference 1. It has a gross weight of 30,000 pounds and is equipped with a single, two-bladed rotor 80 feet in diameter. Yaw is controlled by laterally deflecting the turbine gases issuing from the exhaust nozzle (fig. 1).

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The blade thickness-chord ratio is 0.12, and the blade section area is $0.0646 \times (\text{chord})^2$. Three-tenths of the blade-section area is used for the compressed air duct.

Helicopter Aerodynamics

Aerodynamic data for the helicopter were derived by the methods of references 4 and 5. Aerodynamic parameters used are given in appendix C. A flat-plate area of 36 square feet, calculated from reference 6, was used for determining the longitudinal drag. Rotor performance in hovering is generalized and presented in figure 5. Equivalent horsepower per pound of gross weight $(hp/\sqrt{\theta_0}\delta_0)/(W_g/\delta_0)$ is plotted against tip Mach number M_t for several equivalent disk loadings $W_g/S\delta_0$. The derivations for the equivalent parameters appear in appendix C.

Power requirements in forward flight and in climb were determined by the procedure of reference 5, which is simpler than that used in reference 1. The power required for forward flight as determined by reference 5 is about 10 percent less than that given in reference 1.

Helicopter Performance

After the rotor power requirements had been determined, helicopter performance was computed in the same manner as in reference 1. Hovering time and forward flight range at 80 knots were computed, the entire disposable load assumed to be fuel. Rate of climb at a forward speed of 60 knots was also computed for a helicopter gross weight of 30,000 pounds. Performance was computed for a range of ambient temperatures from 20° to 95° F and for pressure altitudes from sea level to 9000 feet.

RESULTS

The results of the generalized pressure-jet analysis are presented in figure 6. On these power-available charts equivalent thrust per unit air flow $\frac{F/\delta_0}{w\sqrt{\theta_2}/\delta_2}$ is plotted against equivalent thrust per unit duct area $F/A_x\delta_0$ for constant values of jet temperature ratio T_6/T_2 and duct Mach number M_x. A separate chart is required for each auxiliary-
3694 compressor pressure ratio and each tip Mach number. Pressure-jet performance is presented for a range of jet temperature ratios from 2 to 8, compressor pressure ratios from 2.25 to 4, and tip Mach numbers from 0.4 to 0.8.

When interpolation is required to find the pressure-jet power available for pressure ratios and tip Mach numbers other than those included on the charts of figure 6, the interpolation for tip Mach number is of secondary importance. For example, with an auxiliary-compressor pressure ratio of 3, a jet temperature ratio of 8, and a duct Mach number of 0.16, the equivalent thrust per unit air flow decreases from 94.7 at a tip Mach number of 0.4 to 89.8 at a tip Mach number of 0.8, a decrease of 5.2 percent.

Effect of Changes in Ambient Conditions on Pressure-Jet Powerplant Performance in Helicopter

Pressure. - In reference 1 is shown how the determination of helicopter design-point power requirements and the selection of powerplant design-point values establish an operating point and operating line on one of the power-available charts. From figure 5 and an assumed rotor blade and duct configuration it is established that the rotor tip thrust required for hovering for a helicopter with a gross weight of 30,000 pounds, a disk loading of 6 pounds per square foot, and a rotor tip Mach number of 0.6 at NACA standard sea-level conditions is 2620 pounds per square foot of duct area. Matching this power requirement with the power available in the charts of figure 6 establishes the powerplant operating conditions. For example, if the design-point auxiliary-compressor pressure ratio is 3.0, the jet temperature ratio is 4.0, and the rotor tip Mach number is 0.6, the match point where the thrust available is equal to the thrust required is shown in figure 6(i) as occurring at a duct Mach number of 0.23 and a thrust per pound of air of 56 pound-seconds per pound. The constant Mach number line through this design operating point is the design operating line.

In order to evaluate the effect of changes in ambient pressure on the performance of the pressure-jet powerplant, an analysis was made of the aforementioned helicopter hovering at standard sea-level temperature (59° F). This analysis shows how the pressure-jet performance has to change to meet a decrease in ambient pressure. From figure 5 it was determined that the rotor tip thrust required varied with ambient pressure, as shown in the lower part of figure 7(a), wherein the rotor tip thrust required is plotted against the ambient pressure parameter δ_0. The other two parts of figure 7(a) were determined with the help of figure 6(i) and a generalized fuel-air ratio chart.

For example, at a value of δ_0 of 0.8 (pressure altitude, 6000 ft), 3964
the rotor tip thrust required (from lower part of figure 7(a)) is 2800 pounds per square foot of duct area. This value of thrust corresponds to an equivalent thrust per unit duct area of 2800/0.8 or 3500 pounds per square foot. Along the operating line in figure 6(i) an equivalent thrust of 3500 pounds per square foot requires a jet temperature ratio of 6.1 in contrast with the design-point value of 4.0 required at sea level. The increase in jet temperature ratio increases the rotor-horsepower specific fuel consumption from 1.78 pounds of fuel per hour per rotor horsepower at sea level to 2.09 at a pressure altitude of 6000 feet. In other words, in order to meet a 7-percent increase in thrust requirement brought about by a 20-percent decrease in ambient pressure, the jet temperature ratio has to be increased 53 percent; this results in a 12-percent increase in specific fuel consumption.

<u>Temperature</u>. - Changes in the ambient temperature affect the pressure-jet helicopter in two independent ways: The Mach number of the auxiliary compressor changes, and the rotor power requirement changes.

Because the auxiliary compressor operates at a constant mechanical speed, an increase in ambient temperature decreases the compressor equivalent speed. Because the auxiliary compressor is constrained to the operating line (fig. 3), a decrease in equivalent speed decreases the air flow and the compressor pressure ratio. With a decrease in both the air flow and the pressure ratio, there is a decrease in the power available in the pressure-jet system if the jet temperature ratio is held constant.

The effect of ambient temperature on rotor tip thrust required for hovering at sea-level ambient pressure is shown in the lower part of figure 7(b). The data were derived from figure 5 with a constant rotor tip speed of 670 feet per second assumed. An increase in ambient temperature decreases the rotor tip Mach number and the ambient density. While the decrease in rotor tip Mach number acts to decrease the thrust required, the effect of the reduced air density to increase the thrust requirements is predominant; there is, therefore, a small increase in rotor tip thrust required as the ambient temperature increases.

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The combined effects of an increase in ambient temperature on the compressor operating condition and on the rotor power requirement means that the jet temperature ratio must be increased along with the increase in ambient temperature in order to maintain the helicopter in hovering flight. The magnitude of the required change in jet temperature ratio and the accompanying change in specific fuel consumption is indicated by the following example.

The change in jet temperature ratio necessary to match the change in required rotor tip thrust shown in figure 7(b) was computed along with the rotor-horsepower specific fuel consumption. The effect of an increase in ambient temperature from the design value of 59° to 95° F on the performance of the pressure-jet powerplant is discussed in detail and evaluated in appendix D. This evaluation shows that the compressor pressure ratio is reduced from 3.0 to 2.8, and the air flow is reduced 6 percent. The appropriate power-available chart and corresponding operating line are shown in figure 6(h). The rotor tip thrust required at 95° F ($\theta_0 = 1.069$) is 2685 pounds per square foot (fig. 7(b)). The equivalent thrust available (fig. 6(h)) must be equal to this required rotor tip thrust at sea-level pressure. On figure 6(h) the intersection of the 2685 abscissa and the operating line yields a required jet temperature ratio of about 4.75. The corresponding rotor specific fuel consumption is 2.0 pounds per rotor horsepower-hour.

In like manner, the required jet temperature ratio and specific fuel consumption can be computed for other ambient temperatures. The power-available chart and operating line for the pressure jet used in this example are shown in figure 6(j) for an ambient temperature of 20° F.

The effect of a range of ambient temperatures on the jet temperature ratio required and the specific fuel consumption is also shown in figure 7(b). For the example illustrated, a change in ambient temperature from 20° to 95° F increases the rotor thrust required 4 percent, the jet-temperature ratio required 23 percent, and the specific fuel consumption 16 percent.

These examples illustrate the deleterious effect that a reduction in ambient pressure and an increase in ambient temperature have on the fuel economy of a pressure-jet system.

Effect of Changes in Ambient Conditions on Pressure-Jet-Helicopter Performance

This section shows how the engine performance changes caused by changes in ambient conditions (discussed in the preceding section) affect helicopter performance. The same helicopter was assumed as in the previous examples. In the results which follow, hovering ceiling and rate of climb were computed for the design gross weight. Hovering time and flight range were computed assuming that all the fuel was burned in flight.

Hovering ceiling. - The discussion in the preceding section shows that, if the ambient pressure is decreased or the ambient temperature increased, an increase in jet temperature ratio is required to maintain hovering flight. Accordingly, some reserve power must be provided for the helicopter if it is to hover in ambient conditions which are more adverse for pressure-jet operation than the design ambient condition. One way to increase the rotor tip thrust under these adverse ambient conditions is to increase the jet temperature. For this analysis an upper limit of 4000° R was assumed for stoichiometric combustion with hydrocarbon fuels.

For the present, let it be assumed that it is desirable to design a helicopter to meet large power requirements under adverse conditions by burning in the tips to the stoichiometric limit, 4000° R. The validity of this assumption is discussed later. The problem now at hand is to determine the helicopter hovering ceiling for a series of design jet temperatures. Here, as in reference 1, design jet temperature is that temperature required for hovering under NACA standard sea-level conditions.

Helicopter ceiling is plotted in terms of the ambient-pressure and -temperature parameters (δ_0 and θ_0) for various design jet temperatures in figure 8. Jet temperature at the hovering ceiling is, in all cases, 4000° R. The hovering ceiling increases considerably as the design jet temperature is lowered because of the increasing margin between design and maximum-available power. Similarly, the ceiling is also increased at the lower ambient temperatures. In order to hover at Denver on a hot day (6000 ft at 95° F) ($\delta_0 = 0.8$, $\theta_0 = 1.069$), a design jet temperature used in sea-level hovering of 2100° R or less is required.

Such low design jet temperatures give large reserve power to the helicopter in the NACA standard sea-level atmosphere. For example, if the design jet temperature were 2076° R (jet-temperature ratio = 4.0), the helicopter would have an available power 59 percent in excess of that required to hover in standard sea-level conditions. The reserve would be available by increasing the jet temperature to 4000° R.

A helicopter with such a low design jet temperature is penalized somewhat in maximum hovering time and ultimate range. Data from reference 1, replotted in figure 9, indicate the magnitude of this penalty. For an auxiliary-compressor pressure ratio of 3.0, the hovering time for a design jet temperature of 2100° R is only 0.1 hour less than the maximum hovering time of 5.45 hours. At this same design jet temperature there is a moderate loss in range of 60 nautical miles from the maximum of 730 miles.

The preceding discussion shows that, for a pressure-jet system of a given size, burning to a jet temperature of 4000° R provides the maximum hovering ceiling. The question still to be answered is: If there is to be considerable hovering under ambient conditions that put greater demand on the pressure-jet system, is it better to use a given compressor and a jet temperature of 4000° R, or use a larger compressor and gas turbine and burn to a lower jet temperature? Calculations were made similar to those used to produce the data of figure 9, but for ambient conditions at Denver on a hot day. The data indicate that maximum hovering time was obtained with a design jet temperature of 4000° R. The auxiliary-compressor pressure ratio for longest hovering was a little above 3. Because of the decreased density of the ambient air, a small increase in auxiliary-compressor pressure ratio is desirable to prevent thermal choking in the tip burners. From these calculations it may be concluded that the most demanding power conditions should be met with a jet temperature equal to the maximum value obtainable. A corollary to this conclusion is that the pressure-jet unit should be the smallest unit that will satisfy the maximum power requirement under the least advantageous ambient conditions. The auxiliary-compressor pressure ratio should be only slightly greater than that which gives the best hovering time at sea level (ref. 1).

Hovering time. - The effect of changes in ambient conditions on hovering time is shown in figure 10. These data are for a design auxiliary-compressor pressure ratio of 3.0 and a design jet-temperature ratio of 4.0 (2076° R). In figure 10(a) hovering time is plotted against the ambient-pressure parameter δ_0 for an ambient-temperature-parameter value of 1.0. Hovering time decreases from 5.4 hours at sea level ($\delta_0 = 1.0$) to about 4.7 hours at an altitude of 9000 feet ($\delta_0 = 0.715$), which is the hovering ceiling for an ambient temperature of 59° F ($\theta_0 = 1.0$).

In figure 10(b) hovering time is plotted against the ambient-temperature parameter for an ambient-pressure parameter of 1.0. The change in hovering time with temperature is small over a likely range of ambient temperatures. As the temperature increases from 20° F ($\theta_0 = 0.925$) to 95° F ($\theta_0 = 1.069$), the hovering time, at a pressure altitude corresponding to sea level, decreases from 5.55 to 5.05 hours.

Range. - Helicopter range, at a flight speed of 80 knots, is shown as a function of the ambient-pressure and -temperature parameters in figure 11. The design jet temperature ratio is 4.0 (2076° R), and the design auxiliary-compressor pressure ratio is 3.0. The effect of changes in ambient pressure was computed at 59° F ($\theta_0 = 1.0$), and the effect of changes in ambient temperature was computed at a pressure altitude of 6000 feet ($\delta_0 = 0.8$). Figure 11(a) shows that maximum range is obtained at some value of pressure altitude other than sea level. A maximum range of 730 nautical miles is obtained at a pressure altitude of about 5500 feet and falls off to 650 miles at sea level and 675 miles at 9000 feet.

The shape of the curve is determined by the rotor power requirements. Rotor power decreases as the altitude initially increases, but the power required begins to increase for altitudes above 6000 feet. There is some increase in the thermodynamic efficiency of the cycle as the altitude increases. At sea level, the rotor power available at the design auxiliary-compressor pressure ratio and no tip burning is in excess of that required after some of the fuel has been burned. In order to further reduce the power available, the jet exhaust-nozzle area at the rotor blade tips was increased and the pressure ratio lowered. This reduction in pressure ratio increases the specific fuel consumption. Forward flight at 9000 feet does not require the operation of the auxiliary compressor at other than its design point. The specific fuel consumption, averaged over the entire flight, is about 9 percent better at 9000 feet than at sea level.

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Changes in ambient temperature have almost no effect on helicopter range over the scale of temperature investigated, as is shown in figure 11(b). At 95° F the range had decreased 25 miles from its maximum value of 730 miles.

Rate of climb. - In the section "Hovering ceiling" it is pointed out that for hovering at some demanding ambient conditions, such as at Denver on a hot day, a helicopter requires a large amount of power in excess of that required for hovering at sea level. With all this power, exceptional rates of climb would be expected. The effect of changes in ambient conditions on rate of climb of a particular helicopter is shown in figure 12. The helicopter is the same as the one whose hovering time and range performance are presented in preceding sections. It has a design jet temperature of 2076° R but uses a jet temperature of 4000° R during climb. Rate of climb was computed for a forward speed of 60 knots, which is near optimum for climb. Rate of climb falls off almost linearly with pressure altitude from a value of 2950 feet per minute at sea level to 1600 feet per minute at 9000 feet.

Increases in ambient temperature have an adverse effect on rate of climb. At a pressure altitude equivalent to sea level, the rate of climb is 3300 feet per minute at 20° F and is reduced to 2350 feet per minute at 95° F.

SUMMARY OF RESULTS

The following results were derived from a generalized analytical study of a pressure-jet powerplant for a helicopter:

1. A decrease in ambient pressure or an increase in ambient temperature adversely affects the performance of a pressure-jet powerplant. Both ambient changes require an increase in jet temperature ratio with a resulting increase in specific fuel consumption in order to maintain the thrust output. In a hovering helicopter the rotor-horsepower specific fuel consumption is 12 percent higher at a pressure altitude of 6000 feet than at sea level and is 16 percent higher at 95° F than at 20° F.

2. In order to be able to hover at 6000 feet on a 95° F day with a 4000° R jet temperature, the pressure-jet helicopter must be designed to hover at standard sea-level conditions with a jet temperature less than 2100° R. With such a design jet temperature there is a power reserve at sea level which is 59 percent above the power required for hovering.

3. Longer hovering time under adverse ambient conditions can be obtained by operating at maximum jet temperature than by installing a larger engine and operating at reduced jet temperature.

4. A helicopter with a power reserve 59 percent over that required for sea-level hovering can climb at a forward speed of 60 knots at the rate of 2950 feet per minute at sea level. At a pressure altitude of 9000 feet the rate of climb decreases 45 percent to 1600 feet per minute. An increase in ambient temperature from 20° to 95° F at sea-level pressure decreases the rate of climb 29 percent, from 3300 to 2350 feet per minute.

5. Changes in ambient conditions of the magnitude investigated have little effect on hovering time or range. When the pressure altitude is increased from sea level to 9000 feet, the hovering time is reduced 13 percent. The range is 12 percent greater at 5500 feet than at sea level. Changes in ambient temperature from 20° to 95° F have even less effect on hovering time and range.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 7, 1956

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
a	velocity of sound, ft/sec
C_Q	torque or power coefficient
C_T	thrust coefficient
$C_{v,j}$	jet velocity coefficient
F	rotor tip thrust
f	fuel-air ratio
g	gravitational constant, 32.2 ft/sec^2
hp	horsepower
k_f	duct friction coefficient
M	Mach number
N	auxiliary-compressor speed
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	gas constant, 53.4 ft-lb/(lb)($^{\circ}$R)
S	rotor disk area, sq ft
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
V	velocity, ft/sec
W_g	helicopter gross weight, lb
w	air flow, lb/sec

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γ	ratio of specific heats of gases
δ	ratio of total pressure to NACA standard pressure of 2116 lb/sq ft
η	efficiency
θ	ratio of total temperature to NACA standard temperature of 519° R
ρ	density, slugs/cu ft

Subscripts:

a	stagnation conditions
b	burner
c	compressor
j	jet
t	rotor tip
x	hub end of duct
0	ambient
1	diffuser inlet
2	compressor inlet
3	compressor discharge
4	burner inlet
5	burner outlet
6	exhaust-nozzle exit

APPENDIX B

PRESSURE-JET CYCLE ANALYSIS

Assumptions

The following detailed assumptions were made in the analysis:

The effect of ram pressure ratio was ignored in forward flight, so that

$$\frac{P_0}{p_0} = \frac{T_0}{t_0} = 1$$

The total temperature at the auxiliary-compressor face was assumed equal to the ambient temperature; hence,

$$T_0 = T_1 = T_2$$

No heat loss was considered between the auxiliary-compressor discharge and the entrance to the tip burner,

$$T_3 = T_x = T_4$$

The total temperature in the tip exhaust nozzle was considered to be that of the tip burner exit,

$$T_5 = T_6$$

No total-pressure loss was assumed between the auxiliary-compressor discharge and the hub end of the duct. That is,

$$P_3 = P_x$$

No total-pressure loss was assumed in the tip nozzle; thus,

$$P_5 = P_6$$

The ratio of the specific heats of the gases γ was considered to be constant at 1.38 through the cycle until fuel was added and burned. γ in the exhaust nozzle was taken as 1.30.

Analysis

Two factors were considered which affected the relation between the total pressure at station 4 and the total pressure at station 3.

The pumping effect of the rotating helicopter blade tended to increase the pressure at station 4 and was of the magnitude $\frac{\rho_x V_t^2}{2}$. The friction effect within the rotor blade duct tended to decrease the pressure at station 4. The magnitude of the friction effect was

$$-\frac{k_f \rho_x V_x^2}{2}$$

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Accordingly, the total pressure at station 4 was

$$P_4 = P_3 + \frac{\rho_x}{2}\left(V_t^2 - k_f V_x^2\right)$$

From the foregoing equation, the duct pressure ratio can be written as

$$\frac{P_4}{P_3} = 1 + \frac{\gamma}{2}\left(\frac{\rho}{\rho_a}\right)_x \left[\frac{M_t^2}{T_3/t_0} - k_f M_x^2 \left(\frac{t}{T}\right)_x\right]$$

From the continuity of flow between stations x and 4,

$$\rho_x V_x A_x = \rho_4 V_4 A_4$$

The definition of $\rho_a a_a$ gives

$$\frac{P_3}{RT_3}\sqrt{\gamma g R T_3}\left(\frac{\rho V}{\rho_a a_a}\right)_x A_x = \frac{P_4}{RT_4}\sqrt{\gamma g R T_4}\left(\frac{\rho V}{\rho_a a_a}\right)_4 A_4$$

and

$$\left(\frac{\rho V}{\rho_a a_a}\right)_x \frac{A_x/A_4}{P_4/P_3} = \left(\frac{\rho V}{\rho_a a_a}\right)_4$$

which may be used to find M_4.

The pressure ratio across the tip burner can be found from M_4, T_6/T_4, and figure 4. The following relations exist among the temperature ratios:

$$\frac{T_6}{T_2} = \frac{T_6}{T_4}\frac{T_3}{T_2}$$

and

$$\frac{T_3}{T_2} = \frac{\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_c} + 1$$

Thrust at the rotor tip can be found by evaluating the jet velocity

$$V_j = C_{v,j}M_j\sqrt{\gamma gRt_6}$$

$$\left(\frac{P_6}{p_0}\right)^{\frac{\gamma-1}{\gamma}} = 1 + \frac{\gamma - 1}{2} M_j^2$$

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$$M_j = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P_6}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

$$\frac{V_j}{\sqrt{\theta_2}} = C_{v,j}M_j \frac{\sqrt{\gamma gR519}}{\sqrt{\left(\frac{P_6}{p_0}\right)^{\frac{\gamma-1}{\gamma}}}}\sqrt{\frac{T_6}{T_2}} = C_{v,j}\sqrt{\frac{2\gamma gR519}{\gamma - 1}}\sqrt{\frac{T_6}{T_2}}\sqrt{1 - \left(\frac{p_0}{P_6}\right)^{\frac{\gamma-1}{\gamma}}}$$

The thrust at the rotor tip is given by

$$\frac{F}{\sqrt{\theta_2}} = \frac{w(1 + f)}{g}\left(\frac{V_j}{\sqrt{\theta_2}} - \frac{V_t}{\sqrt{\theta_2}}\right) = \frac{w(1 + f)}{g}\left(\frac{V_j}{\sqrt{\theta_2}} - \frac{M_t\sqrt{\gamma gRt_0}}{\sqrt{T_2/519}}\right)$$

$$\frac{F}{w\sqrt{\theta_2}} = \frac{1 + f}{g}\left(\frac{V_j}{\sqrt{\theta_2}} - M_t\sqrt{\frac{\gamma gR519}{T_2/t_0}}\right)$$

$$\frac{p_0}{P_0}\frac{F/\delta_0}{w\sqrt{\theta_2}/\delta_2} = \frac{P_2}{P_0}\left(\frac{V_j}{\sqrt{\theta_2}} - M_t\sqrt{\frac{\gamma gR519}{T_2/t_0}}\right)\frac{1 + f}{g}$$

Thrust per unit duct area is computed by writing the continuity equation

$$w = g\rho_x V_x A_x$$

$$= \frac{P_3}{RT_3}\sqrt{\gamma gRT_3}\left(\frac{\rho V}{\rho_a a_a}\right)_x A_x$$

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$$\frac{w\sqrt{\theta_2}}{A_x\delta_2} = \frac{P_3}{P_2}\sqrt{\frac{\gamma g T_2}{RT_3}}\left(\frac{\rho V}{\rho_a a_a}\right)_x \frac{2116}{\sqrt{519}} = \frac{P_3}{P_2}\,\frac{2116}{\sqrt{T_3/T_2}}\sqrt{\frac{\gamma g}{519R}}\left(\frac{\rho V}{\rho_a a_a}\right)_x$$

$$= 84.8\,\frac{P_3/P_2}{\sqrt{T_3/T_2}}\left(\frac{\rho V}{\rho_a a_a}\right)_x$$

$$\frac{p_0}{p_0}\,\frac{F/\delta_0}{A_x} = \frac{p_0 F/\delta_0}{P_0 w\sqrt{\theta_2}/\delta_2} \times \frac{w\sqrt{\theta_2}}{\delta_2 A_x}$$

The power-available charts of figure 6 were calculated by means of the above analysis by selecting an auxiliary-compressor pressure ratio P_3/P_2 and tip Mach number M_t and computing thrust per unit duct area $F/A_x\delta_0$ and thrust per unit air flow $\frac{F/\delta_0}{w\sqrt{\theta_2}/\delta_2}$ for a series of jet temperature ratios T_6/T_2 and duct Mach numbers M_x.

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APPENDIX C

ROTOR AERODYNAMICS IN HOVERING

Power and thrust coefficients are defined in the following relations:

$$\text{Power} = C_Q \rho V_t^3 S$$

$$W_g = C_T \rho V_t^2 S$$

Then rotor horsepower is

$$hp = \frac{C_Q}{550} \rho V_t^3 \frac{W_g}{C_T \rho V_t^2}$$

$$= \frac{C_Q}{C_T} V_t \frac{W_g}{550}$$

and horsepower per unit gross weight is

$$\frac{hp/\sqrt{\theta_0}\,\delta_0}{W_g/\delta_0} = 2.031 \frac{C_Q}{C_T} M_t$$

The relation between C_Q and C_T is from reference 4, page 83, for

$$B^2 = 0.95 \qquad \delta_1 = -0.0216$$

$$\delta_0 = 0.0087 \qquad \delta_2 = 0.4$$

$$\sigma = 0.0732 \qquad a = 5.73$$

The preceding symbol notation is that of reference 4.

APPENDIX D

DETERMINATION OF PRESSURE-JET OPERATING LINE

WITH CHANGE IN AMBIENT TEMPERATURE

The text of this report and reference 1 show how the helicopter rotor power requirement and pressure-jet-system parameters establish the operating point at design conditions and the system operating line for the design ambient temperature. The purpose of this appendix is to show how to determine the appropriate power-available chart and corresponding operating line for the system at some other ambient temperature.

The procedure is as follows:

(1) Find the design equivalent air flow per unit duct area $\frac{w\sqrt{\theta_2}}{\delta_2 A_x}$ by dividing the equivalent thrust per unit duct area by the equivalent thrust per unit air flow at the design operating point or anywhere along the system operating line for design ambient temperature.

For the ambient temperature, other than design ambient temperature, under consideration,

(2) Find the rotor tip Mach number $V_t/\sqrt{\gamma g R T_0}$.

(3) Find the fraction rated equivalent speed $\frac{N/\sqrt{\theta_2}}{(N/\sqrt{\theta_2})_{rated}}$.

(4) Find the compressor pressure ratio and fraction rated equivalent air flow $\frac{w\sqrt{\theta_2}/\delta_2}{(w\sqrt{\theta_2}/\delta_2)_{rated}}$ corresponding to the fraction rated equivalent speed of (3) along the compressor operating line of figure 3.

(5) Select the power-available chart (fig. 6) corresponding to the compressor pressure ratio of (4) and the rotor tip Mach number of (2).

The system operating line for the ambient temperature under consideration should be drawn through the origin of the chart selected in (5). The slope will be the reciprocal of the product of the design equivalent air flow per unit duct area of (1) and the fraction rated equivalent air flow of (4).

The following determination is an example of the use of the foregoing procedure. It is assumed that a pressure-jet system with an auxiliary-compressor pressure ratio of 3.0, a tip Mach number of 0.6, and a jet temperature ratio of 4.0 is to be matched at NACA standard sea-level conditions to a helicopter requiring a tip thrust of 2625 pounds per unit duct area to hover at a rotor tip speed of 670 feet per second. It is further assumed that both rotor tip speed and the auxiliary-compressor mechanical speed are to be held constant. In order to find the power-available chart and establish the system operating line (ambient temperature, $T_0 = T_2 = 59^\circ$ F = 519° R), the following procedure is used: 3964

(1) The design-point chart, corresponding to design pressure ratio of 3.0 and design tip Mach number of 0.6, is figure 6(i). At the design point (intersection of the 2625-pound-per-unit-duct-area abscissa and 4.0 jet temperature ratio), the equivalent thrust per unit air flow on the ordinate is 55.4 pound-seconds per pound. The design equivalent air flow per unit duct area is 2625/55.4 or 47.4 pounds per second per square foot.

For the ambient temperature of 555° R,

(2) Rotor tip Mach number equals $670/\sqrt{1.4 \times 32.2 \times 53.3 \times 555}$ or 0.58.

(3) Fraction rated equivalent speed is $\sqrt{\frac{519}{555}}$ or 0.966.

(4) Along the operating line of figure 3 at 0.966 rated equivalent speed, the compressor pressure ratio is 2.8 and the fraction rated equivalent air flow is 0.94.

(5) The power-available curve for a pressure ratio of 2.8 and a rotor tip Mach number of 0.58 is figure 6(h).

On figure 6(h) draw an operating line through the origin with a slope of $1/(47.4 \times 0.94)$ or 0.02245.

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1. Krebs, Richard P., and Miller, William S., Jr.: Analysis of a Pressure-Jet Powerplant for a Helicopter. NACA RM E54L23, 1955.

2. Warner, D. F., and Auyer, E. L.: Contemporary Jet-Propulsion Gas Turbines for Aircraft. Mech. Eng., vol. 67, no. 11, Nov. 1945, pp. 707-714.

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3. Sanders, Newell D.: Performance Parameters for Jet-Propulsion Engines. NACA TN 1106, 1946.

4. Gessow, A., and Myers, G. C.: Aerodynamics of the Helicopter. The Macmillan Co., 1952.

5. Gessow, Alfred, and Tapscott, Robert J.: Charts for Estimating Performance of High-Performance Helicopters. NACA TN 3323, 1955.

6. Johnson, J. A., et al.: Helicopter Propulsion System Study. Thermal Res. and Eng. Corp., Conshohocken (Penn.), Sept. 1952. (USAF Contract AF 33(038)-22185.)

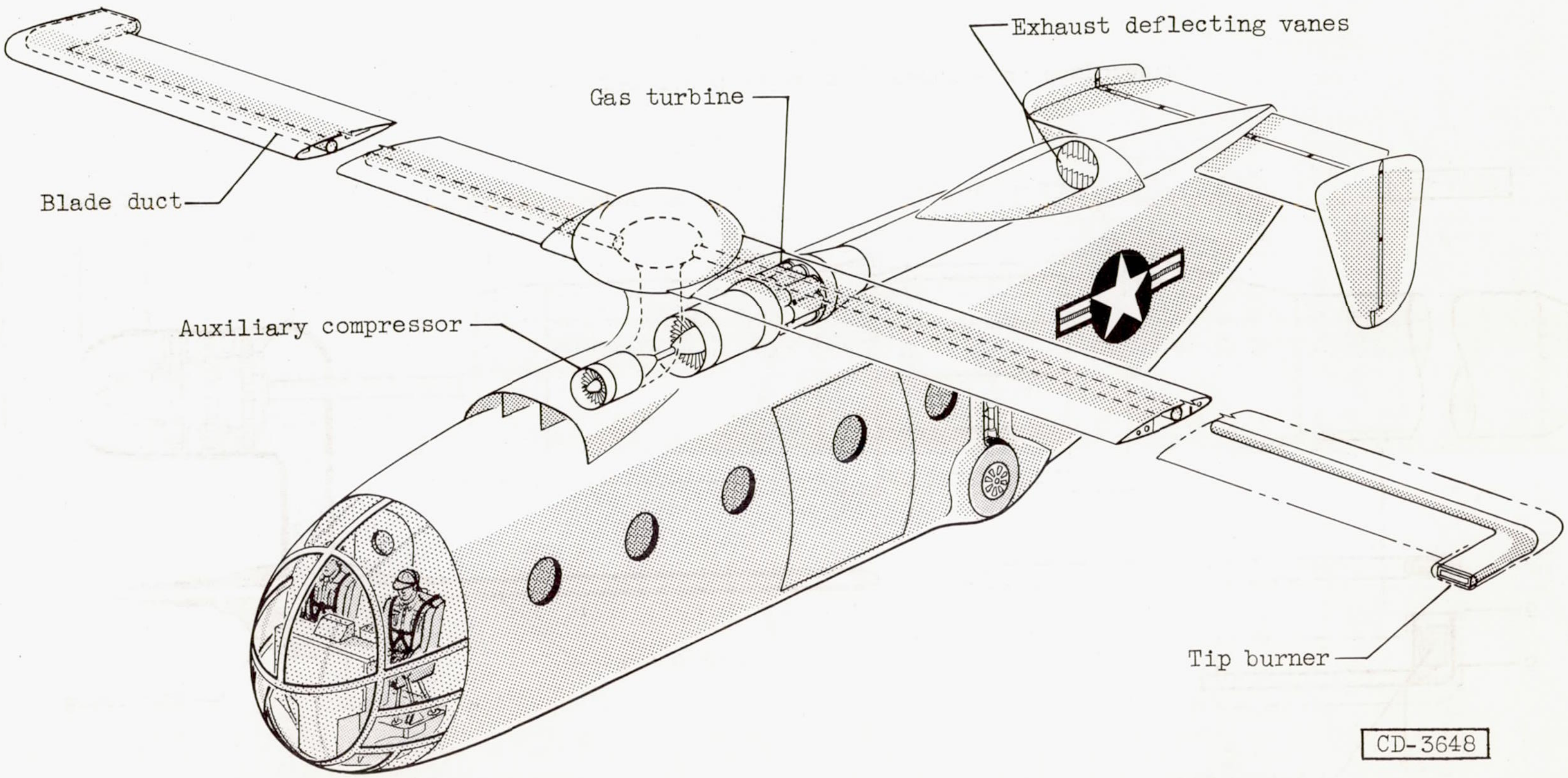

Figure 1. - Assumed configuration for pressure-jet helicopter.

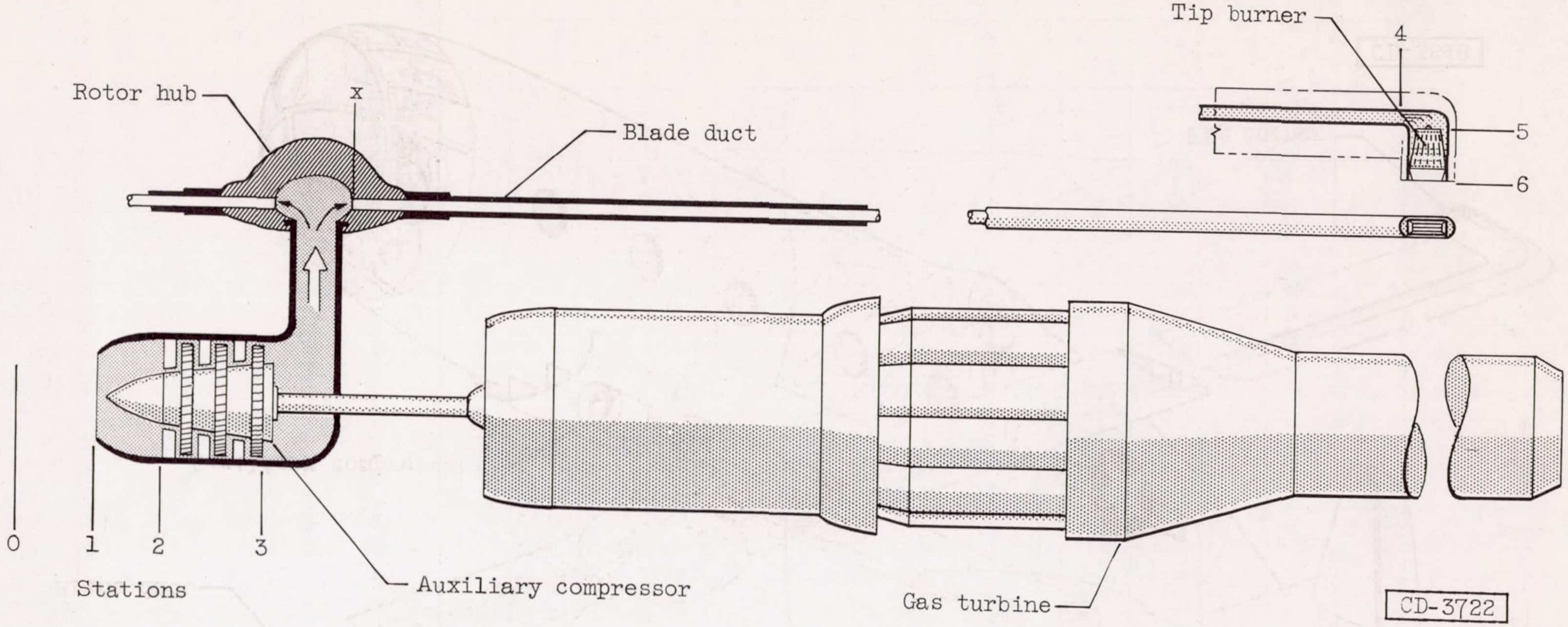

Figure 2. - Schematic drawing of pressure-jet components.

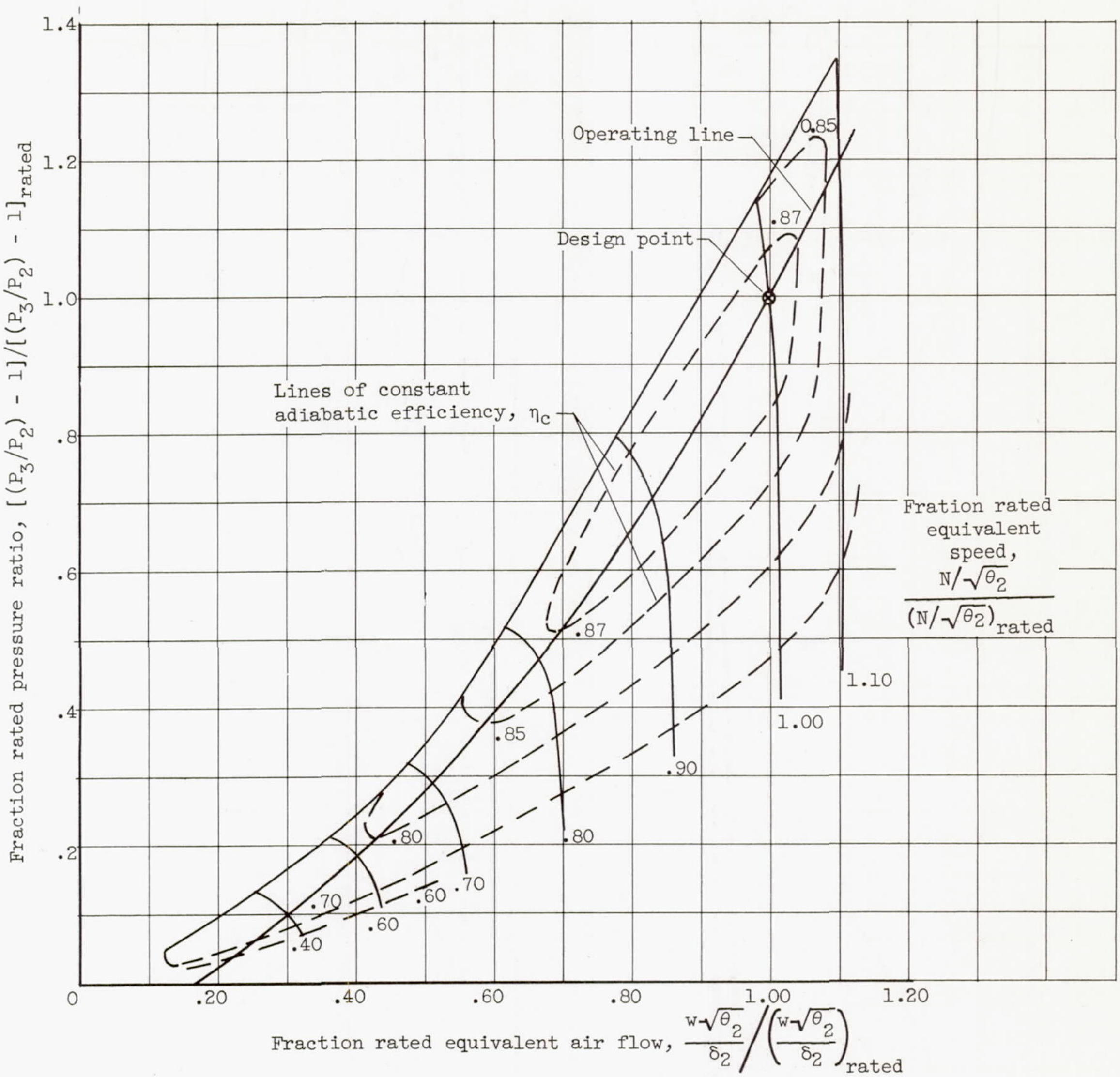

Figure 3. - Compressor characteristics.

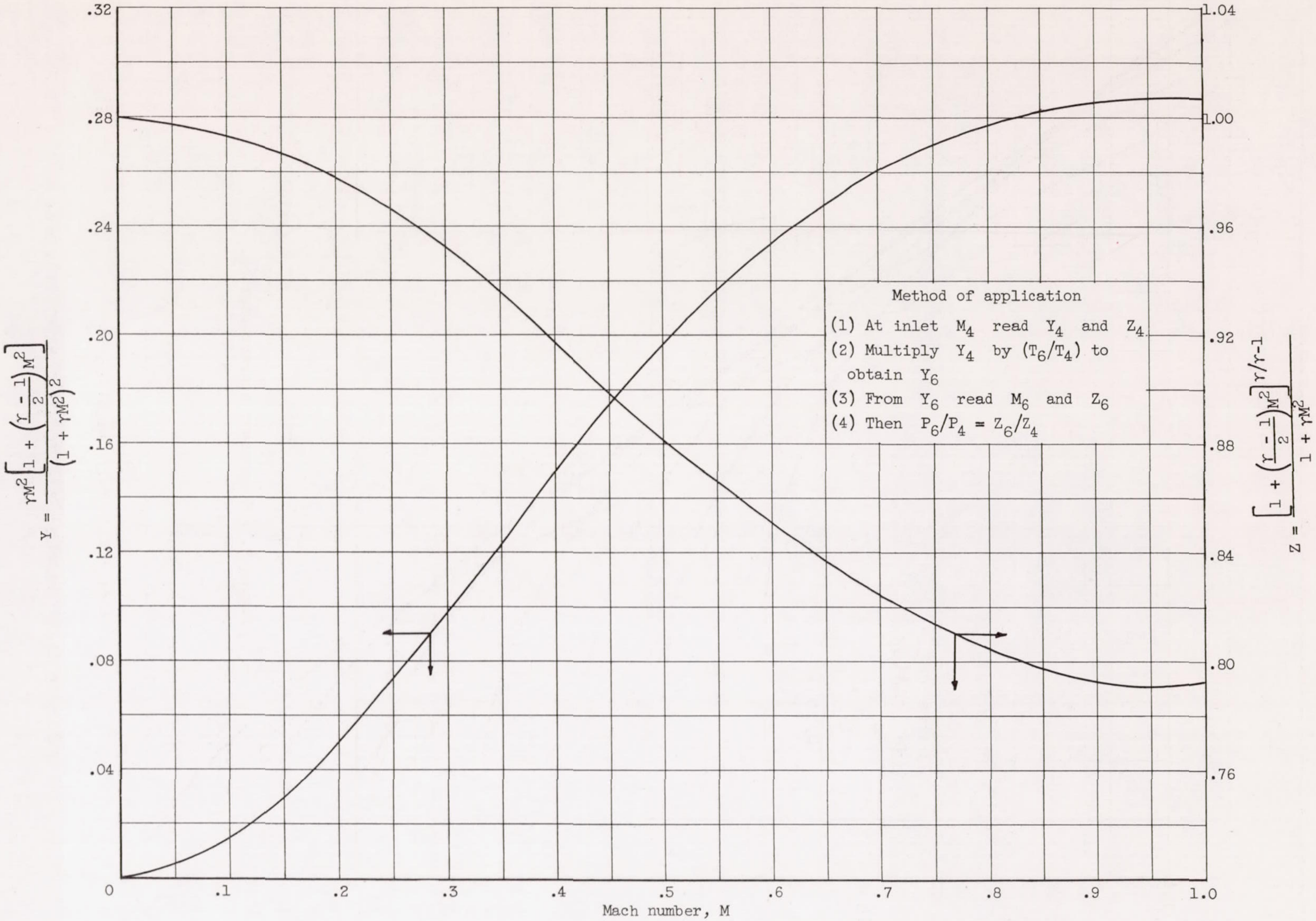

Figure 4. - Chart for estimating momentum pressure loss in tube of constant area.

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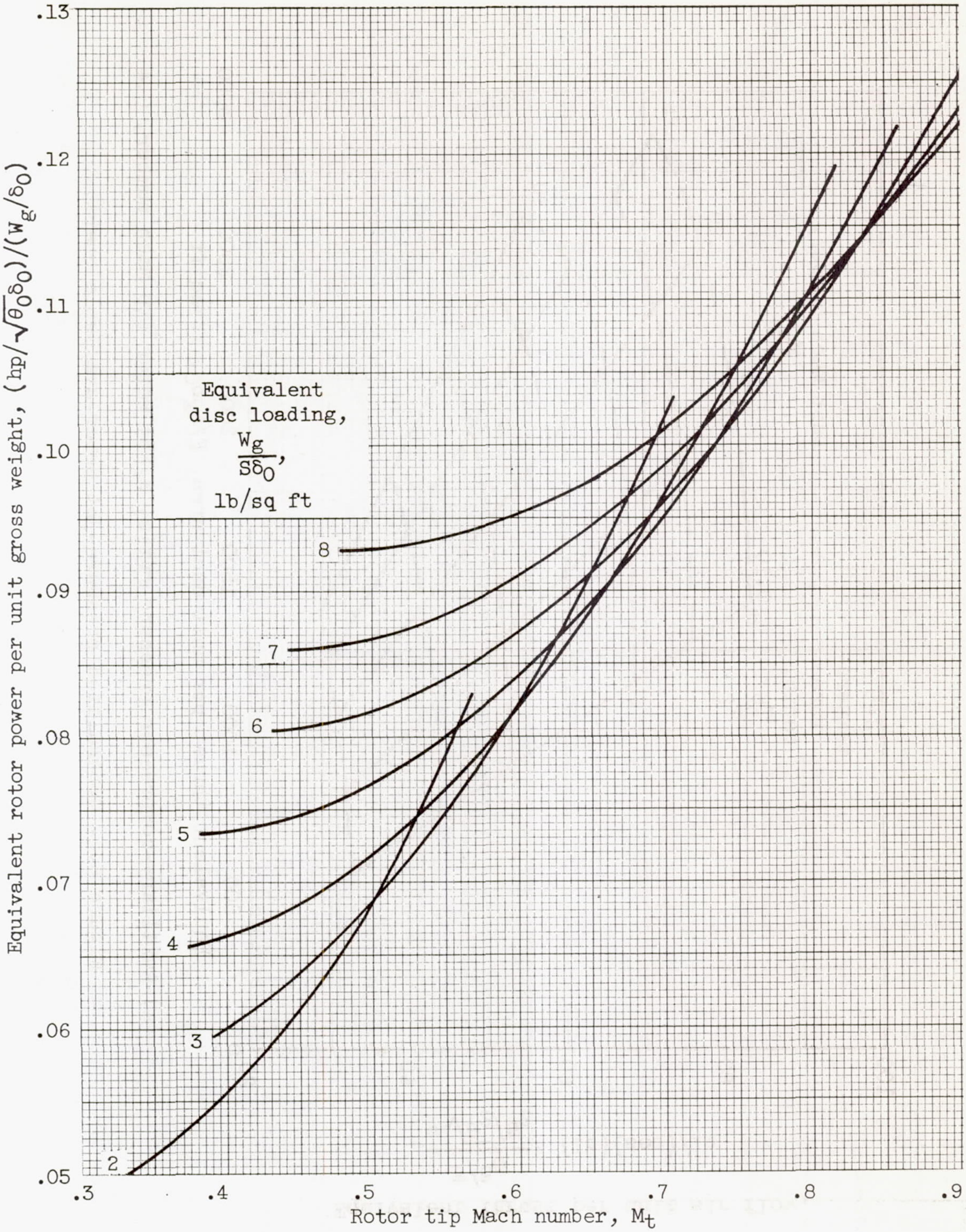
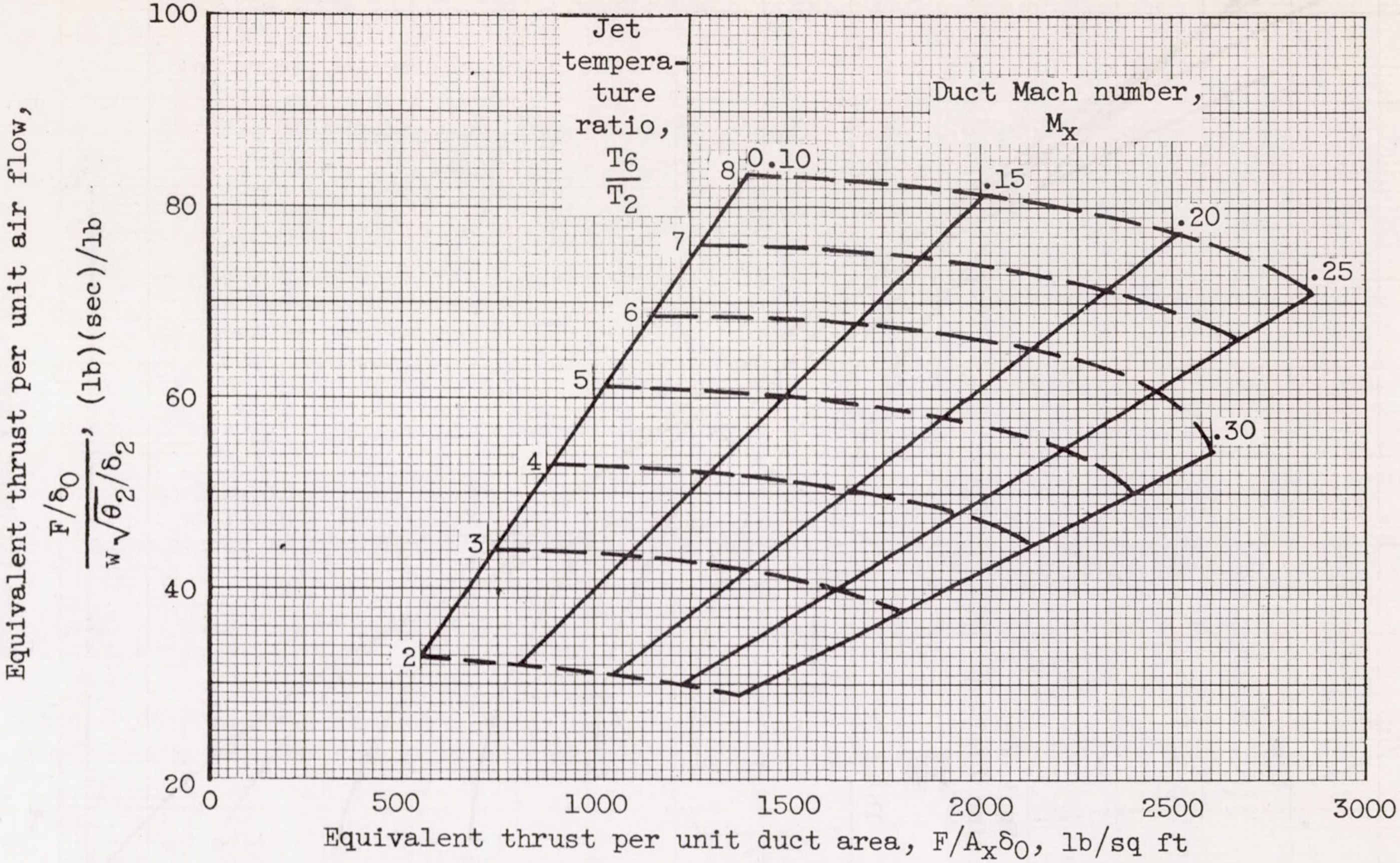
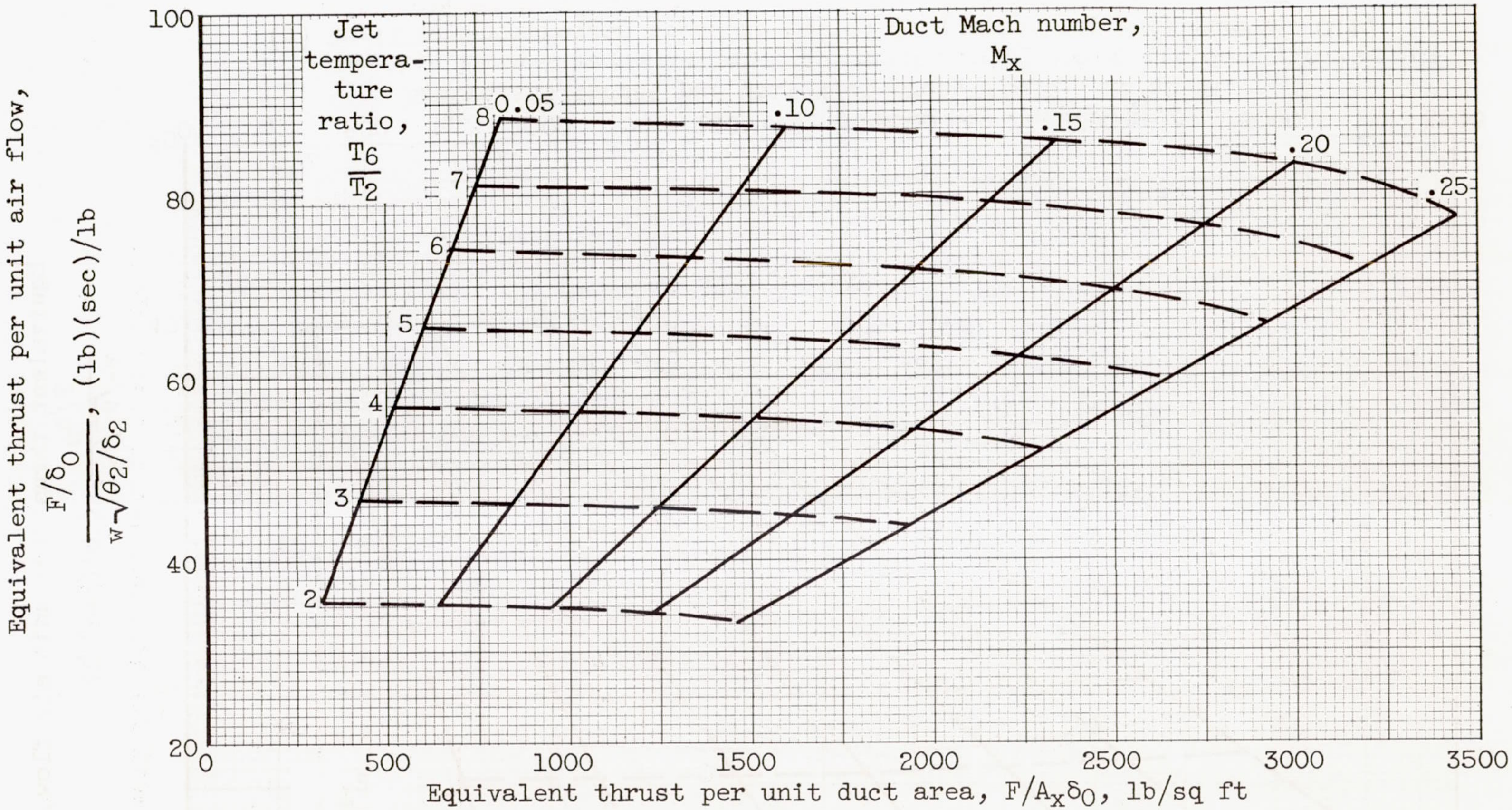


Figure 5. - Generalized rotor characteristics.



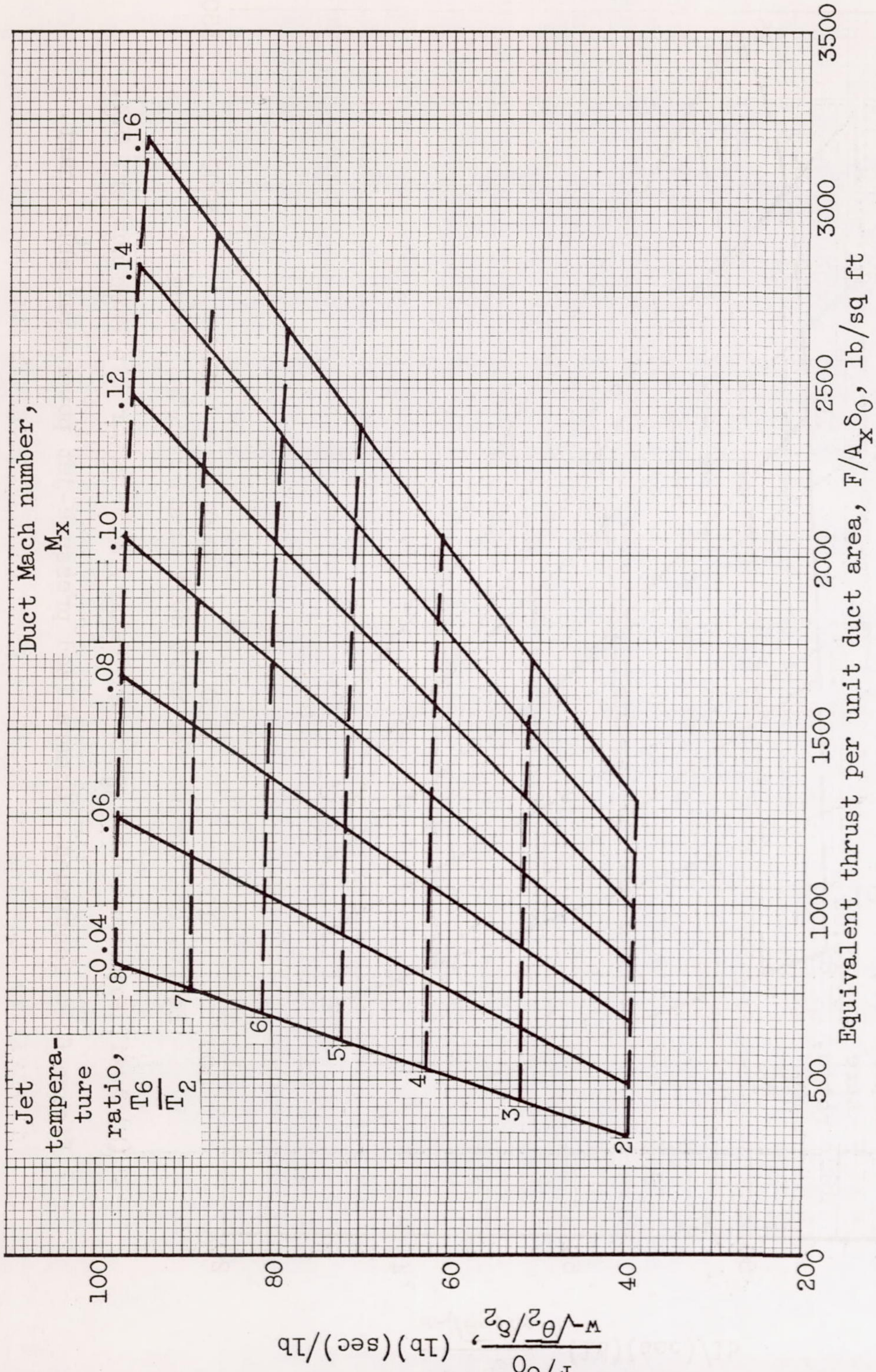
(a) Auxiliary-compressor pressure ratio, 2.25; rotor tip Mach number, 0.4.

Figure 6. - Generalized pressure-jet power-available chart.



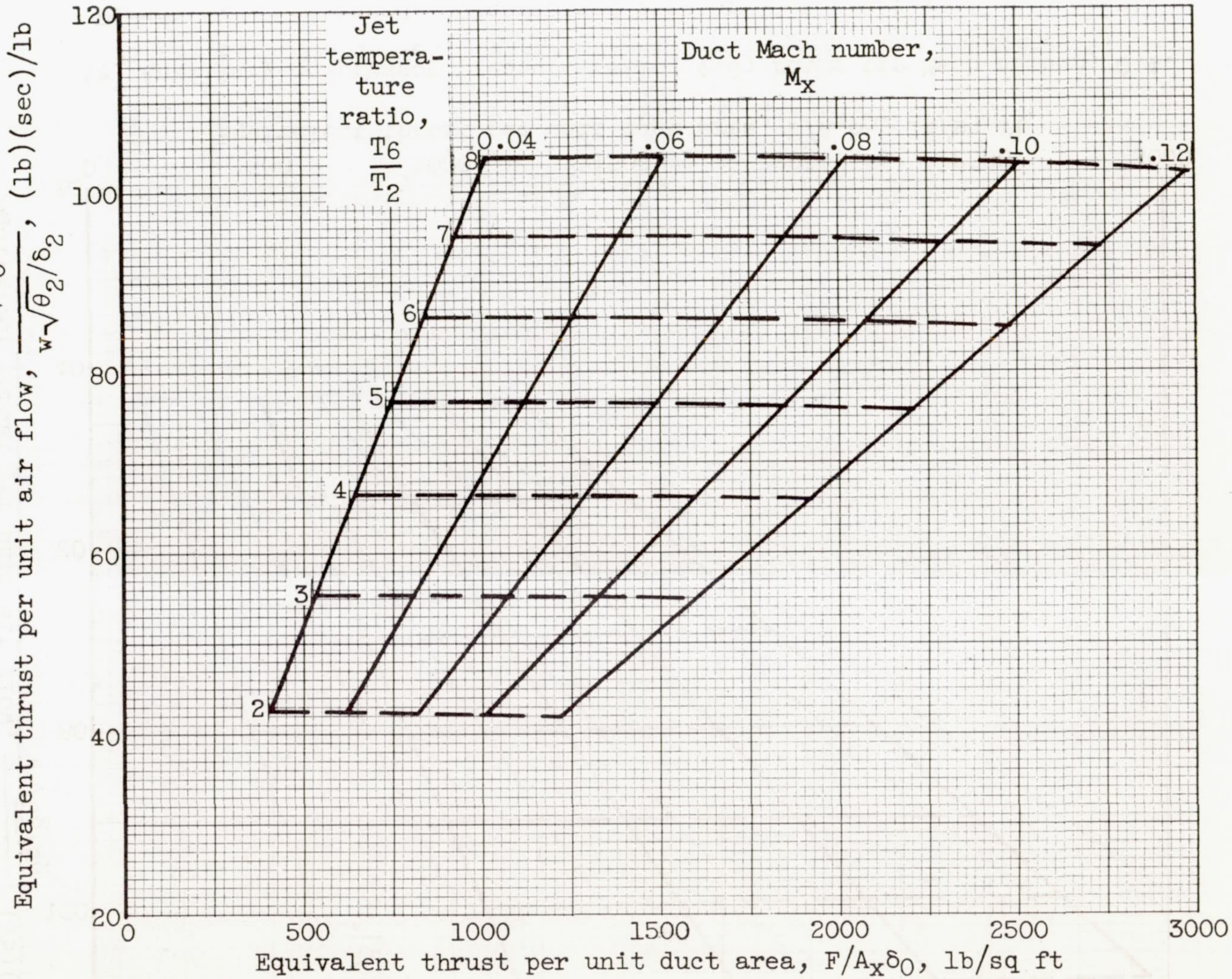
(b) Auxiliary-compressor pressure ratio, 2.5; rotor tip Mach number, 0.4.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



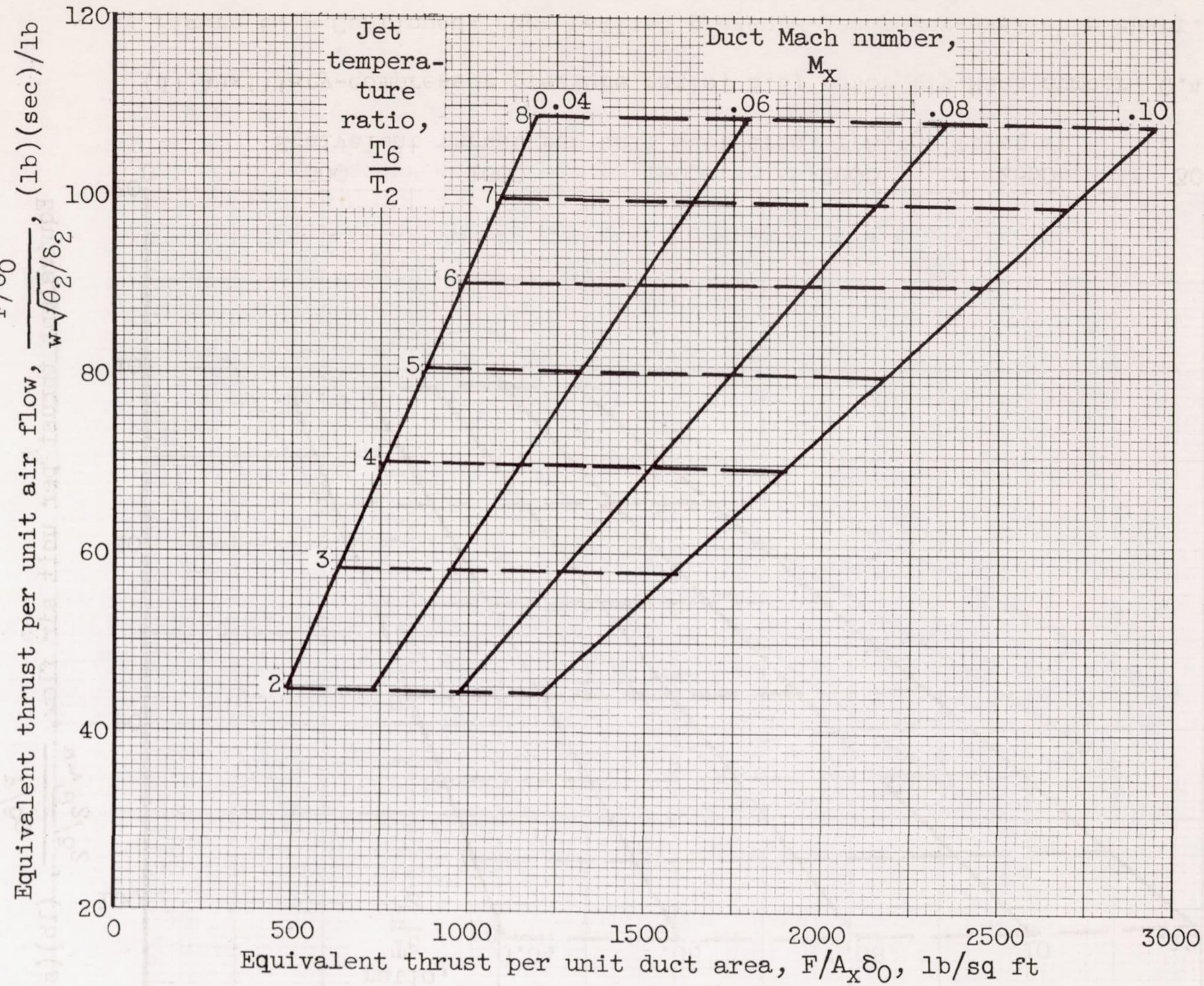
(c) Auxiliary-compressor pressure ratio, 3.0; rotor tip Mach number, 0.4.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



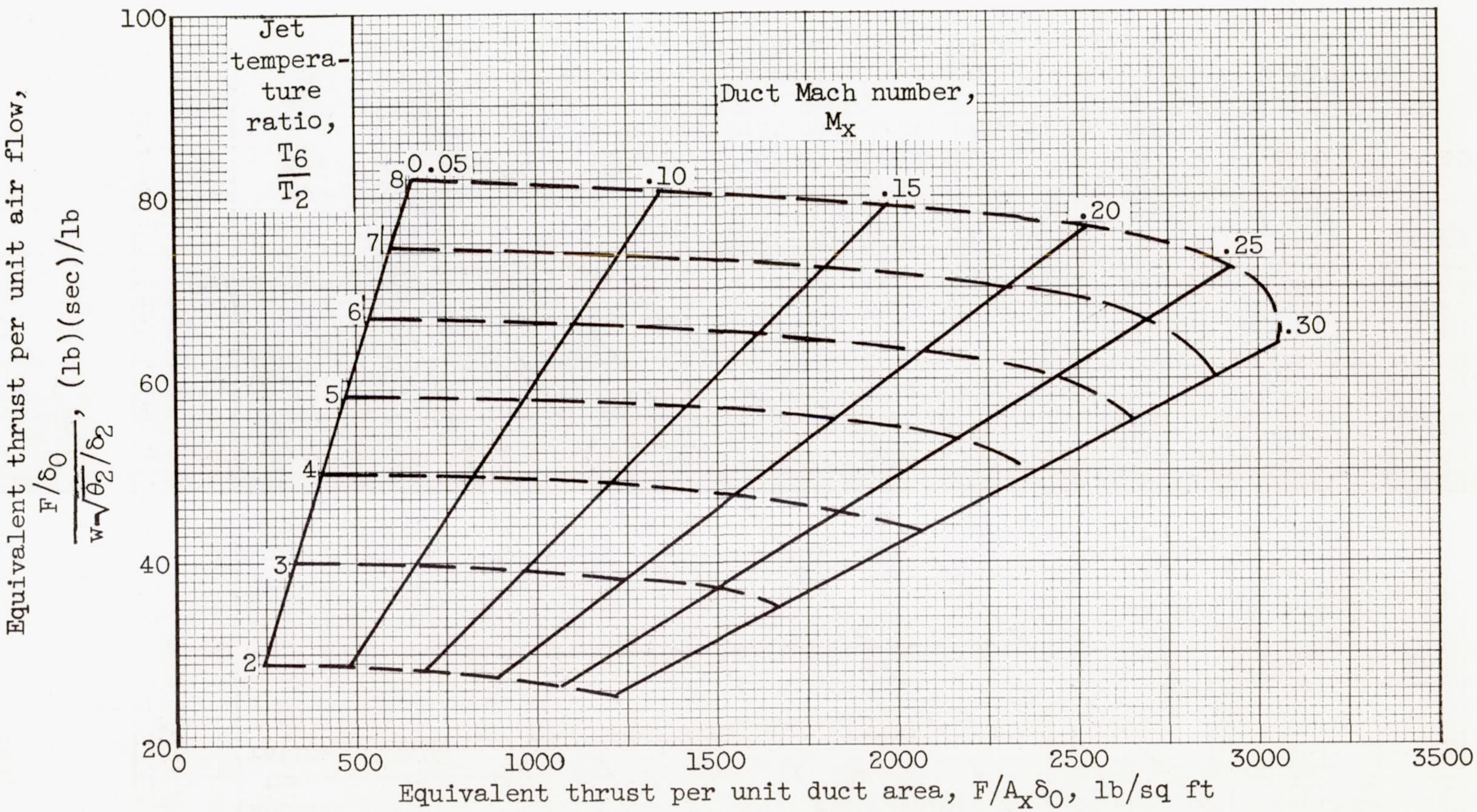
(d) Auxiliary-compressor pressure ratio, 3.5; rotor tip Mach number, 0.4.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



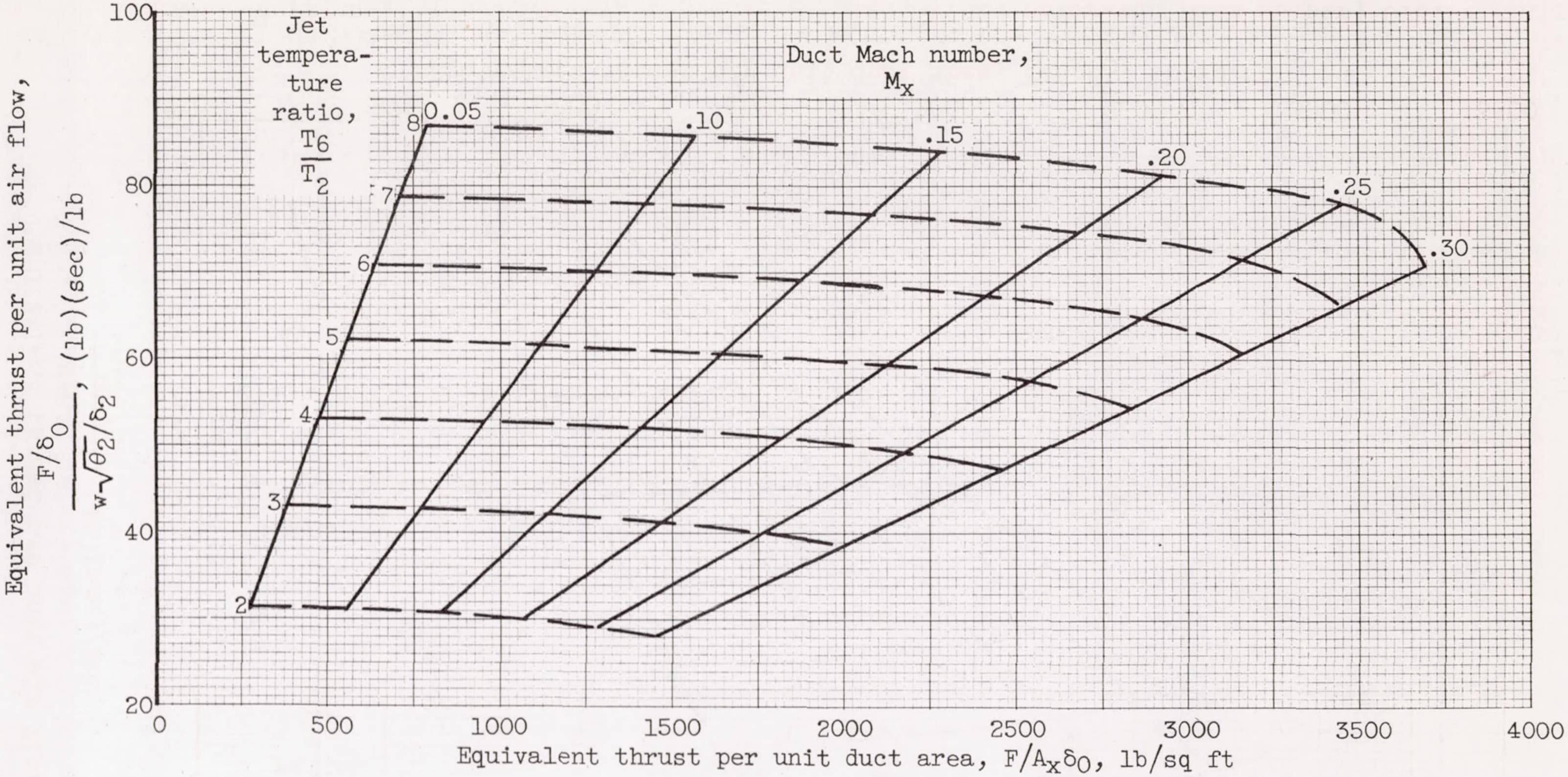
(e) Auxiliary-compressor pressure ratio, 4.0; rotor tip Mach number, 0.4.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



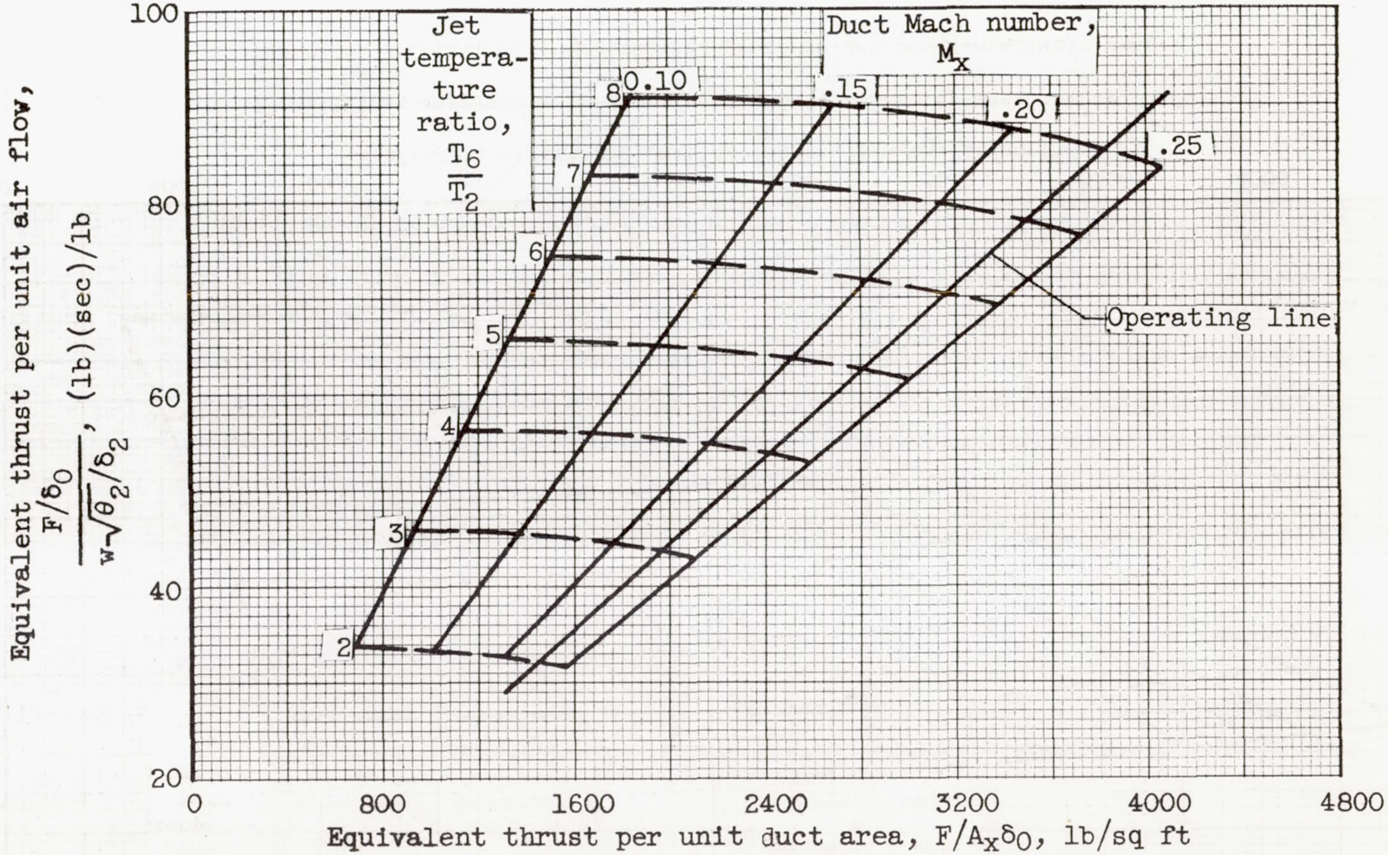
(f) Auxiliary-compressor pressure ratio, 2.25; rotor tip Mach number, 0.6.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



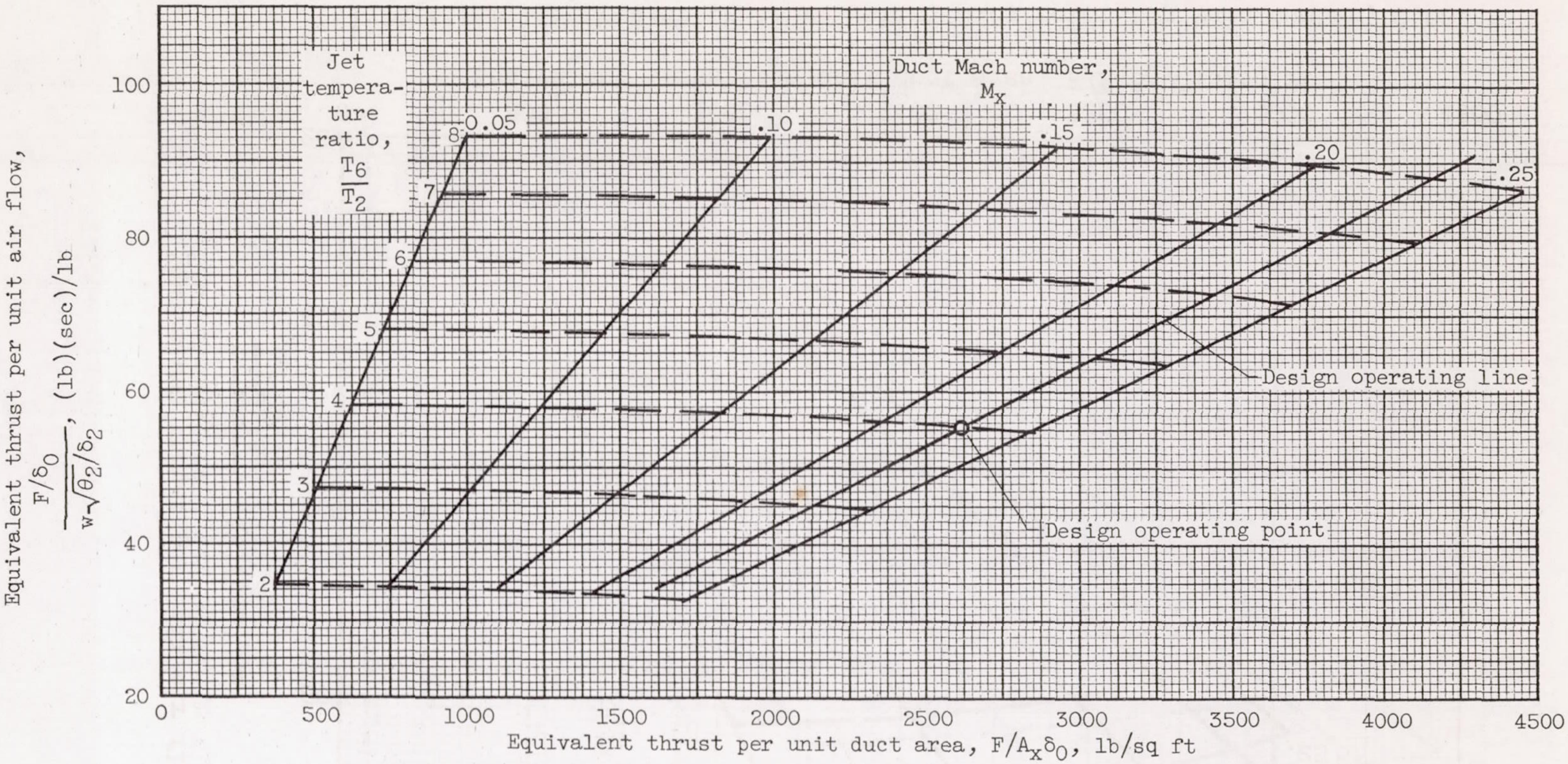
(g) Auxiliary-compressor pressure ratio, 2.5; rotor tip Mach number, 0.6.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



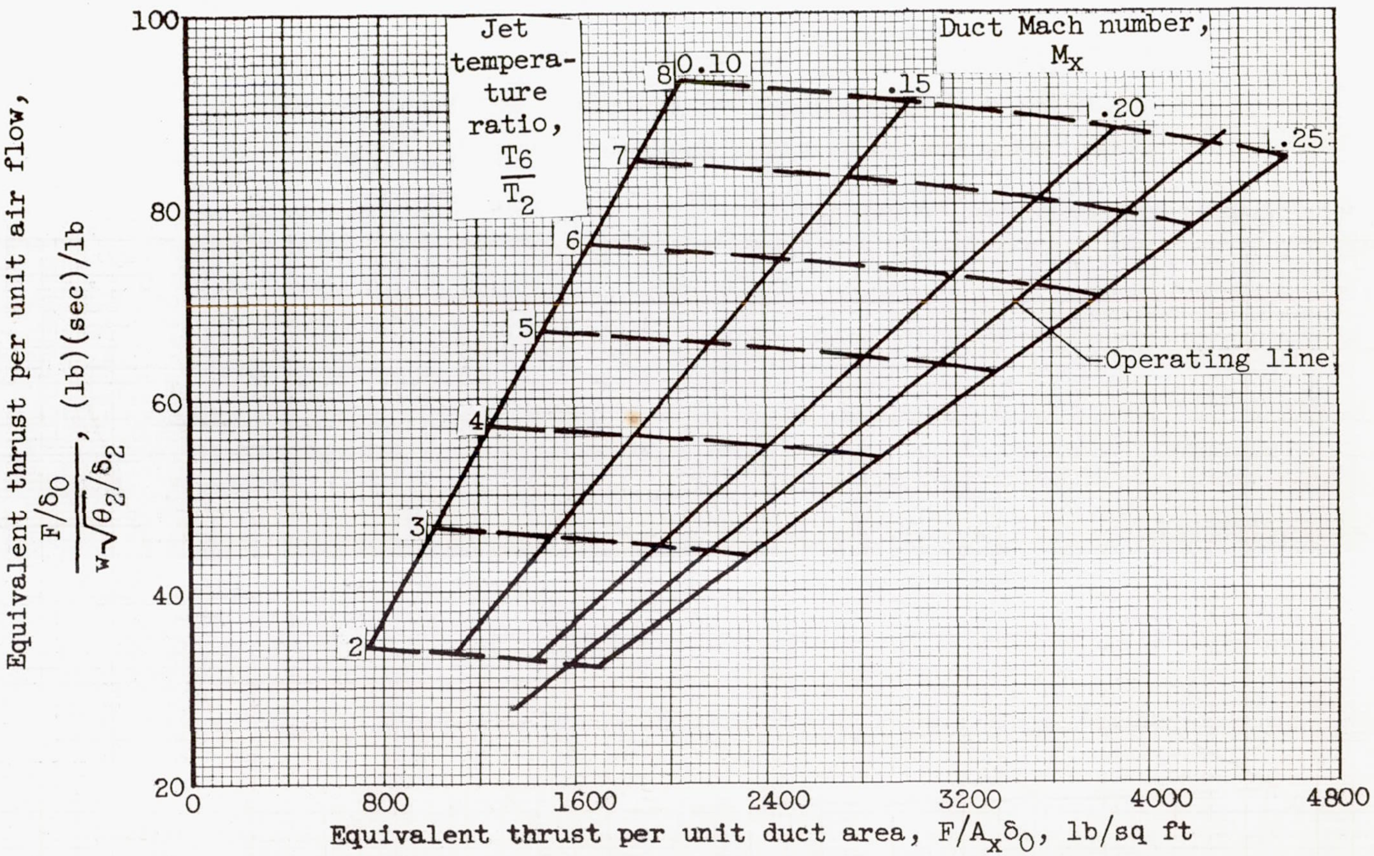
(h) Auxiliary-compressor pressure ratio, 2.8; rotor tip Mach number, 0.58.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



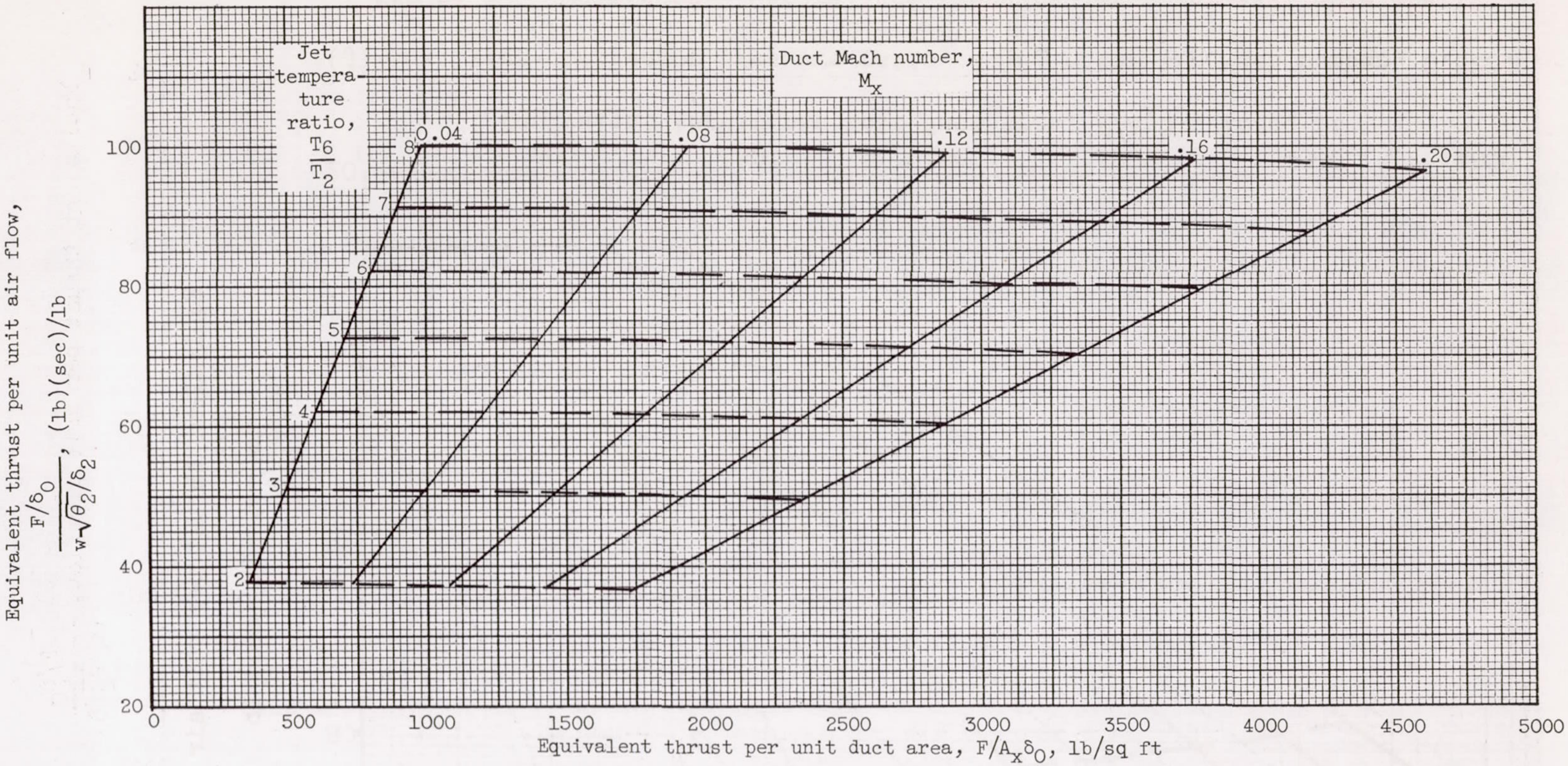
(i) Auxiliary-compressor pressure ratio, 3.0; rotor tip Mach number, 0.6.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



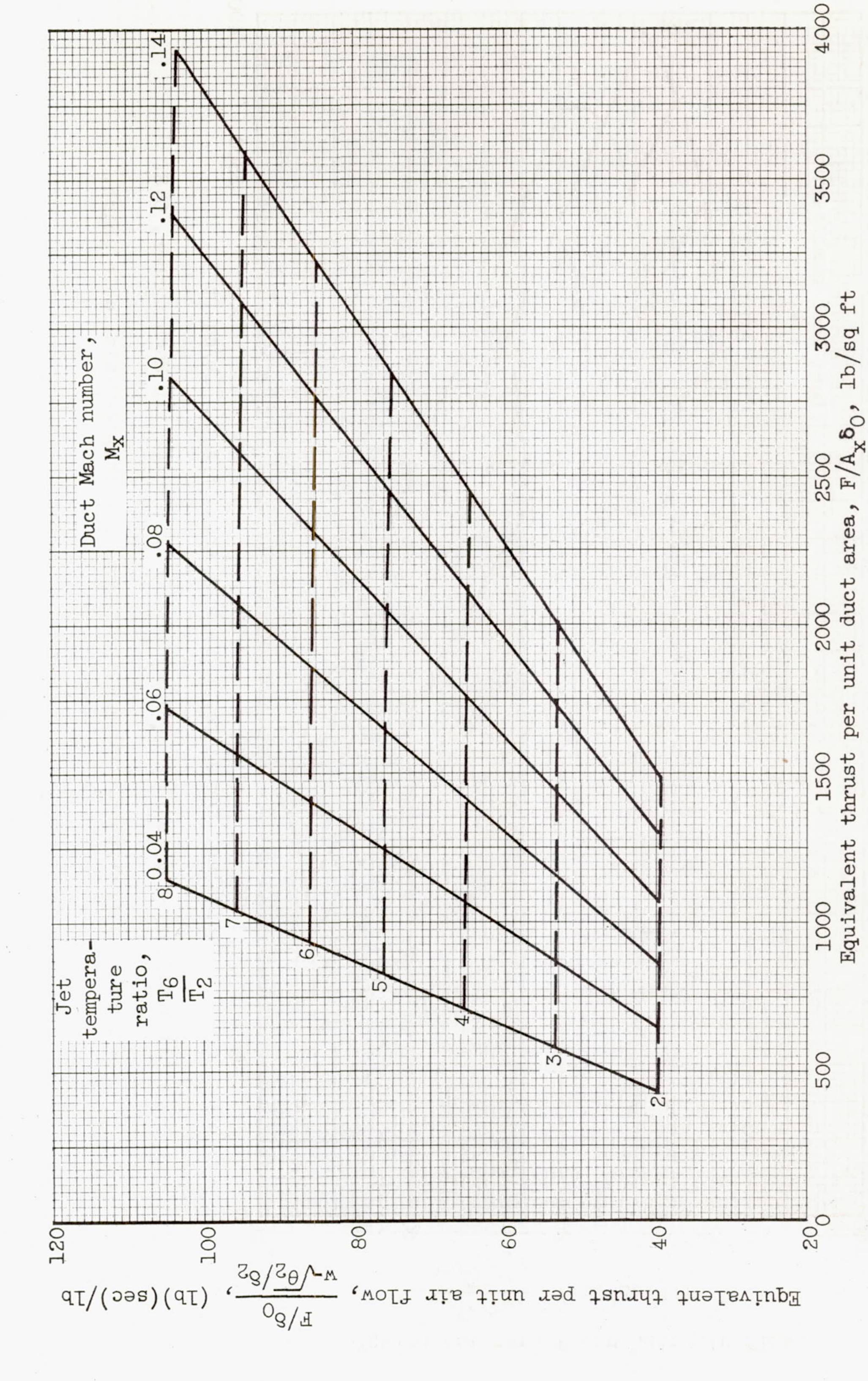
(j) Auxiliary-compressor pressure ratio, 3.16; rotor tip Mach number, 0.623.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



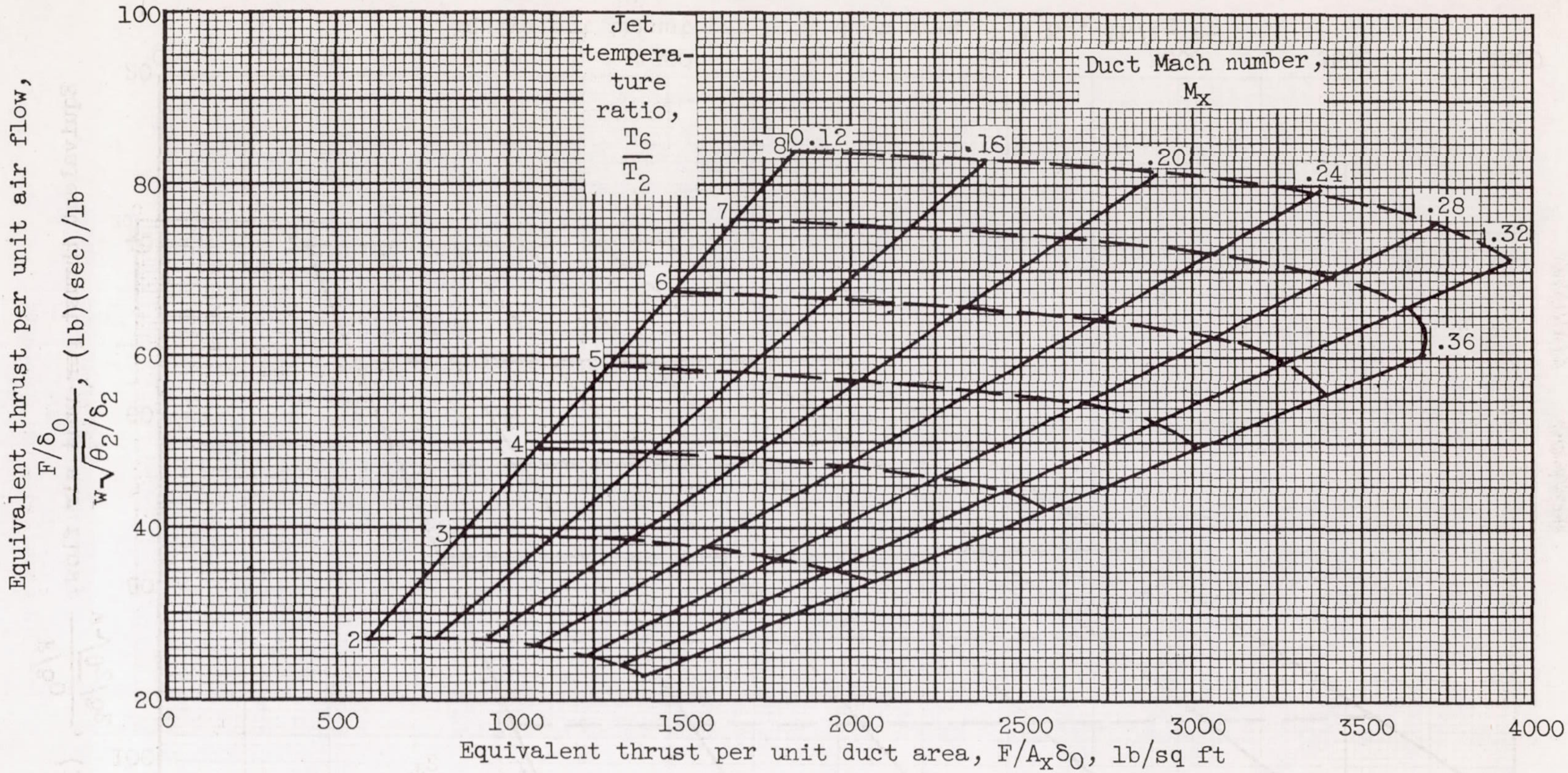
(k) Auxiliary-compressor pressure ratio, 3.5; rotor tip Mach number, 0.6.

Figure 6. - Continued. *Generalized pressure-jet power-available chart.*



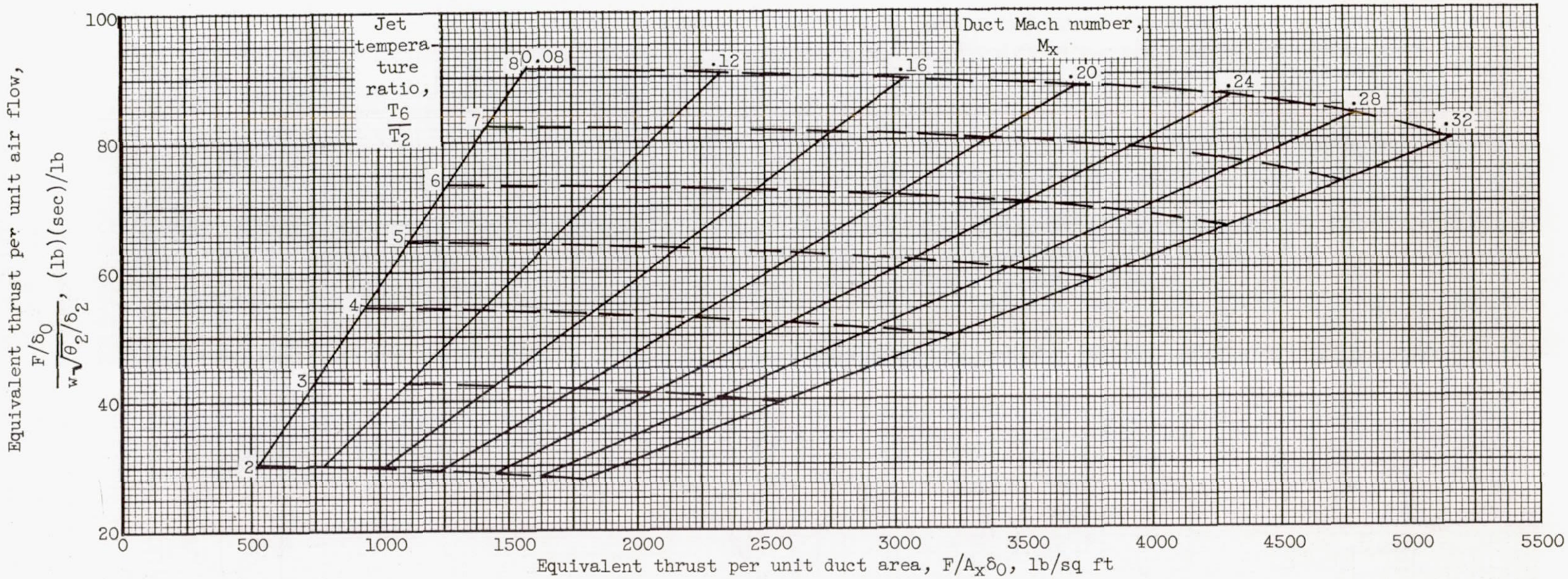
(l) Auxiliary-compressor pressure ratio, 4.0; rotor tip Mach number, 0.6.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



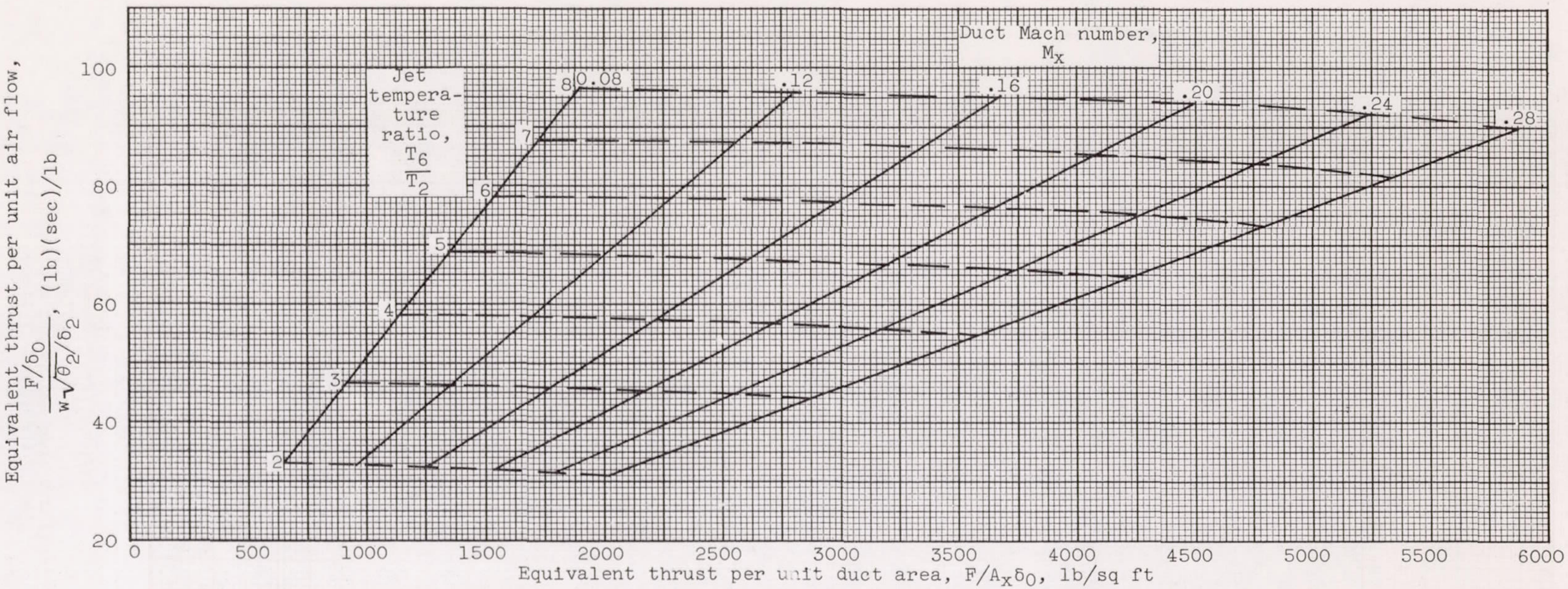
(m) Auxiliary-compressor pressure ratio, 2.5; rotor tip Mach number, 0.8.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



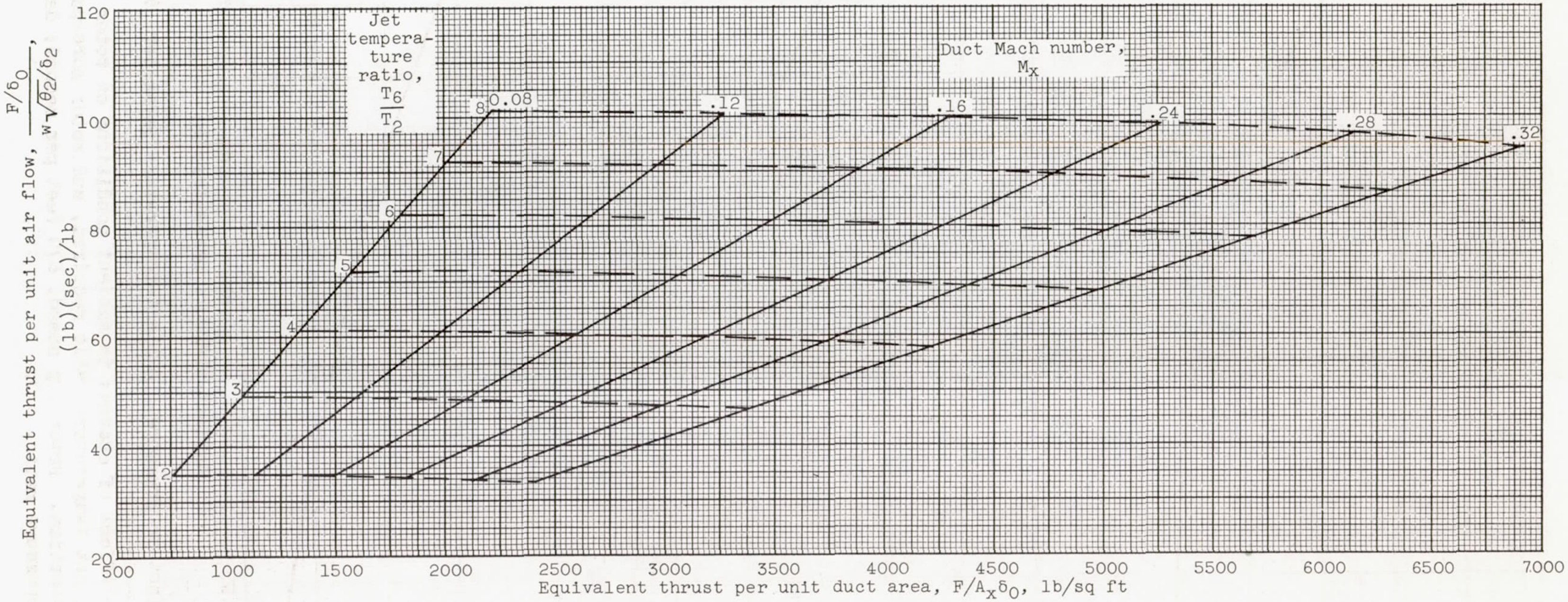
(n) Auxiliary-compressor pressure ratio, 3.0; rotor tip Mach number, 0.8.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



(o) Auxiliary-compressor pressure ratio, 3.5; rotor tip Mach number, 0.8.

Figure 6. - Continued. Generalized pressure-jet power-available chart.



(p) Auxiliary-compressor pressure ratio, 4.0; rotor tip Mach number, 0.8.

Figure 6. - Concluded. Generalized pressure-jet power-available chart.

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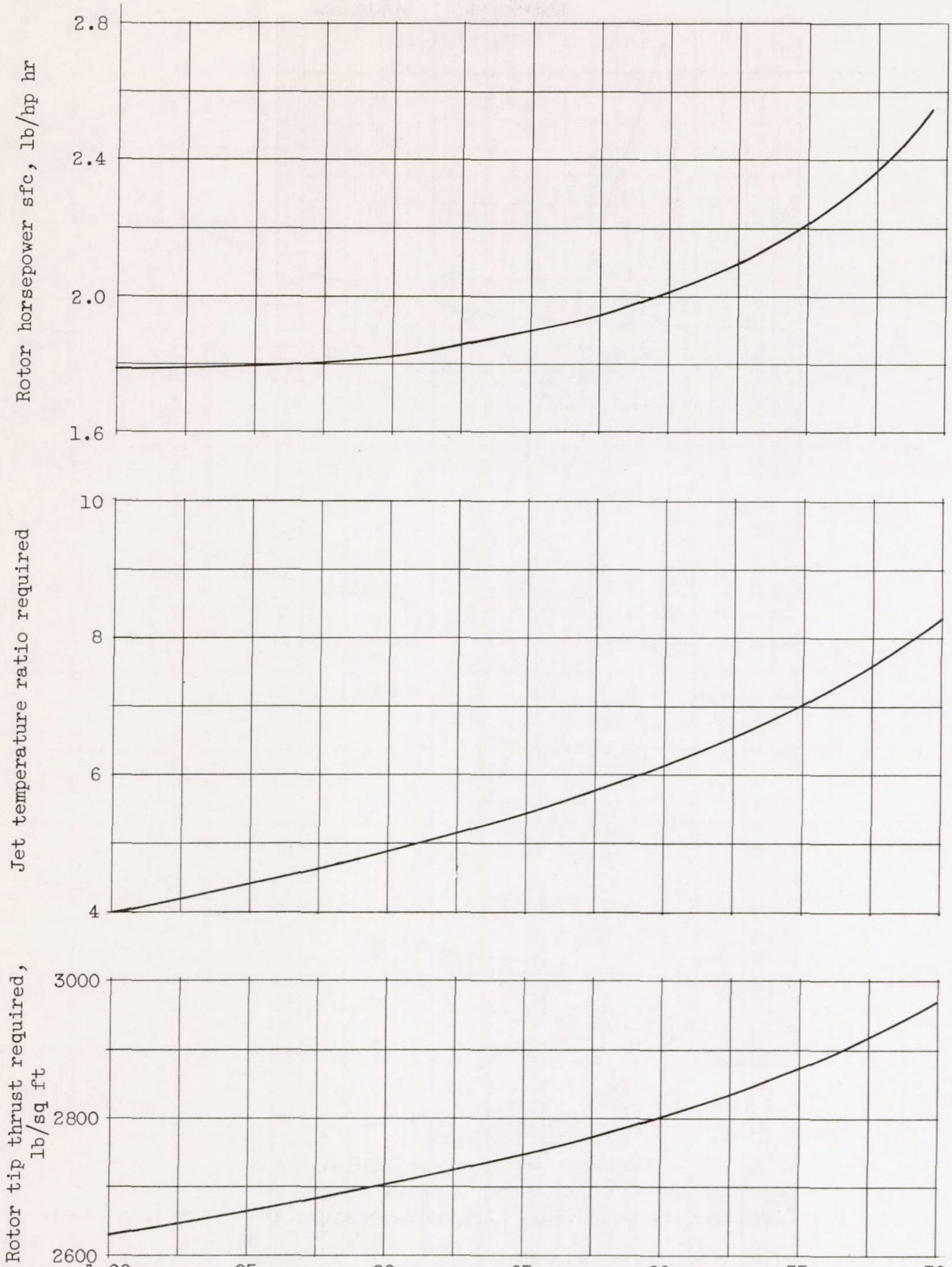
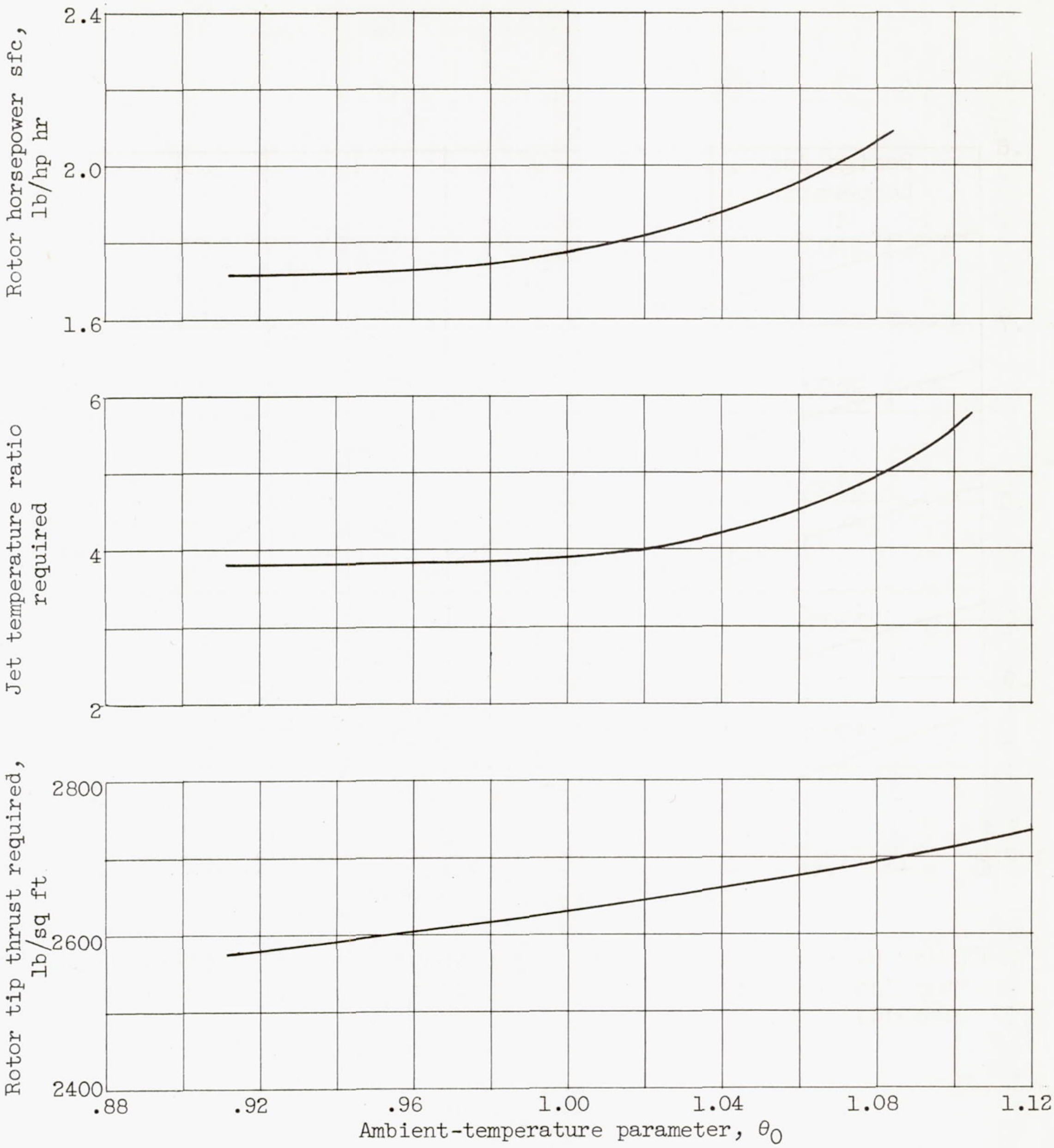
CG-6 back



(a) Effect of pressure. Ambient-temperature parameter, θ_0, 1.0.

Figure 7. - Effect of changes in ambient conditions on rotor tip thrust required, jet temperature ratio required, and rotor horsepower specific fuel consumption. Rotor tip speed, 670 feet per second; design compressor pressure ratio, 3.0.



(b) Effect of temperature. Ambient-pressure parameter δ_0, 1.0.

Figure 7. - Concluded. Effect of changes in ambient conditions on rotor tip thrust required, jet temperature ratio required, and rotor horsepower specific fuel consumption. Rotor tip speed, 670 feet per second; design compressor pressure ratio, 3.0.

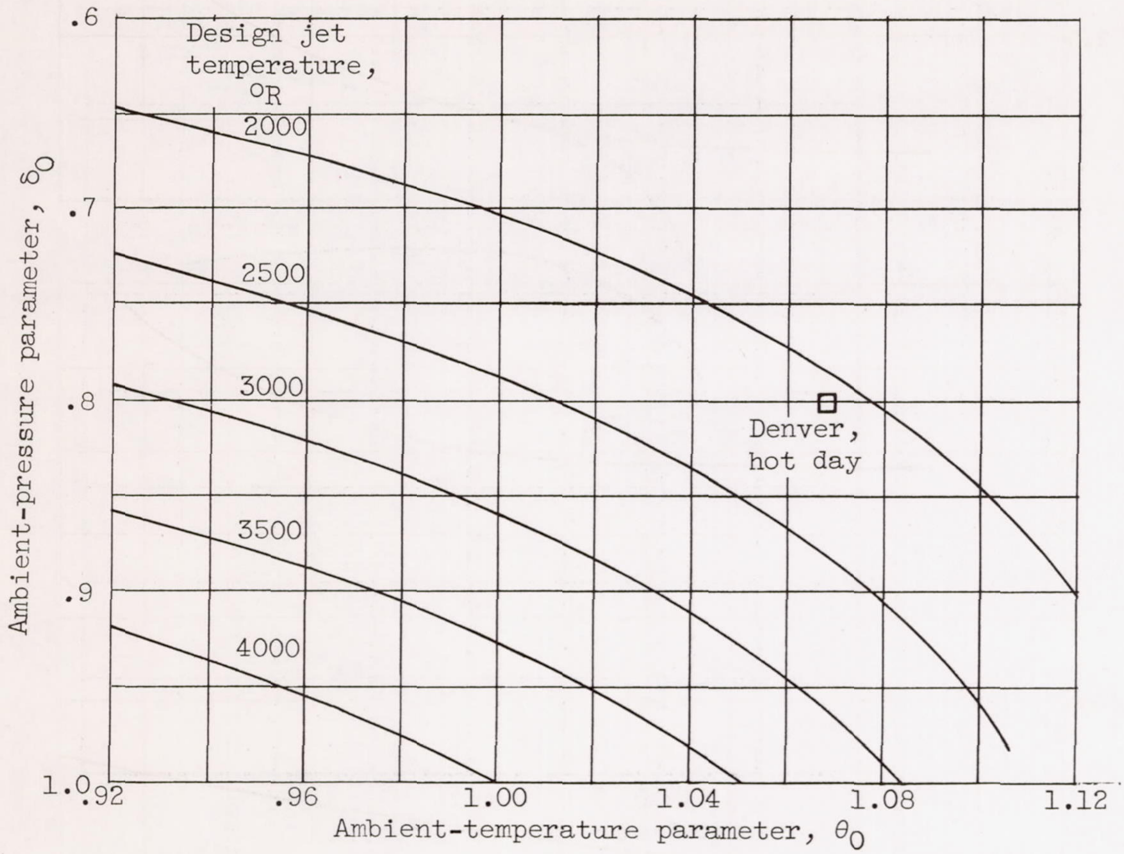


Figure 8. - Hovering ceiling for pressure-jet helicopter. Maximum jet temperature, 4000° R; rotor tip velocity, 670 feet per second.

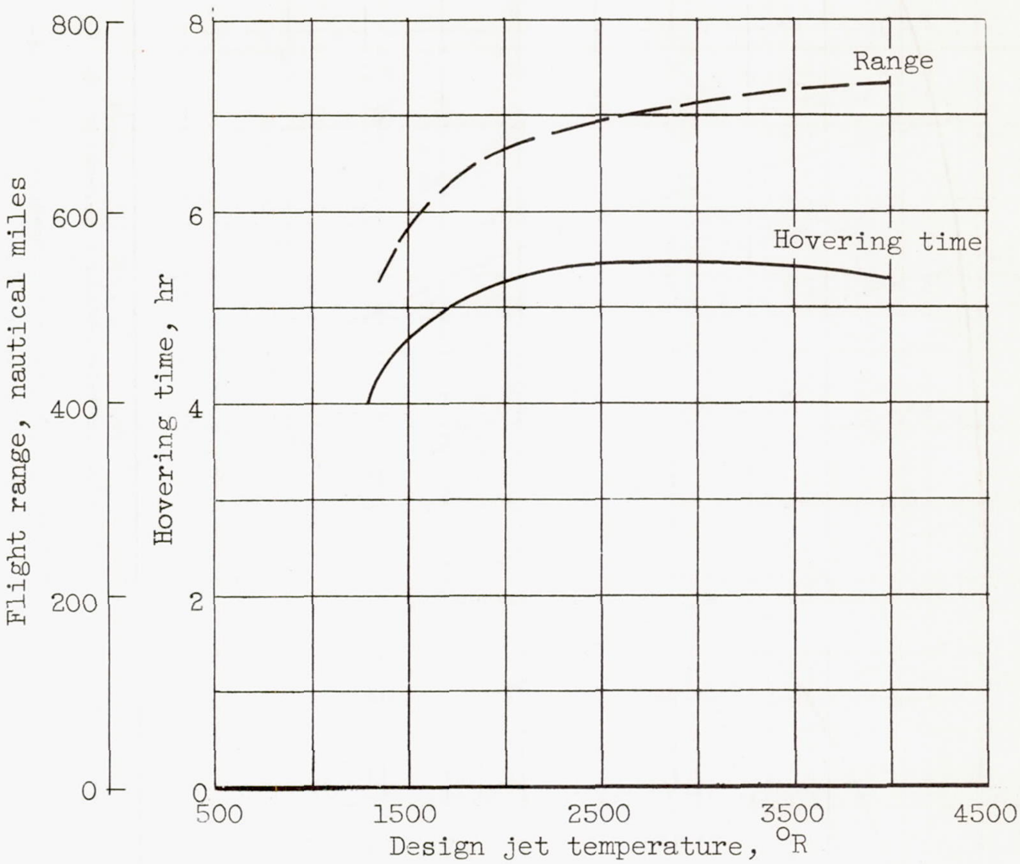
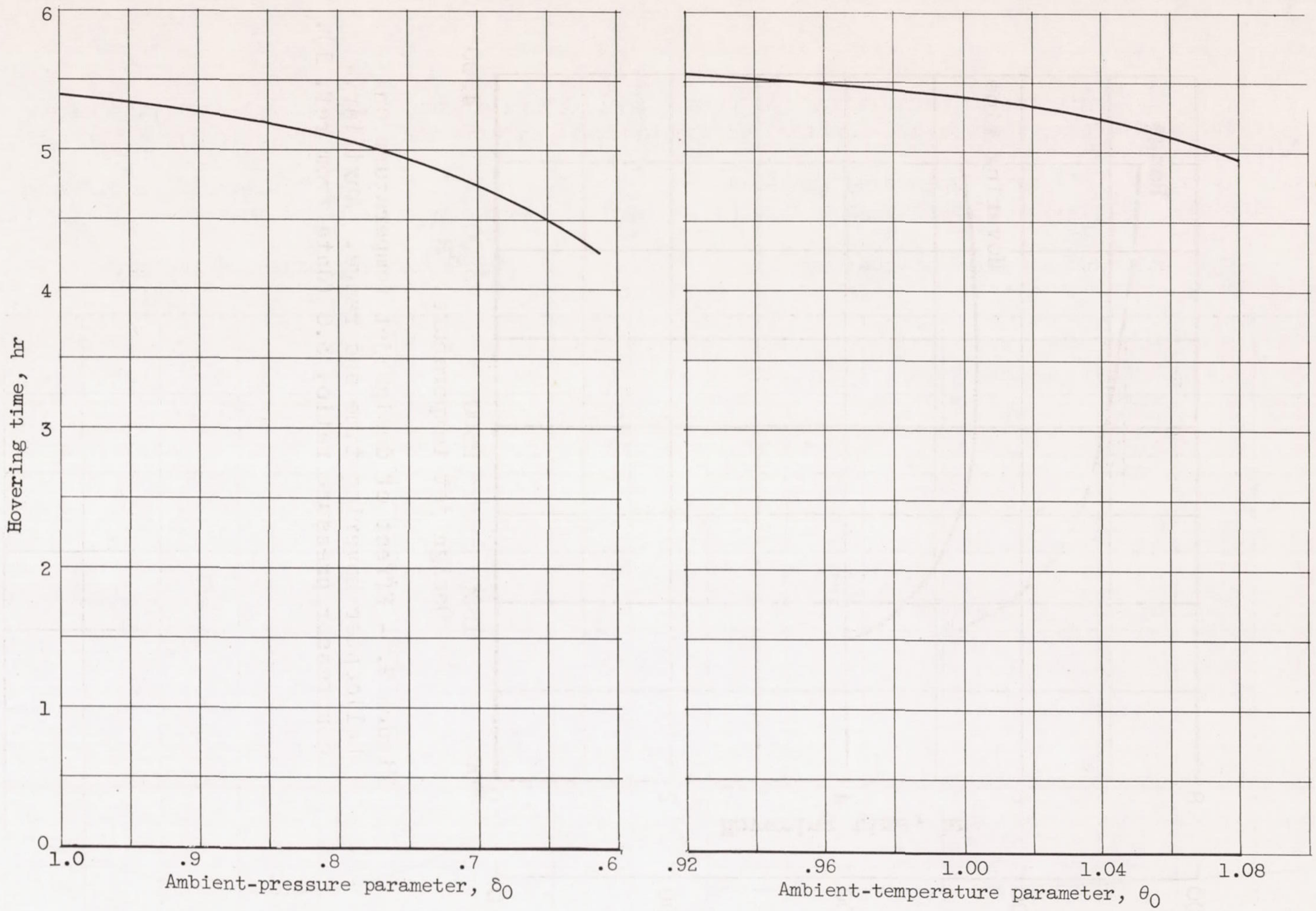


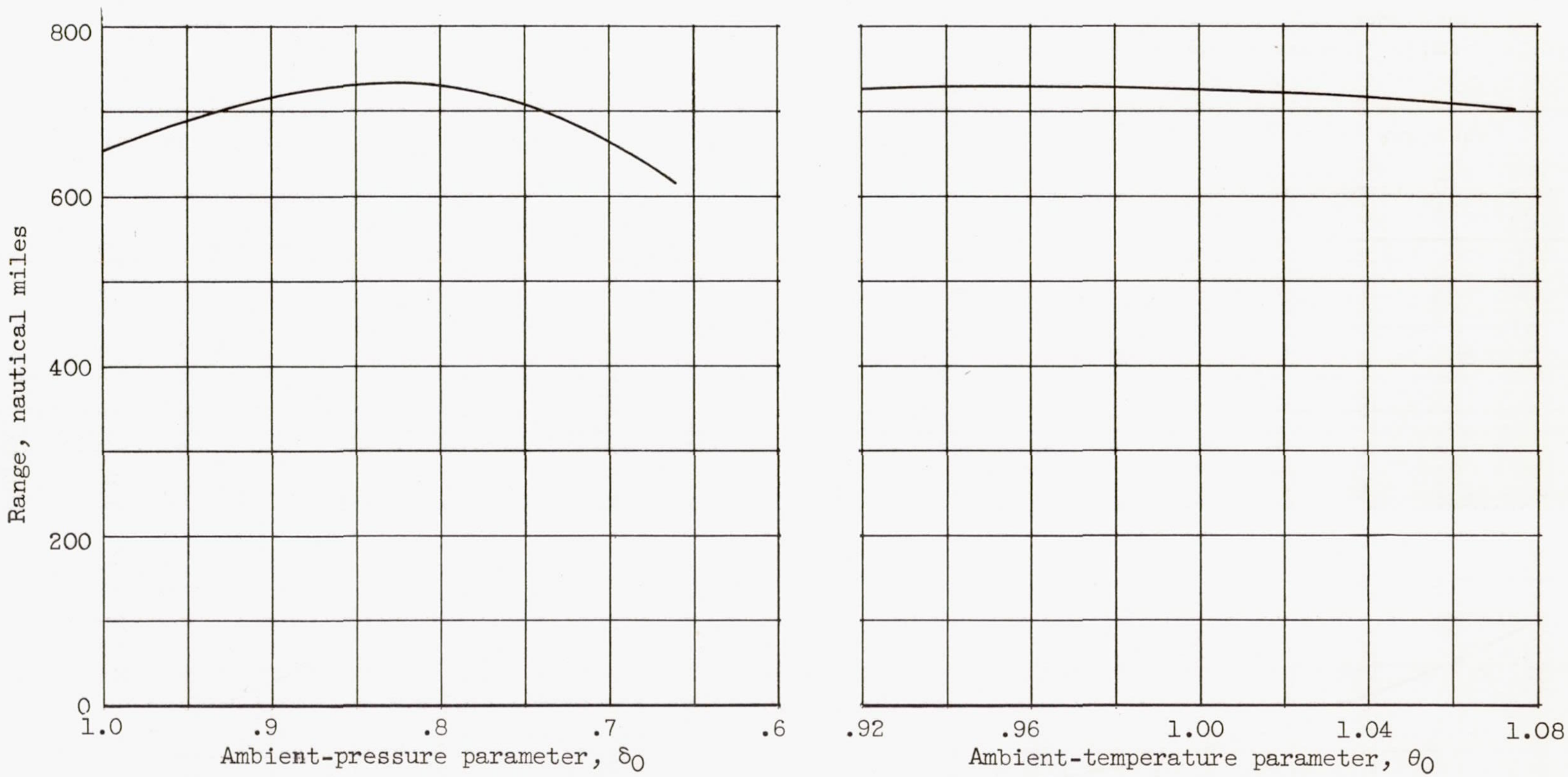
Figure 9. - Effect of design jet temperature on helicopter hovering time and range. Auxiliary-compressor pressure ratio, 3.0 (data from ref. 1).



(a) Effect of ambient pressure. Ambient-temperature parameter, 1.0.

(b) Effect of ambient temperature. Ambient-pressure parameter, 1.0.

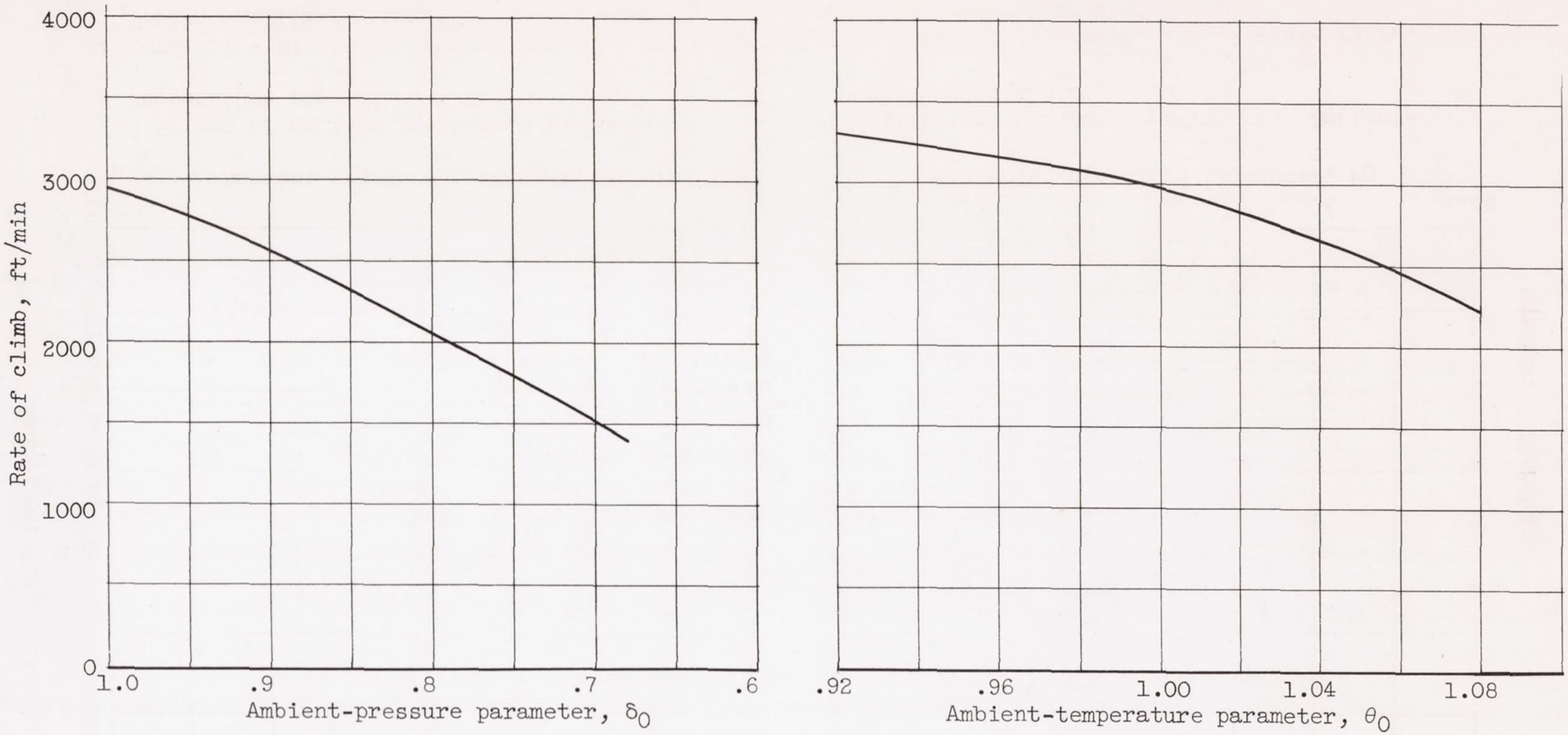
Figure 10. - Effect of ambient pressure and temperature on pressure-jet-helicopter hovering time. Design auxiliary-compressor pressure ratio, 3.0; design jet-temperature ratio, 4.0.



(a) Effect of ambient pressure. Ambient-temperature parameter, 1.0.

(b) Effect of ambient temperature. Ambient-pressure parameter, 0.8.

Figure 11. - Effect of ambient pressure and temperature on pressure-jet-helicopter ultimate range. Design auxiliary-compressor pressure ratio, 3.0; design jet temperature ratio, 4.0.



(a) Effect of ambient pressure. Ambient-temperature parameter, 1.0.

(b) Effect of ambient temperature. Ambient-pressure parameter, 1.0.

Figure 12. - Effect of ambient pressure and temperature on pressure-jet-helicopter rate of climb. Forward speed, 60 knots; design auxiliary-compressor pressure ratio, 3.0; design jet temperature ratio, 4.0.

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