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PERFORMANCE ANALYSIS OF FIXED- AND FREE-TURBINE HELICOPTER ENGINES

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SUMMARY

An analysis of fixed- and free-turbine engines applicable to helicopter propulsion was made at the NACA Lewis laboratory. Generalized performance charts are presented for these engines; and comparisons are made of off-design specific fuel consumption, altitude performance, power-speed characteristics, and response times. Calculations are made for the flight performance of an assumed 30,000-pound helicopter powered by the fixed- and free-turbine engines.

Components for the fixed- and free-turbine engines are so chosen that the design-point specific power outputs and fuel consumptions are identical.

Variations in free-turbine power with changes in shaft speed (constant turbine-inlet temperature) were small. The fixed-turbine engine, on the other hand, showed significant reduction in power with decreased shaft speed at constant temperature.

Variations in compressor-inlet temperature had nearly identical effects on the power outputs of the two engines. Power modulation of the fixed-turbine engine at constant shaft speed was very rapid, while the response speed of the free-turbine engine was limited by the accelerating characteristics of the gas-generator component. Simultaneous changes in speed and power were executed by the fixed- and free-turbine engines in about the same time.

No significant differences in range or hovering time were found for the fixed- and free-turbine helicopters. Range and hovering time for both were slightly improved when operational tip speeds were reduced from 650 to 550 feet per second. At a tip speed of 550 feet per second, the free-turbine helicopter gave slightly improved rate of climb over that obtained at 650 feet per second, primarily because of the flat power-speed characteristic of the engine and the improved aerodynamics of the rotor. In contrast, the rate of climb for the fixed-turbine

helicopter was greatly reduced when the tip speed was decreased from 650 to 550 feet per second.

INTRODUCTION

The gas-turbine engine shows considerable promise as a solution to the propulsion requirements of the high-performance helicopter. These requirements are (1) high ratio of rotor power available to engine weight, (2) speed-power characteristics that permit a relatively free choice of rotor tip speeds, (3) satisfactory fuel economy over a wide range of speed and power settings, and (4) dynamic response characteristics that are suitable to transitional flight operations.

In a number of prior investigations (refs. 1 and 2, e.g.), these requirements are shown to be more nearly satisfied by the free-turbine engine than by the fixed-turbine engine. These published accounts give good coverage to the over-all engine performance characteristics, but they do not give sufficient quantitative information about the engine components to permit a complete understanding of the basis of the results. This report assumes engine components representative of contemporary high-performance design, and similar components are used in the fixed- and free-turbine engines wherever possible. When different components had to be used, as in the case of the turbines themselves, a selection was made so that the fixed- and free-turbine engines had the same specific power outputs and fuel consumptions at their design points.

For fixed- and free-turbine engines with identical compressors, equality of design-point performance is established when the adiabatic efficiency of the fixed turbine is set equal to the over-all adiabatic efficiency of the two turbines in the free-turbine engine. Further discussion of these component characteristics is given in the section Component Characteristics.

Calculated performance characteristics of the two engines are presented herein in terms of the appropriate equivalent parameters (ref. 3), and performance comparisons are drawn for off-design-point and altitude conditions of engine operation. The behavior of the engines during rapid power and speed modulation and their dynamic response characteristics when coupled to a helicopter rotor are also examined.

In order to determine whether differences in fixed- and free-turbine off-design performance are important when these engines are used as helicopter power plants, flight performance for an assumed 30,000-pound helicopter is calculated. The respective merits of the two powerplant installations are determined by comparing flight ranges, hovering durations, rates of climb, and altitude performance.

POWERPLANT ASSUMPTIONS

Fixed- and Free-Turbine Engines

Component arrangements for the fixed- and free-turbine engines are shown schematically in figure 1. As illustrated in figure 1(a), the fixed-turbine engine utilizes a single three-stage turbine to drive the compressor and to provide useful shaft power. Because all rotating parts are rigidly coupled, the turbine, compressor, and power shaft rotate at the same mechanical speeds.

The free-turbine engine (fig. 1(b)) has two mechanically independent turbines mounted on separate concentric shafts. The gas-generator turbine, which directly follows the combustors, is a single-stage unit and drives only the compressor; the two-stage power turbine, sometimes called the free turbine, provides useful shaft power. Because these turbines are gas-coupled, their mechanical speeds are not necessarily in constant ratio.

The station numbers noted in figure 1 are those assigned in the cycle analysis.

Component Characteristics

Compressor characteristics. - The characteristics of the compressors used in the fixed- and free-turbine engines are identical. These characteristics (fig. 2) are representative of a compressor of conservative design with low axial Mach number. At the compressor design point, the pressure ratio P_3/P_2 is 7.0, the adiabatic efficiency η_c is 86.8 percent, and the specific weight flow is 20 pounds per second per square foot. (Symbols are defined in appendix A.)

Turbine characteristics. - The performance characteristics of the turbines in both the fixed- and free-turbine engines are considered representative of good current design, and with some modification are taken from existing turbine performance data.

Free-turbine engine: The gas-generator turbine of the free-turbine engine (single stage) is shown in appendix C to operate within a narrow range of corrected speeds and pressure ratios. Because of its restricted operating range, the adiabatic efficiency of this turbine is assumed to be constant at 85 percent.

However, the power turbine of the free-turbine engine (two stage) may operate over a considerable range of speeds and pressure ratios, particularly during variable-tip-speed operation of the helicopter.

Accordingly, its off-design performance characteristics are taken from a map shown in figure 3. At design point, the adiabatic efficiency of this component is also 85 percent.

Fixed-turbine engine: The assumption that both fixed- and free-turbine engines have identical performance at design point determines the design adiabatic efficiency that is used for the three-stage fixed turbine. In order to satisfy this assumption, the fixed-turbine adiabatic efficiency is set equal to an over-all efficiency of 86.4 percent calculated for the two turbines of the free-turbine engine. Like the free turbine, the fixed turbine must operate over a wide range of speeds and pressure ratios; consequently, its off-design operating characteristics are taken from a representative map shown in figure 4.

Limiting engine cross-sectional areas. - When representative values are assigned for turbine blade stresses, exit Mach numbers, power extraction rates, and hub-tip ratios, the turbine frontal areas must be approximately 40 percent larger than the compressor frontal areas. In this report, the turbine frontal areas are considered to be the limiting areas for both engines.

Exhaust-nozzle areas. - When the residual jet thrust of a turbine engine is considered to be of secondary value, as in a helicopter installation, minimum specific fuel consumption is obtained when the turbine-exit gases are expanded by a large exhaust nozzle to near-ambient pressures. For the fixed- and free-turbine engines, exhaust-nozzle areas are made as large as the limiting engine areas, that is, 40 percent larger than the compressor frontal areas.

Fixed parameters. - Parameters held constant in the analysis of both the fixed- and free-turbine engines are:

Inlet diffuser total-pressure ratio, P_2/P_1	0.95
Burner total-pressure ratio, P_4/P_3	0.95
Combustion efficiency, η_b, percent	95
Design turbine-inlet temperature, $T_{4,d}$, °R	2000

CYCLE ANALYSIS OF FIXED- AND FREE-TURBINE ENGINES

Generalized performance characteristics of the fixed- and free-turbine engines are calculated by conventional methods similar to those presented in reference 4. The mechanical details of the cycle calculations differ somewhat for the two engines, primarily because of the additional variables introduced by the power turbine in the free-turbine engine. An outline of the cycle-analysis techniques appears in appendix B.

FIXED- AND FREE-TURBINE ENGINE PERFORMANCE

General Performance Characteristics

Equivalent shaft power. - The results of the fixed- and free-turbine cycle analyses are given in figure 5, where equivalent shaft power is shown as a function of equivalent shaft speed and turbine-inlet temperature ratio. The rated turbine-inlet temperature ratio is 3.853 for both engines, corresponding to the design turbine-inlet temperature of 2000° R. At their design operating points, the rated equivalent shaft power of both engines is 91.4 horsepower per pound of air per second.

Comparison of figures 5(a) and (b) shows that an equal reduction in equivalent shaft speeds reduces the fixed-turbine power more than it does the free-turbine power. At rated temperature ratio, for example, the shaft power of the fixed turbine falls off about 30 percent when its equivalent speed is cut back from rated to 0.85 rated. On the other hand, for the same change in speed, the free-turbine power drops only about 2 percent.

This small variation in free-turbine power with changes in shaft speed (constant T_4/T_2) is evidence of the relative independence of the gas-generator- and power-turbine operating points. Because the inlet stages of the power turbine are choked, changes in the power-turbine speed have little effect on the gas power produced by the gas-generator turbine. At a constant value of the gas-generator temperature ratio T_4/T_2, there is, in fact, a single gas-generator equivalent speed which satisfies the continuity requirements of the engine. The relation between $N/\sqrt{\theta_2}$ and T_4/T_2 is plotted in figure 6(a). The relation between free-turbine power and gas-generator speed (and therefore T_4/T_2) is given for a range of power-turbine speeds in figure 6(b). Taken together, these two plots show that for a given T_4/T_2 the gas-generator speed is fixed; and, furthermore, for fixed gas-generator speed, the power developed by the power turbine is affected only slightly by changes in its rotational speed.

Very small variations in free-turbine power with speed are, of course, observed (figs. 5(b) and 6(b)); and these variations are a result of the small changes in free-turbine efficiency that accompany changes in rotor incidence angle with changes in power-turbine equivalent speed.

In contrast with the free-turbine engine, the power of the fixed-turbine engine drops off rapidly as its speed is reduced. This is a direct result of the rigid coupling of the compressor and turbine in this engine. With this arrangement a reduction in turbine speed gives a simultaneous decrease in compressor speed, air flow, and pressure ratio; and shaft power consequently drops off. In addition to this effect, a further small reduction in turbine power is brought about by the decreased adiabatic efficiency of the fixed turbine at reduced speeds.

Fixed- and free-turbine-engine specific fuel consumption. - Specific fuel consumptions for the fixed- and free-turbine engines were identical at design point, being calculated as 0.61 pound per horsepower per hour. As mentioned previously, equality of fuel consumption is a consequence of the use of identical compressors and consistent over-all turbine efficiencies, and was one of the initial assumptions for the investigation. In figure 7, specific fuel consumptions for the two engines are plotted as functions of equivalent power and shaft speed. Comparison of fuel economies at less than rated powers and at rated shaft speeds reveals no significant difference between the two engines. At less than rated speeds, the free-turbine engine shows slightly better specific fuel consumption than the fixed-turbine engine.

Effect of change in ambient temperatures. - As will be shown in the section "Reserve-power requirements," a considerable margin of reserve power over sea-level hovering power must be provided for a gas-turbine helicopter if it is to perform satisfactorily during hot-day conditions of operation. This reserve-power requirement is primarily due to the unfortunate tendency of the gas-turbine engine to lose power rapidly with increasing compressor-inlet temperature.

Equivalent power developed by the fixed- and free-turbine engines is plotted as a function of the compressor-inlet temperature ratio $T_2/519^\circ$ R in figure 8. For convenience, an auxiliary scale is plotted giving compressor-inlet temperature in $^\circ$F. Generalized performance data presented in figure 5 were used in the preparation of figure 8; operation of the fixed- and free-turbine engines at design turbine-inlet temperature ($T_4 = 2000^\circ$ R) and at rated mechanical shaft speed ($N/N_{rated} = 1.0$) is assumed.

In figure 8, both engines show a reduction in equivalent power to about 79 percent of rated value when the compressor-inlet temperature is raised from standard (59° F) to 95° F. This power loss is due to the loss of mass flow through the engine and to the proportional decrease in T_4/T_2 accompanying an increase in T_2 (T_4 = constant).

Engine-Rotor Response Time and Stability

The generalized performance characteristics of the fixed- and free-turbine engines are presented in preceding sections of this report for a range of primary operating variables and ambient conditions. The purpose of this section is to examine analytically some aspects of the dynamic behavior of these engines when used as a powerplant for a 30,000-pound helicopter.

Speed of response, or response time, of the engine-rotor combination to a step change in turbine-inlet temperature is one phase of the engine dynamics to be considered. Response time, as used in this report, will be defined as the time required for a specific combination of rotating elements to complete 98 percent of a speed change initiated by a step in one of the engine parameters, usually turbine-inlet temperature. Another phase of the dynamics to be investigated is the stability of the engine-rotor combination.

Power modulation at constant shaft speed. - The power changes involved in a flare-out from autorotation put a considerable demand on the dynamic response of a helicopter powerplant. During the autorotative descent, little or no power is being supplied to the rotor. In the flare-out, sufficient power must be applied to the rotor to support the helicopter and reverse its vertical component of velocity. Rotor speed cannot be allowed to decrease appreciably or the required lift will suffer.

In the fixed-turbine engine all the rotating components maintain fixed speed relations to the rotor. Even though little power is being supplied to the rotor in autorotation, nonetheless the entire engine is rotating at nearly rated speed. When full power for the flare-out is demanded, it can be supplied almost instantaneously, the only delay being that inherent in the fuel supply system. Furthermore, rated temperature can be set immediately without danger of compressor surge or stall.

With the free-turbine engine a change in power at constant power-turbine speed requires a change in both the temperature and the rotational speed of the gas generator. The time required to accelerate the gas generator is appreciable. The unbalanced torque available to accelerate the gas generator of a 4200-horsepower free-turbine engine is shown in figure 9 as a function of gas-generator speed for several turbine-inlet temperature ratios. Because the relation between torque and speed for constant turbine-inlet temperature is nearly linear, the speed of response of the gas generator can be integrated from the relation

$$Q = I \frac{dN}{dt}$$

The moment of inertia of the gas generator was taken as 5.25 slugs per square foot. The response time from 0.92 rated speed (half rated power) to rated speed using the rated turbine-inlet temperature ratio was found to be about 4.5 seconds. In the case of autorotation the power requirement would be less than half rated, and the gas-generator speed would probably be considerably less than 0.92 rated. In such a case the application of rated temperature at reduced speed and air flow might cause compressor surge, and the acceleration would have to be made at a reduced temperature. Figure 9 shows how the unbalanced torque at a given speed is decreased by a reduction in temperature. Accordingly, response times at turbine-inlet temperatures less than rated would be greater than the 4.5 seconds previously computed.

Simultaneous power and speed change. - A simultaneous change in rotor speed and power may often be desirable in a transition from hovering to high-speed forward flight. Response times for both the fixed- and free-turbine engines were computed for a transient from half power at 0.85 rated shaft speed to rated power at rated speed. On both engines rated turbine-inlet temperature was maintained during the transient, and the rotor-blade angle was scheduled with shaft speed as indicated by the load line in figure 10. Response times were computed by integrating the available torque-speed relation. The torque available for rotor acceleration is the difference between the transient operating line and the rotor load line at a given shaft speed. 3840

The response time for the fixed-turbine engine, in which the transient operating line is the rated temperature-ratio line, is computed to be about 6 seconds. Use of the rated temperature line as the transient operating line in computing response time for the free-turbine engine would have neglected the time required for the gas generator to accelerate from a speed corresponding to half-rated power to a speed corresponding to rated power. During the transient from half to rated power at rated turbine-inlet temperature ratio, the relation between shaft torque and shaft speed is given by the line AB in figure 10(b). The actual torque available for accelerating the power turbine and rotor is the difference between the line AB and the line CB in figure 10(b). The response time for the free-turbine engine, found by integrating the available torque-speed relation, is about the same as that for the fixed-turbine engine.

Torque-speed characteristics at constant fuel flow. - During helicopter operation in gusty air, the rotor may experience sudden forces that tend to disturb its rotational-speed equilibrium. The magnitude of the rotor-speed excursions from equilibrium and the rapidity of recovery depend on the torque-speed characteristics of the engine at constant fuel flow and on the torque-speed characteristics of the rotor at constant blade pitch angle. These torque characteristics are shown for the two engines in figure 11 at two different fuel flows (rated and 0.73 rated). A typical torque-speed characteristic of the rotor for constant pitch angle is also given in the figure.

A typical equilibrium operating point for either rotor-engine combination is represented by the intersection of the torque line and the load line (point A). For purposes of this example, the magnitude of the speed disturbance will be exaggerated. Assuming that the rotor speed is suddenly reduced by a gust, with fuel flow and pitch angle remaining unchanged, the rotor operating point will move to some other point, such as point B. Because the rotor and engine are direct-coupled through the transmission, the engine operating point will move to point C for the fixed turbine or to point D for the free turbine. The restoration of torque, which tends to accelerate the load, is then represented by BC for the fixed turbine or by BD for the free turbine. Rotor-speed stability is ensured when, as in this example, the load line has a greater slope than the engine torque line; the degree of stability is measured by the difference in slopes.

In figure 11, the slope of the fixed-turbine torque line is seen to depend upon the magnitude of the fuel flow, increasing from -1.7 at rated fuel flow to -1.1 at 0.73 rated fuel flow. The slope of the free-turbine torque line increases somewhat less rapidly, from -1.0 to -0.9 for the same difference in fuel flow. For the range of fuel flows investigated, the fixed- and free-turbine engines were about equally stable; small differences in slopes of the torque lines, such as those shown in figure 11, are not considered to be significant.

Lag-hinge resonance. - One other aspect of engine-rotor stability was analytically investigated. The possibility of exciting oscillations of speed and torque in the engine-rotor system due to the presence of lag hinges on rotor blades is studied experimentally in reference 5. The question arises in a gas-turbine-driven rotor as to whether this lag resonance phenomenon can be damped by the natural damping action of the engine in the presence of its high inertia. In order to answer this question, frequency-response characteristics were determined for an engine-rotor combination similar to the one assumed in the preceding sections. The rotor characteristics are those shown in figure 10, but the fixed-turbine rated horsepower was only 2640 horsepower. A lag-hinged rotor was assumed, and a simplified case of hovering with flapping neglected was considered.

In figure 12(a) is shown the frequency-response characteristics of the fixed-turbine engine-rotor system for the case of no damper on the lag hinge. The responses shown are those of rotor speed to fuel flow, rotor speed to blade angle, shaft torque to fuel flow, and shaft torque to blade angle. The system is resonant at a frequency ratio of 1.4; the frequencies are shown relative to the undamped natural frequency of the lag-hinged rotor blade.

The speed responses show a corner frequency ratio of 0.045, corresponding to a time constant of 4.5 seconds for the configuration studied. The response of rotor speed to fuel flow has an antiresonant point at 1. The shaft-torque response shows a large resonant peak at 1.2.

When a damper is applied to the lag hinge, set for a damping ratio of 1/2 on the characteristic equation for lagging, the results are as shown in figure 12(b). The resonant motion has been completely damped out. No stability or resonant problem is apparent. But the introduction of a lag damper causes a moment at the blade root to appear. This blade moment increases with increasing frequency to a frequency ratio of 1.5, where the entire shaft torque is transferred to the blade root; both the shaft and blade moments fall off at still higher frequencies.

When a free-turbine engine with the same horsepower rating was substituted for the fixed-turbine engine, the frequency-response curves were about the same as those shown in figure 12. The time constants for both engines were equal. Resonant motion was somewhat greater with the free turbine and occurred at a higher frequency. Damping was equally effective in reducing resonance in the two systems.

Summary of engine dynamics. - The dynamic characteristics, discussed in the foregoing sections, are briefly summarized in the following table:

Dynamic characteristic	Fixed turbine	Free turbine
Response time to power change at constant rotor speed, sec	Almost instantaneous	4.5
Response time to simultaneous power change and speed change, sec	6	6
Stability of constant fuel-flow operation	Adequate	Good
Damping required for lag-hinge resonance	Some	More

HELICOPTER PERFORMANCE WITH FIXED- AND FREE-TURBINE ENGINES

Helicopter Configuration and Powerplant Installation

Helicopter design parameters. - Differences in off-design fuel consumption and in other significant performance characteristics for the fixed- and free-turbine engines are best evaluated by calculation of helicopter flight performance. Inasmuch as these calculations are intended to give comparative rather than absolute results, no attempt was made to optimize the helicopter design for a particular powerplant installation. The following parameters were therefore held constant in the flight-performance evaluation:

General:

Gross weight, W_g, lb	30,000
Number of rotors	1
Number of blades per rotor, b	3
Fuselage flat-plate area, S_f, sq ft	42
Ratio of structure plus equipment weight to gross weight	0.375
Ratio of crew weight to gross weight	0.0133

Rotor:

Blade section and plan form	Ref. 6
Rotor solidity, σ	0.075
Disk loading, lb/sq ft	4.53
Design tip speed, V_t, ft/sec	650

Powerplant installation. - For both fixed- and free-turbine engine installations, engine specific weight was assumed to be 0.5 pound per horsepower. Transmission weight was calculated from rated engine torque and averaged about 9.5 percent of the helicopter gross weight. Fuel tank weight was assumed to be 10 percent of the calculated fuel load.

Determination of Powerplant Size

By use of the engine performance data given in a preceding section (FIXED- AND FREE-TURBINE ENGINE PERFORMANCE), engine size for the assumed helicopter can be determined when the helicopter power requirements are known. In this analysis, the fixed- and free-turbine engines are sized to provide sea-level hovering power plus a specified power reserve. Methods for determining helicopter power requirements and the effects of helicopter operating modes on the reserve-power requirements are discussed in the following sections.

Calculation of rotor power. - The methods presented in references 6 and 7 were used to calculate the rotor power required by the helicopter. A typical plot showing rotor power required by the helicopter as a function of the tip-speed ratio for tip speeds of 550 and 650 feet per second is given in figure 13. Intersections of the curves with the ordinate axis ($\mu = 0$) give the rotor-power requirements for hovering flight at maximum gross weight. As an allowance for tail-rotor and transmission losses, the rotor-power values shown in figure 13 were multiplied by the factor 1.08, giving total power required by the helicopter. Similar charts were constructed for part-load operation of the helicopter and were used in the calculation of flight range and hovering duration.

Reserve-power requirements. - If design-weight hovering flight is to be accomplished at altitudes above sea level and at high ambient temperatures, the helicopter powerplant must be sized to provide considerable reserve power over that required at sea level. Hovering power required by the helicopter is given by the solid curves in figure 14 for a range of ambient temperature and pressure ratios. As a design specification for the helicopter in this analysis, it was required that the helicopter be capable of design-weight hovering flight at a pressure altitude of 6000 feet and an ambient temperature of 95° F. At this Denver hot-day condition the equivalent power required is about 1.27 times the sea-level power, as shown by the circled point in figure 14.

In a preceding discussion of figure 8, it is demonstrated that the equivalent powers generated by the fixed- and free-turbine engines fall off in nearly identical manners when ambient temperatures are raised above standard value. Equivalent power against ambient temperature can therefore be represented as a single function for the two engines, and such a line is plotted as the lower dashed curve in figure 14. For this power-available line, both engines were sized to provide exactly sea-level hovering power at standard conditions, that is, the reserve-power margin is zero. Obviously, hovering flight is impossible for any combination of ambient temperature and altitude that gives a power-required point above this power-available line.

However, if the engines are sized to provide 60-percent reserve power at sea-level standard conditions, the upper dashed curve shows that hovering flight at design weight is just possible at the Denver hot-day condition. Here, both fixed and free turbines generate 1.27 times the equivalent sea-level power required. In subsequent flight performance calculations, both engines are therefore sized to provide 60-percent reserve power over the sea-level hovering power.

Effects of variation in operational tip speeds on reserve power. - There are well-known aerodynamic advantages that accrue to the helicopter if its rotor can be operated at variable tip speed (ref. 7). Low tip speeds, for example, are usually advantageous in hovering; high tip speeds are used to delay retreating-blade stall at high flight speeds. When the tip speed is varied in flight, however, the speed-power characteristic of the powerplant will often change the margin of available reserve power, with considerable effect on helicopter performance. Such a change in reserve-power margin is illustrated in figure 15.

In figure 15, hovering power required by the assumed helicopter is given as a function of tip speed by the lower curves in both parts of the figure. Free-turbine power available at variable shaft speed, corresponding to the tip speed, is given by the upper curve in figure 15(a); a similar curve is given for the fixed-turbine engine in figure 15(b).

In both instances, the engines are sized to provide 60-percent reserve power over the hovering power required at the design tip speed of 650 feet per second. Furthermore, because the upper curves represent the maximum power available from the engines, operation at rated turbine-inlet temperature ratio is implied.

For a reduction in free-turbine shaft speed from rated to 0.85 rated, that is, reduction in V_t from 650 to 550 feet per second, figure 15(a) shows that the reserve-power margin is increased from 60 to 73 percent. A subsequent discussion in the section "Climb performance" will show that this increase in reserve-power margin will give the free-turbine helicopter a better rate of climb at a tip speed of 550 feet per second than at 650 feet per second.

For the fixed-turbine powerplant installation, the same reduction in tip speed is shown to decrease the reserve-power margin from 60 to about 22 percent (fig. 15(b)). The smaller power reserve of the fixed-turbine engine at off-rated speeds, as compared with the free turbine, will be shown to place it at a decided disadvantage during climb (also in the section "Climb performance").

Helicopter Flight Performance

Inasmuch as the specific power outputs and specific weights of the fixed- and free-turbine powerplants are assumed identical, and because equal reserve-power requirements are assumed, the weights of the installed powerplants are equal; furthermore, useful loads for the fixed- and free-turbine helicopters are identical. For the flight performance results that follow, the hovering durations and ranges given are those calculated for fuel loads equal to the helicopter useful load minus crew weight and 10-percent fuel reserve.

Range and hovering duration. - Ranges and hovering durations at sea level are compared for the fixed- and free-turbine helicopters in figure 16. Range is shown as a function of flight speed for tip speeds of 550 and 650 feet per second; hovering durations are given in the table. Stall-limited forward-flight speeds are indicated by the circled points on the curves.

Ranges and hovering times at a given tip speed are not significantly different for the two helicopters. For both fixed- and free-turbine helicopters, maximum ranges and hovering times at a tip speed of 550 feet per second are 10 to 12 percent higher than the corresponding values at 650 feet per second. The improved performance at the reduced tip speed is attributed to reduced rotor-power requirements.

Climb performance. - Sea-level rates of climb for the two helicopters are plotted as functions of flight speed in figure 17(a). Inasmuch as the fixed- and free-turbine engines have the same rated power, rates of climb at design rotor tip speeds (650 ft/sec) are identical at all flight speeds. However, when rotor speeds are reduced to below-rated values, markedly different effects on climb performance are found. For example, a reduction in tip speed of the free-turbine helicopter from 650 to 550 feet per second gives about a 6-percent increase in best rate of climb. This improved climb performance is due to both the higher rotor efficiency at the lower tip speed and to the flat power-speed characteristic of the free-turbine engine. In contrast, the same reduction in tip speed for the fixed-turbine helicopter decreases its best rate of climb by about 35 percent. This reduction in climb performance is a consequence of the reduced power available from the fixed-turbine engine at below-rated shaft speeds (see fig. 15(b)).

Rates of climb for the two helicopters are plotted as functions of altitude in figure 17(b) for a flight speed of approximately 60 knots. The fixed- and free-turbine helicopters give nearly identical altitude climb performance at design tip speed (650 ft/sec). This is an expected result inasmuch as the two engine types have nearly identical altitude power outputs at rated shaft speeds and limiting turbine-inlet temperatures (see discussion of fig. 8). However, in figure 17(b), the free-turbine helicopter is shown to have significantly better climb performance than the fixed-turbine helicopter when rotor tip speeds are reduced to 550 feet per second. This performance difference is again the result of the different power-speed characteristics of the two engine types.

Effects of helicopter reserve-power requirement on flight performance. - When helicopter design gross weight is fixed, demands for large reserve-power margins can be satisfied only by the installation of large engines with a corresponding reduction in useful load. Moreover, the large engine will normally operate farther from its design point than will a small engine, and specific fuel consumption will therefore be higher.

The effects of increased reserve-power margins on the fixed-turbine helicopter of this study are illustrated in figure 18. Nearly identical results are obtained for the free-turbine helicopter. Flight range is plotted as a function of flight speed for three fixed-turbine machines having engines sized to provide 0-, 30-, and 60-percent reserve power over the hovering power required. As compared with the installation with zero reserve power, the 30- and 60-percent-reserve-power helicopters are shown to give about 6- and 25-percent shorter maximum flight ranges, respectively.

SUMMARY OF RESULTS

At design shaft speeds and turbine-inlet temperature ratios, the equivalent power developed by both the fixed- and free-turbine engines was about 91.4 horsepower per pound of air per second. For both engines, specific fuel consumption was 0.61 pound of fuel per horsepower per hour. The assumption of identical compressors and the use of consistent over-all turbine efficiencies for the two engines explains the identical performance at design point.

A change in shaft speed of the free-turbine engine from rated to 0.85 rated speed gave a 2-percent reduction in equivalent power at design turbine-inlet temperature ratio. A similar reduction in the fixed-turbine shaft speed gave a 30-percent reduction in equivalent shaft power.

Variations in the compressor-inlet temperature had nearly identical effects on the power output of the two engines. Raising the compressor-inlet temperature from sea-level standard to 95° F reduced the equivalent power of both engines to about 79 percent of rated value.

During power modulation at constant shaft speed, the fixed-turbine engine showed advantages over the free-turbine engine. Since no acceleration of the fixed-turbine rotating mass is required, power modulation by changes in fuel flow was extremely rapid, limited only by the response of the fuel system or load. However, power modulation of the free-turbine engine at constant power-turbine speed was limited by the accelerating characteristics of the gas-generator component.

The time required to accelerate a helicopter rotor from a condition in which it was absorbing one-half rated engine power at 0.85 rated speed to a condition requiring rated speed at rated power was computed for both the fixed- and free-turbine engines. The response times for both engines were about the same.

Lag hinges on the rotor blades caused resonant fluctuation in the engine-rotor speed and torque. Damping in the lag hinges was effective in reducing the severity of the resonance.

For both fixed- and free-turbine helicopters, a reserve-power margin of 60 percent over the sea-level hovering power was required to permit hovering flight on a 95° F day at a pressure altitude of 6000 feet. Reserve power provided by the free-turbine installation increased from 60 to 73 percent over the hovering power required when the rotor tip speed was reduced from 650 to 550 feet per second. In contrast, the reserve-power margin of the fixed-turbine helicopter decreased from 60 to 22 percent for the same change in operational tip speed. As a consequence, the best rate of climb for the free-turbine helicopter increased about 6 percent when the tip speed was reduced from 650 to 550 feet per second, while the rate of climb for the fixed-turbine helicopter fell off about 35 percent.

No significant differences in range or hovering time were found for the fixed- and free-turbine helicopters. Range and hovering time were both slightly improved when operational tip speeds were reduced from 650 to 550 feet per second.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 3, 1956

APPENDIX A

SYMBOLS

b	number of blades per rotor
c_p	specific heat
f/a	fuel-air ratio
H	total enthalpy, Btu/lb
hp	horsepower
I	moment of inertia
K	constant
N	rotational speed
P	total pressure, lb/sq ft
Q	torque
S_f	fuselage flat-plate area, sq ft
sfc	specific fuel consumption
T	total temperature, $^{\circ}R$
t	time
V	velocity, ft/sec
W_g	helicopter gross weight, lb
w	engine weight flow
γ	ratio of specific heats
δ	ratio of total pressure to NACA standard pressure of 2116 lb/sq ft
η	adiabatic efficiency
θ	ratio of total temperature to NACA standard temperature of 519° R
μ	tip-speed ratio, ratio of flight speed to rotor tip speed
σ	rotor solidity

Subscripts:

b	combustion chamber
c	compressor
d	design point
sl	sea level
t	rotor tip
0	ambient
1	engine inlet
2	compressor inlet
3	combustion-chamber inlet
4	turbine inlet (fixed-turbine engine) gas-generator turbine inlet (free-turbine engine)
5	power-turbine inlet (free-turbine engine)
6	turbine discharge
7	exhaust-nozzle exit

APPENDIX B

FIXED- AND FREE-TURBINE PERFORMANCE ANALYSIS

Performance calculations and component matching techniques for the fixed- and free-turbine engines are, for the most part, conventional and require a station-by-station computation of the state of the gas in the engines. The fundamental relations employed are (1) continuity of mass flow through the engines, (2) equivalence of rotational speeds for rigidly connected compressors and turbines, and (3) equivalence of power developed by turbines with power required by compressors and shafts.

The power turbine of the free-turbine engine represents a component not found in the fixed-turbine engine. Inasmuch as the speed of this component is not related directly to the speed of the gas generator, additional variables are introduced in the free-turbine analysis. Certain differences in the performance computation procedures are therefore required for the two engines, and these differences are outlined briefly in this appendix.

Continuity of Mass Flow

The continuity relation for both the fixed-turbine engine and the gas-generator component of the free-turbine engine may be written in terms of generalized parameters as follows:

$$\frac{w_2\sqrt{\theta_2}}{\delta_2} = \frac{w_4\sqrt{\theta_4}}{\delta_4}\,\frac{1}{1 + f/a}\,\frac{P_3}{P_2}\,\frac{P_4}{P_3}\sqrt{\frac{T_2}{T_4}} \qquad \text{(B1)}$$

Because the total-pressure ratios are normally higher than critical across the gas-generator turbine and the fixed turbine, the inlet stages of both these turbines are choked, giving a constant value for the equivalent weight flow term $\frac{w_4\sqrt{\theta_4}}{\delta_4}$. Equation (B1) may therefore be written as

$$\frac{w_2\sqrt{\theta_2}/\delta_2}{(w_2\sqrt{\theta_2}/\delta_2)_{rated}} = K_1\,\frac{P_3}{P_2}\,\frac{P_4}{P_3}\,\frac{1}{1 + f/a}\sqrt{\frac{T_2}{T_4}} \qquad \text{(B2)}$$

The constant K_1 is evaluated by entering rated values for the remaining terms in the equation; for example, $\frac{w_2\sqrt{\theta_2}}{\delta_2}\Big/\left(\frac{w_2\sqrt{\theta_2}}{\delta_2}\right)_{rated} = 1.0$.

From this equation, pressure ratios corresponding to a given air flow can be found for a series of assigned turbine-inlet temperature ratios T_4/T_2.

Fixed-Turbine Performance Calculations

In the fixed-turbine engine, the power developed by the turbine equals the sum of the power required by the compressor and the useful shaft power. In equivalent parameters, this relation is expressed by the equation

$$\frac{\Delta H}{\theta_4} = \frac{519 c_{p,c}\left(\frac{T_3}{T_2} - 1\right)}{(1 + f/a)T_4/T_2} + \frac{0.707}{(1 + f/a)T_4/T_2} \, \frac{\dfrac{hp}{\sqrt{\theta_0}\delta_0} \Bigg/ \left(\dfrac{w_2\sqrt{\theta_2}}{\delta_2}\right)_{rated}}{\dfrac{w_2\sqrt{\theta_2}}{\delta_2} \Bigg/ \left(\dfrac{w_2\sqrt{\theta_2}}{\delta_2}\right)_{rated}} \, \frac{P_0}{P_2} \tag{B3}$$

Specific shaft power developed by the fixed-turbine engine is determined as follows:

(1) Select a set of discrete values for the turbine-inlet temperature ratio T_4/T_2, and for each T_4/T_2, assume several values of the shaft-speed parameter $N/\sqrt{\theta_2}\Big/(N/\sqrt{\theta_2})_{rated}$.

(2) For each combination of speed and temperature ratio, calculate the compressor pressure ratio P_3/P_2 from the compressor mass flow - speed relation (fig. 2) and equation (B2).

(3) By use of equation (B3), calculate the turbine work parameter $\Delta H/\theta_4$ for a trial range of the shaft-work parameter $\dfrac{hp}{\sqrt{\theta_0}\delta_0}\Bigg/\left(\dfrac{w_2\sqrt{\theta_2}}{\delta_2}\right)_{rated}$.

(4) Obtain the turbine total-pressure ratio P_4/P_5 from the turbine map (fig. 4).

(5) Calculate the required nozzle area for each of the preceding conditions.

For each combination of engine speed and turbine-inlet temperature ratio, equilibrium shaft power is that power requiring a nozzle area 40 percent larger than the compressor frontal area.

Free-Turbine Performance Calculations

In the free-turbine engine, the power developed by the gas-generator turbine equals the power required by the compressor. The equation expressing this relation is similar to equation (B3), but the useful shaft-power term is equal to zero. With the aid of this equation, and by methods similar to those used in the fixed-turbine analysis, conditions are calculated at station 5, which is the exit station of the gas-generator component. Operating points for the gas generator are limited to those that give a value of equivalent exit weight flow equal to the choked flow of the free-turbine inlet. The magnitude of this inlet critical weight flow parameter is given by the maximum abscissa of the rated speed line plotted in the free-turbine map (fig. 3). Because the free turbine is choked, there is a single operating line for the gas generator, that is, a single-valued relation exists between the gas-generator temperature ratio T_4/T_2 and its equivalent shaft speed $N/\sqrt{\theta_2}/(N/\sqrt{\theta_2})_{rated}$.

For each combination of gas-generator temperature and speed, and for a selected range of free-turbine speeds, a trial range of the free-turbine shaft-power parameter $\Delta H/\theta_5$ is assumed. At a given gas-generator temperature and free-turbine speed, the equilibrium value of the shaft-power parameter is that which requires an exhaust-nozzle area 40 percent larger than the compressor frontal area.

APPENDIX C

DERIVATION OF OPERATING LINE FOR GAS-GENERATOR TURBINE

In the cycle analysis of the free-turbine engine, the adiabatic efficiency of the gas-generator turbine was assumed constant. The validity of this assumption depends upon the range of pressure ratios and equivalent speeds required of this component. Consideration of the gas-generator continuity relations and the choked-flow conditions of both the gas-generator and power turbines shows that this range of corrected speeds and pressure ratios is, in fact, quite limited.

Because the pressure ratios across both the gas-generator and power turbines of the free-turbine engine are normally higher than critical, these components are choked. The equivalent weight flows through these components are, therefore, constant and may be related by the equation:

$$\frac{w_4\sqrt{\theta_4}}{\delta_4} = K_6 \frac{w_5\sqrt{\theta_5}}{\delta_5} \tag{C1}$$

where K_6 is a constant. Because $w_4 = w_5$, equation (C1) can be rewritten to give

$$\frac{P_5}{P_4} = K_6\sqrt{\frac{T_5}{T_4}} \tag{C2}$$

From the definition of the gas-generator work parameter $\Delta H/\theta_4$ and from the compressor-turbine energy-balance relation,

$$\frac{\Delta H}{\theta_4} = \frac{519c_{p,t}}{T_4}(T_4 - T_5) = \frac{519c_{p,c}}{\eta_c}\frac{1}{T_4/T_2}\left[\left(\frac{P_3}{P_2}\right)^{\frac{\gamma_c-1}{\gamma_c}} - 1\right] \tag{C3}$$

The defining equation for turbine work (eq. (C3)) is solved for T_5/T_4:

$$\frac{T_5}{T_4} = 1 - \frac{1}{519c_{p,t}}\frac{\Delta H}{\theta_4} \tag{C4}$$

When equations (C2) and (C4) are combined, the following relation is obtained:

$$\frac{P_5}{P_4} = K_6\left(1 - \frac{\Delta H}{\theta_4}\frac{1}{519c_{p,t}}\right)^{\frac{1}{2}} \tag{C5}$$

By ignoring the mass flow addition in the combustors $w_2 = w_4$, the weight flow - speed parameter for the gas-generator turbine is

$$\frac{Nw_4}{\delta_4} = K_7 \frac{N/\sqrt{\theta_2}}{(N/\sqrt{\theta_2})_{rated}} \frac{w_2\sqrt{\theta_2}/\delta_2}{(w_2\sqrt{\theta_2}/\delta_2)_{rated}} \frac{1}{P_4/P_2} \tag{C6}$$

where $P_4/P_2 = 0.95\ P_3/P_2$, and K_7 is a constant.

The final equation needed to specify the operating region of the gas-generator turbine is obtained from the continuity relation in the gas generator (eq. (B2)):

$$\frac{P_3}{P_2} = K_8 \frac{w_2\sqrt{\theta_2}/\delta_2}{(w_2\sqrt{\theta_2}/\delta_2)_{rated}} \sqrt{\frac{T_4}{T_2}} \tag{C7}$$

The operating region for the gas-generator turbine is obtained from equations (C3) and (C5) to (C7) by the following procedure:

(1) To find lines on a turbine map satisfying both the gas-generator continuity relation and the compressor-turbine energy-balance requirement:

(a) Find the constants K_7 and K_8 in equations (C6) and (C7) by substituting rated values for the other parameters in the equations.

(b) Assume a range of $\frac{w_2\sqrt{\theta_2}/\delta_2}{(w_2\sqrt{\theta_2}/\delta_2)_{rated}}$, and for a specified T_4/T_2, calculate P_3/P_2 from equation (C7).

(c) With these values of P_3/P_2, and with the corresponding values of $\frac{w_2\sqrt{\theta_2}/\delta_2}{(w_2\sqrt{\theta_2}/\delta_2)_{rated}}$, calculate $Nw_4/4$ by use of equation (C6). Use the relation between $\frac{N/\sqrt{\theta_2}}{(N/\sqrt{\theta_2})_{rated}}$ and $\frac{w_2\sqrt{\theta_2}/\delta_2}{(w_2\sqrt{\theta_2}/\delta_2)_{rated}}$ shown in figure 2.

(d) From corresponding P_3/P_2 and T_4/T_2, find $\Delta H/\theta_4$ from equation (C3).

(e) Plot $\Delta H/\theta_4$ as a function of $Nw_4/4$ with T_4/T_2 as a parameter on the turbine map.

(f) Repeat procedure for range of T_4/T_2.

(2) To find a line on a turbine map satisfying the double-choking conditions of the gas-generator turbine and power turbine:

(a) Determine the constant K_6 in equation (C5) by substituting rated values for $\Delta H/\theta_4$ and P_5/P_4.

(b) Assume a range of $\Delta H/\theta_4$ and calculate P_5/P_4 from equation (C5).

(c) Plot P_4/P_5 as a function of $\Delta H/\theta_4$ on the turbine map.

The foregoing procedure (steps 1 and 2) locates those operating points on the gas-generator turbine map that simultaneously satisfy (1) the choked-flow conditions for both the gas-generator and power turbines, (2) the gas-generator continuity requirements, and (3) the compressor-turbine energy-balance requirements.

The results of step 1 are plotted in figure 19 as a family of nearly straight lines with $\Delta H/\theta_4$ as a function of $\dfrac{w_4N}{\delta_4}\Big/\left(\dfrac{w_4N}{\delta_4}\right)_{rated}$ and with T_4/T_2 as a parameter. Step 2 demonstrates that the consequence of the double-choking condition for the two turbines is to restrict the gas-generator turbine to operation at very nearly constant pressure ratio. A line representing a typical turbine constant-pressure-ratio line is drawn in figure 19 through the point that marks the design-point values for w_4N/δ_4 and $\Delta H/\theta_4$. Inasmuch as the gas generator is restricted to the narrow operating region bounded by the intersections of the T_4/T_2 lines and the constant P_4/P_5 line, the exact shape of the constant-pressure-ratio line, approximated in this example, is of little consequence.

For the range of T_4/T_2 considered herein, the intersections, which represent turbine operating points, show a variation in w_4N/δ_4 of less than 2 percent of its design value. The range of operating conditions for the gas-generator turbine is therefore extremely limited, and the use of constant adiabatic efficiency for this component is justified.

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2. Young, R. A.: Some Notes on Helicopter Power Systems. Paper presented at Am. Helicopter Soc. meeting, Los Angeles section, Mar. 31, 1954.

3. Pinkel, Benjamin, and Karp, Irving M.: A Thermodynamic Study of the Turbine-Propeller Engine. NACA Rep. 1114, 1953. (Supersedes NACA TN 2653.)

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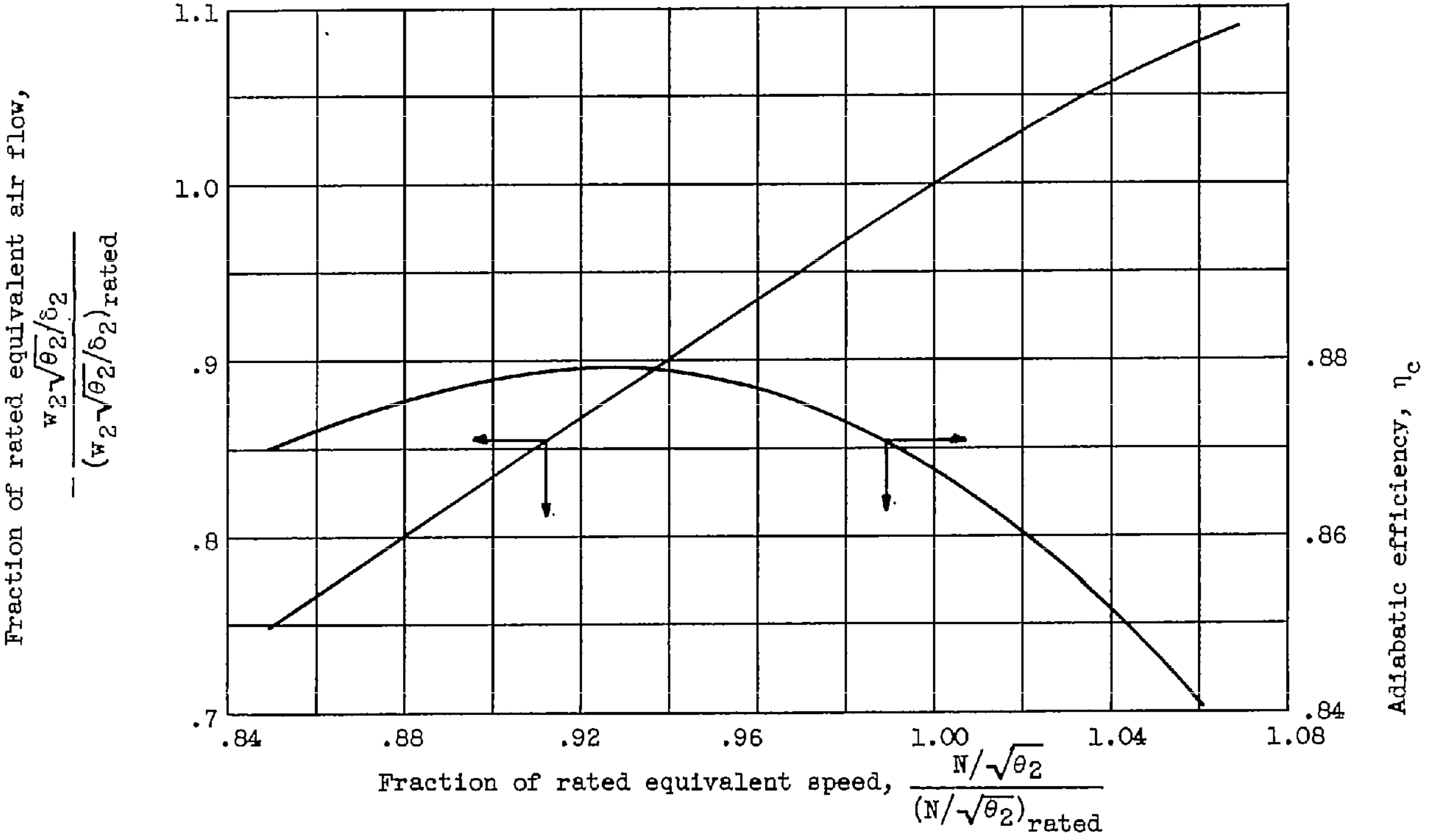


Figure 2. - Compressor characteristics. Design pressure ratio, 7.0; design specific air flow, 20 lb/(sec)(sq ft).

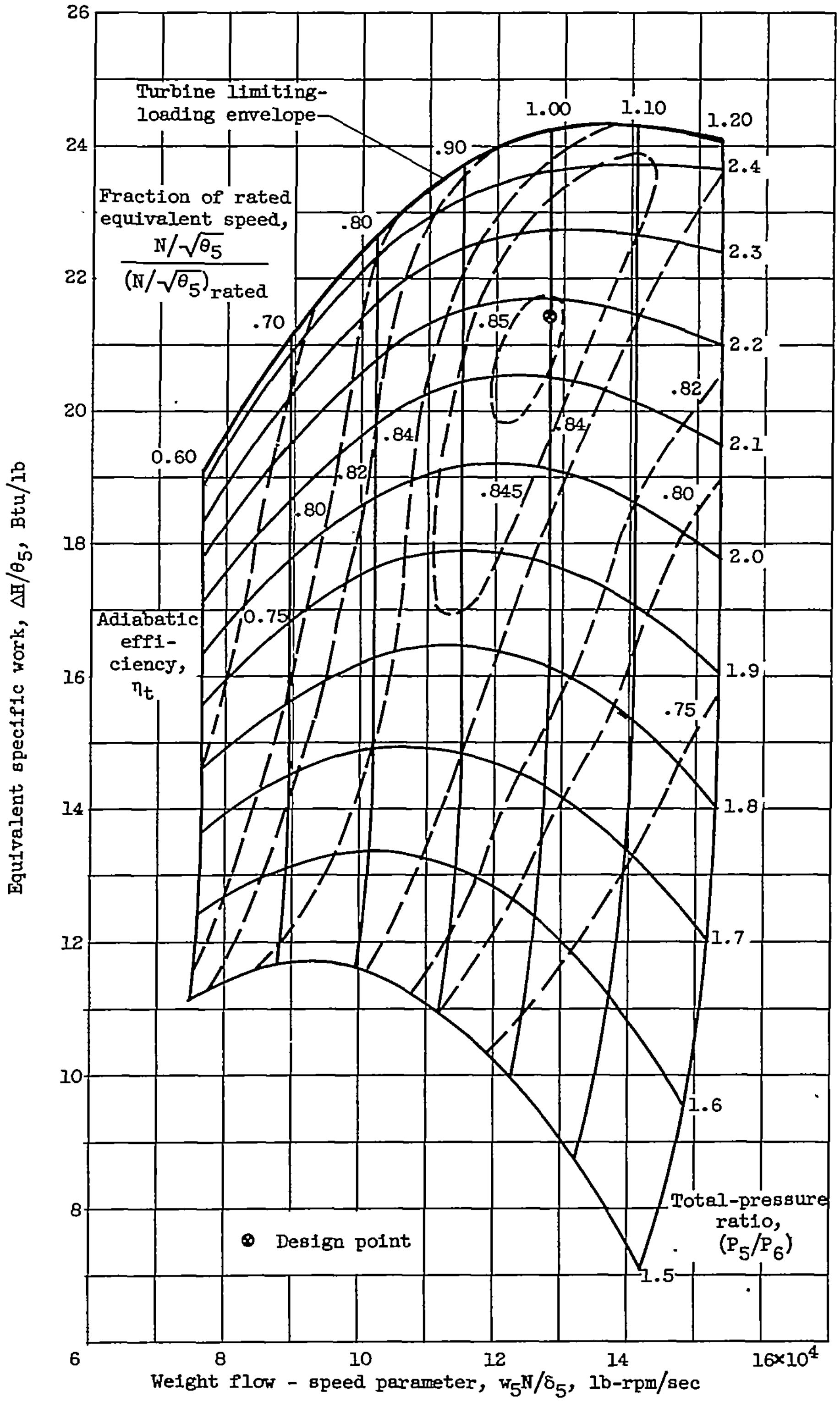


Figure 3. - Free-turbine performance characteristics.

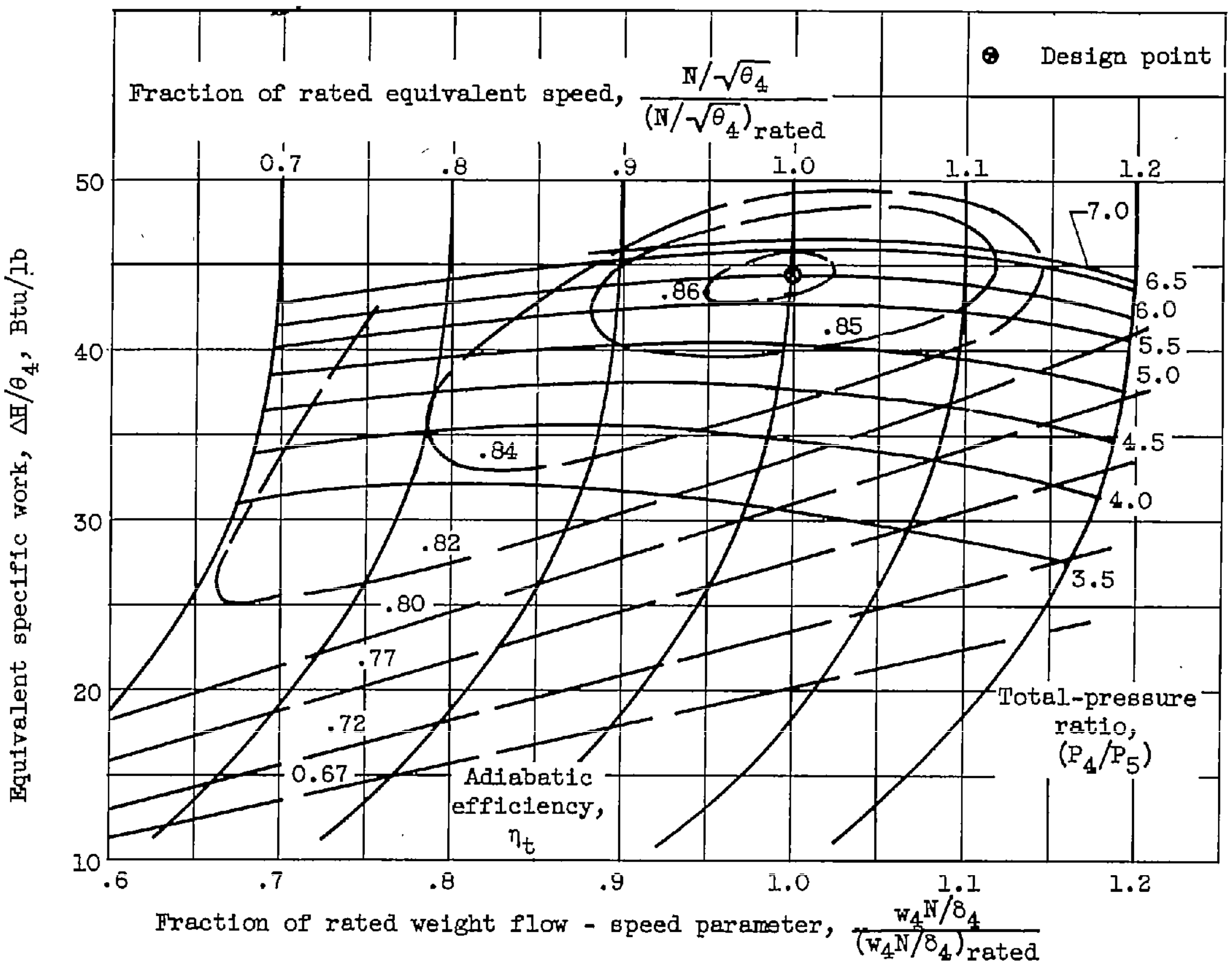
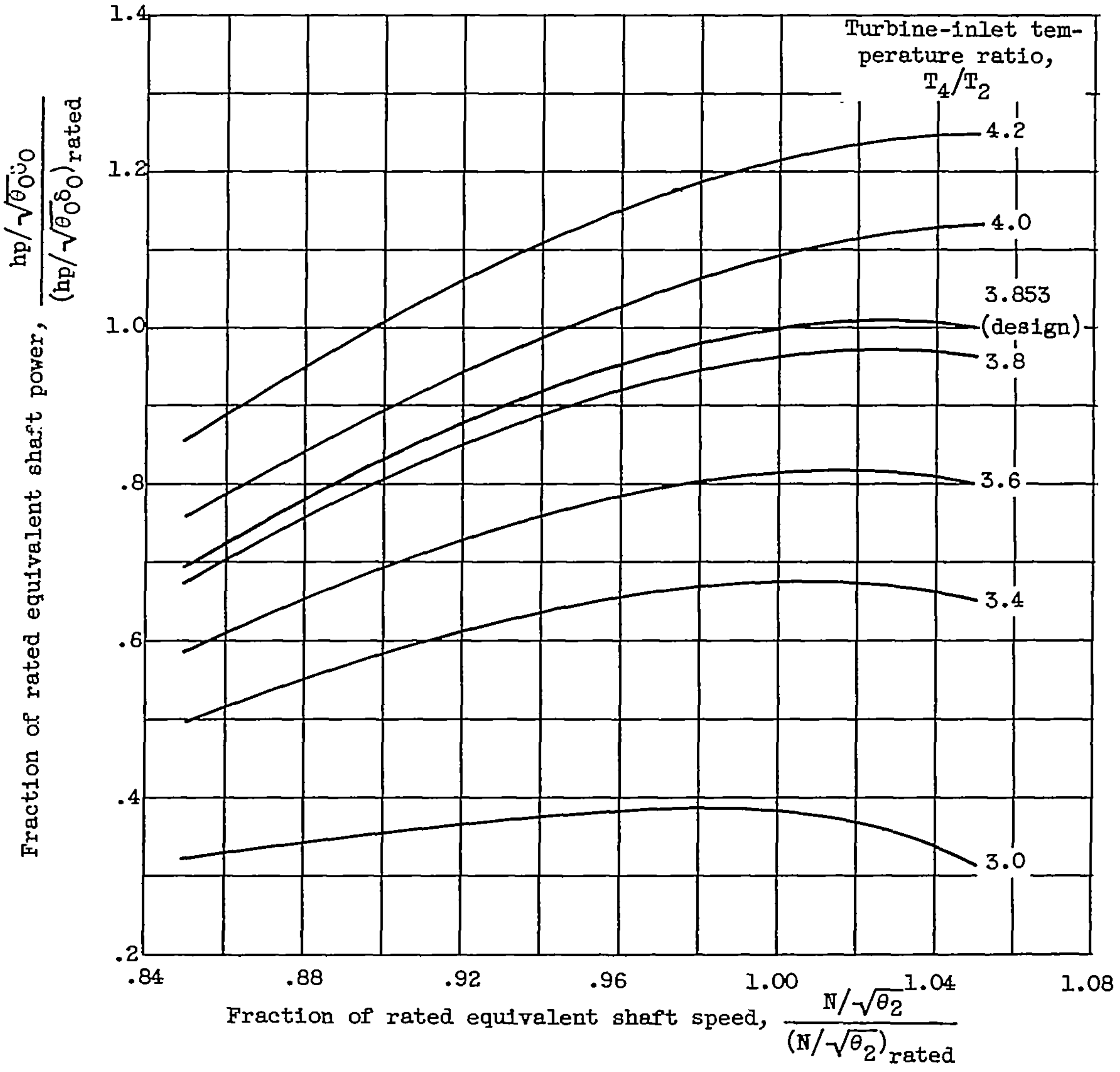
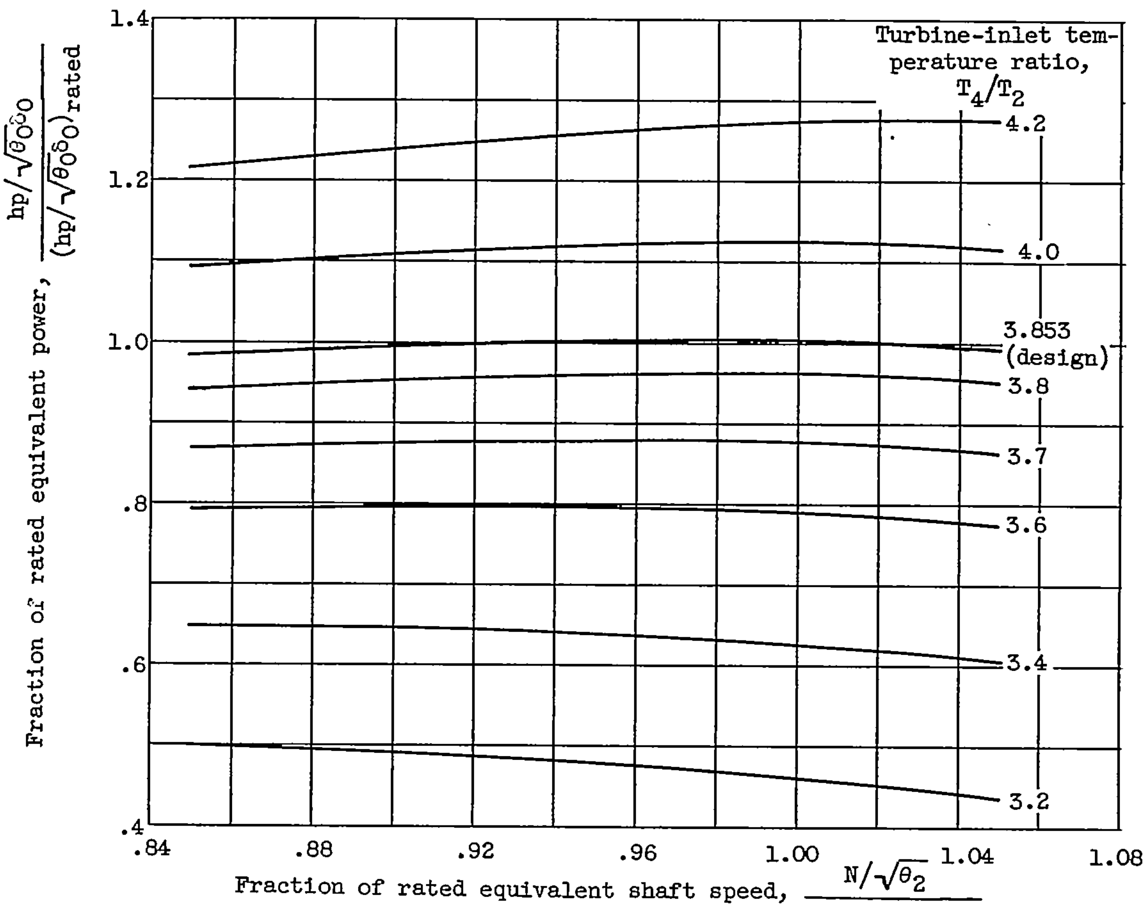


Figure 4. - Fixed-turbine performance characteristics.



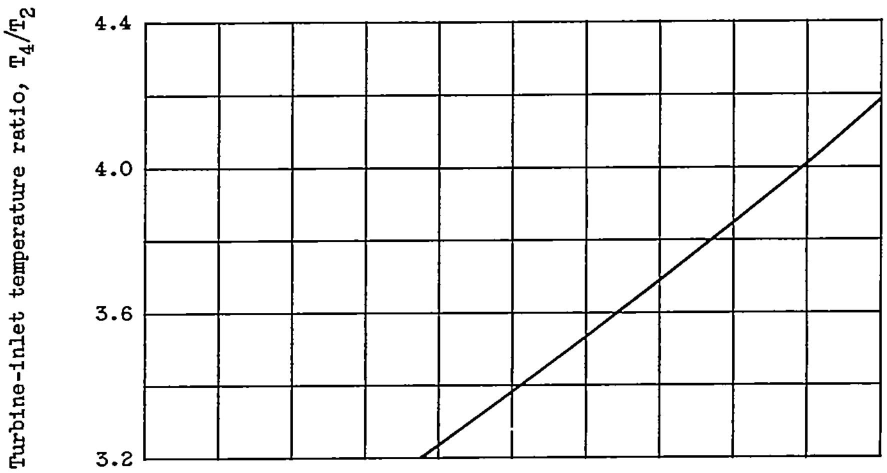
(a) Fixed-turbine engine.

Figure 5. - Generalized engine performance. Design turbine-inlet temperature, 2000° R; design compressor pressure ratio, 7.0; ratio of jet-nozzle area to compressor frontal area, 1.4.

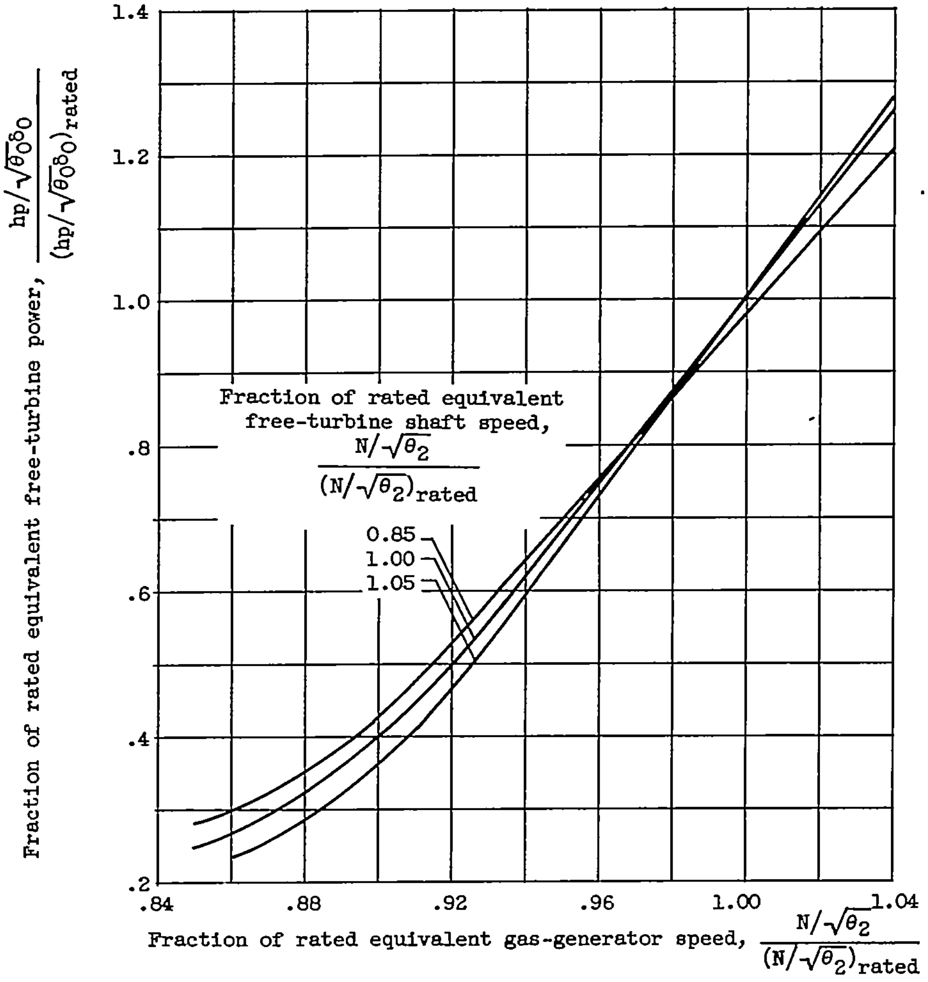


(b) Free-turbine engine.

Figure 5. - Concluded. Generalized engine performance. Design turbine-inlet temperature, 2000° R; design compressor pressure ratio, 7.0; ratio of jet-nozzle area to compressor frontal area, 1.4.

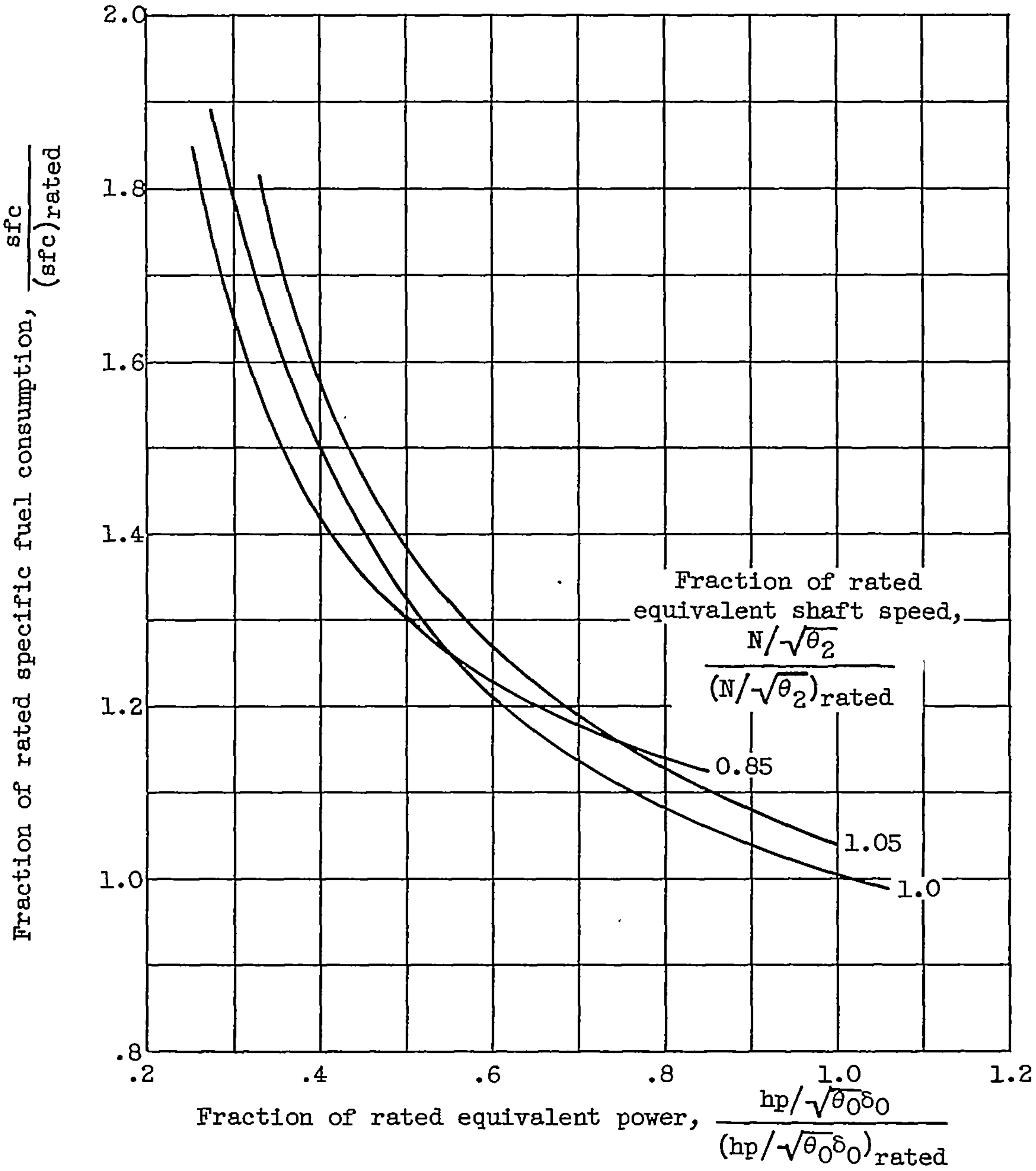


(a) Turbine-inlet temperature ratio.



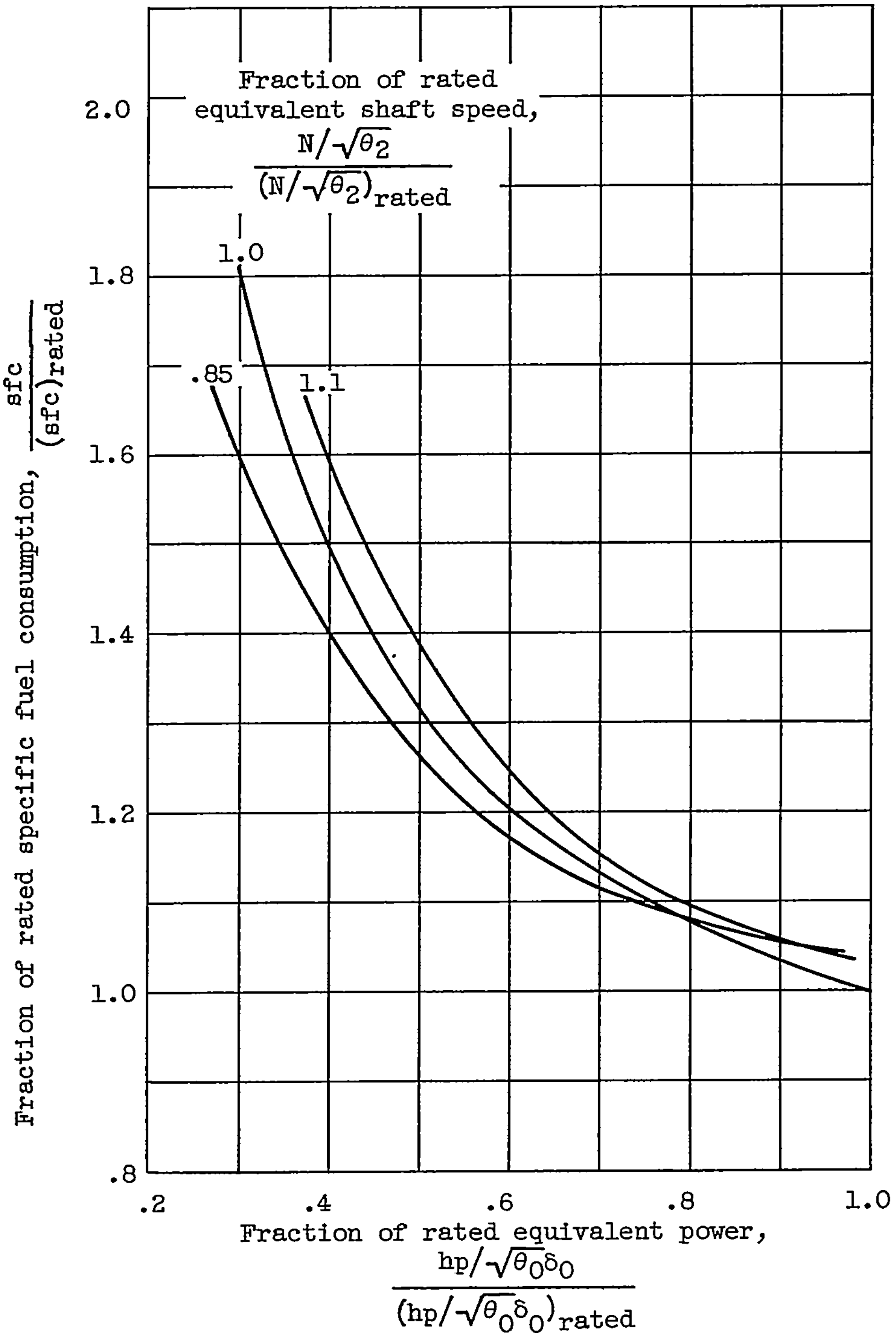
(b) Equivalent power.

Figure 6. - Variation of free-turbine engine equivalent power and turbine-inlet temperature ratio with gas-generator equivalent speed.



(a) Fixed-turbine engine.

Figure 7. - Engine specific fuel consumption.



(b) Free-turbine engine.

Figure 7. - Concluded. Engine specific fuel consumption.

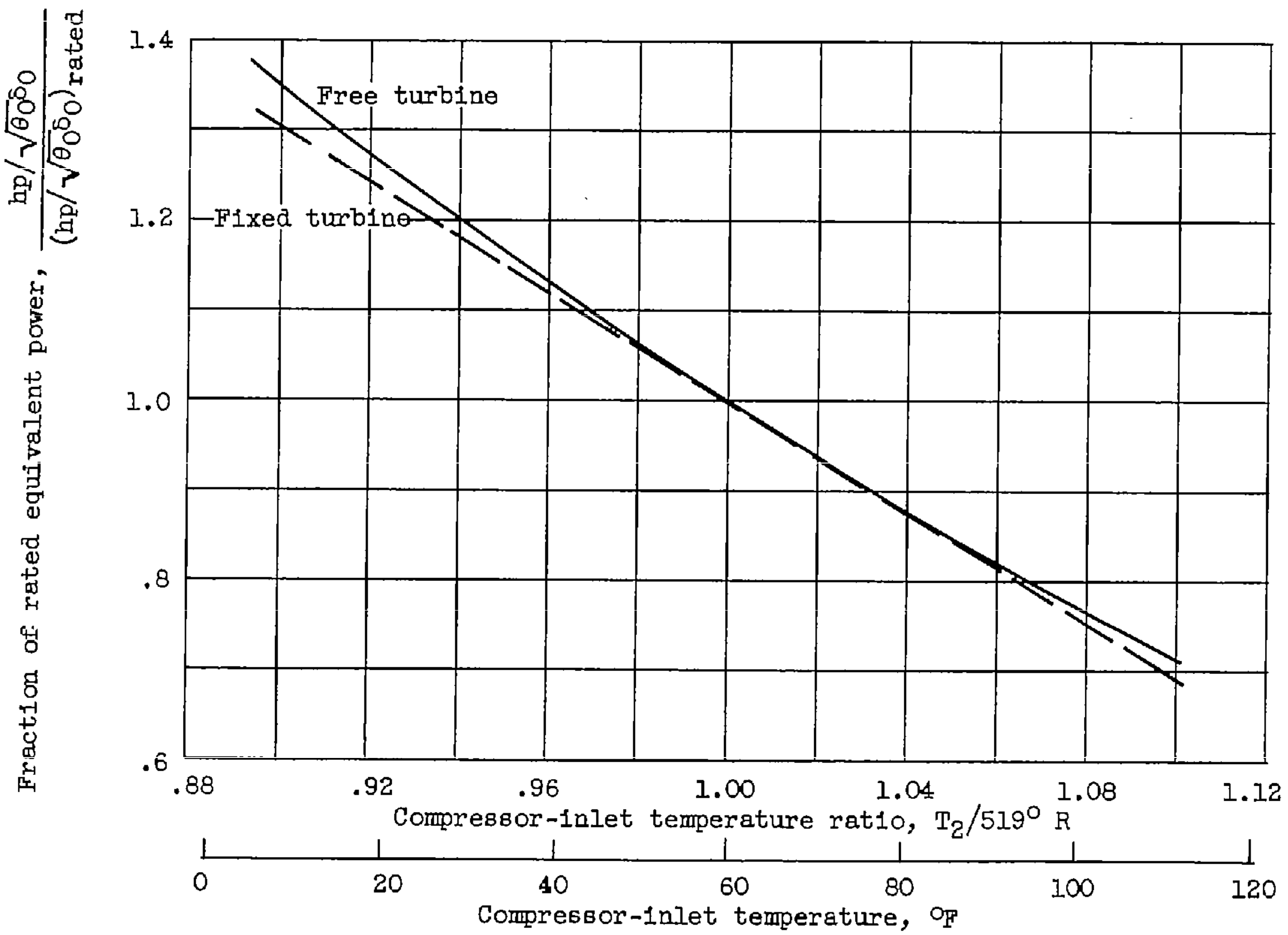


Figure 8. - Fixed- and free-turbine power as function of compressor-inlet temperature. Rated shaft speed; turbine-inlet temperature, 2000° R.

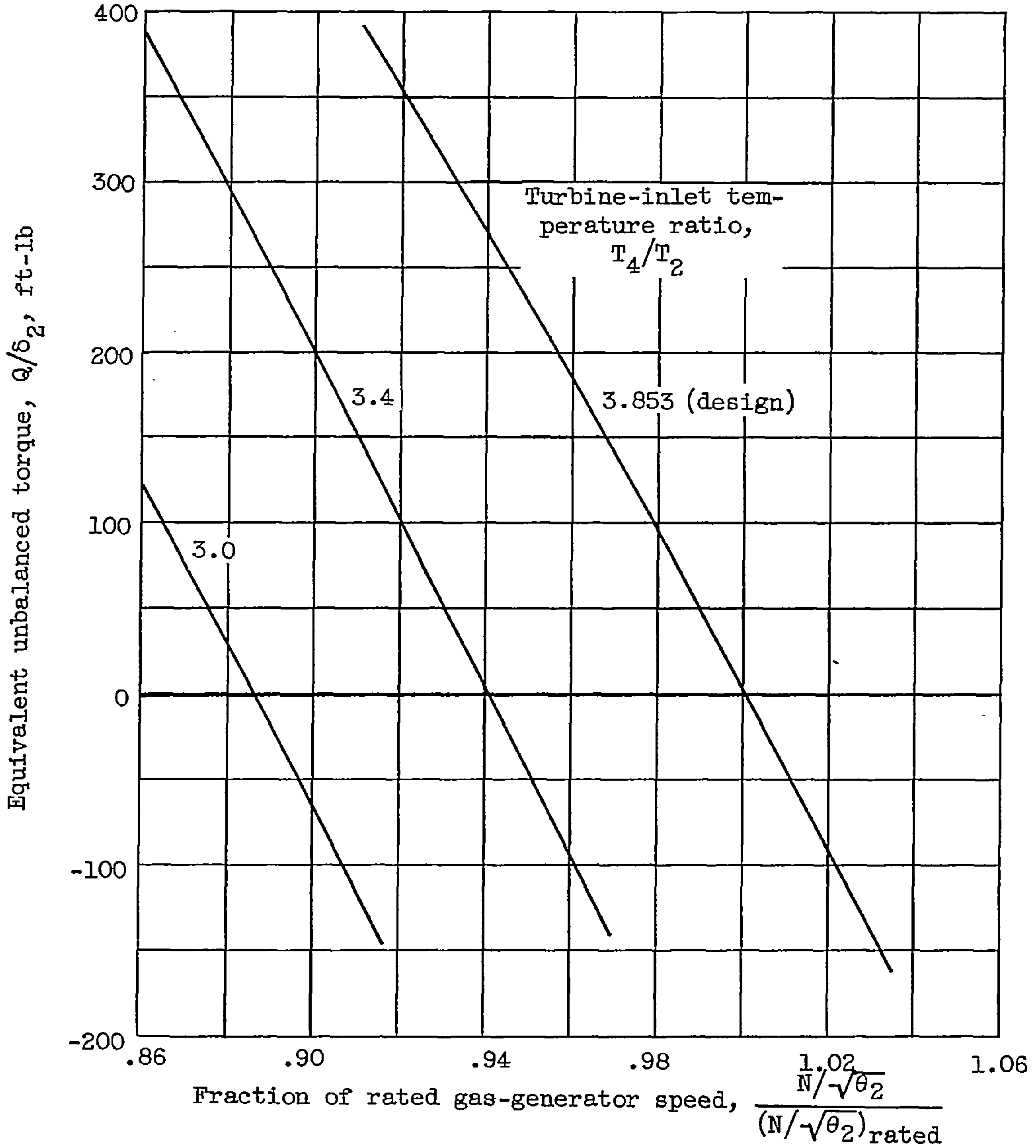
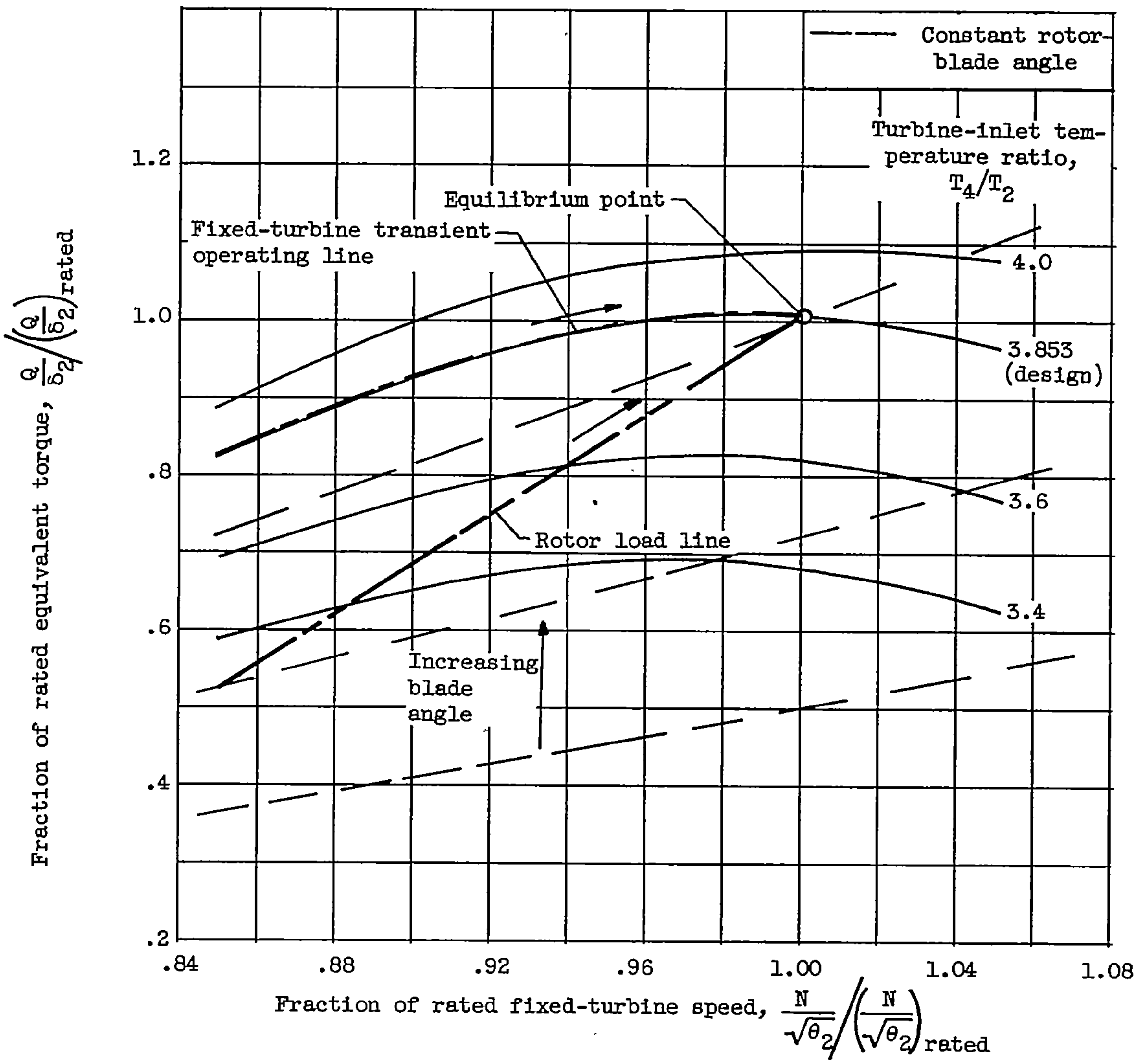
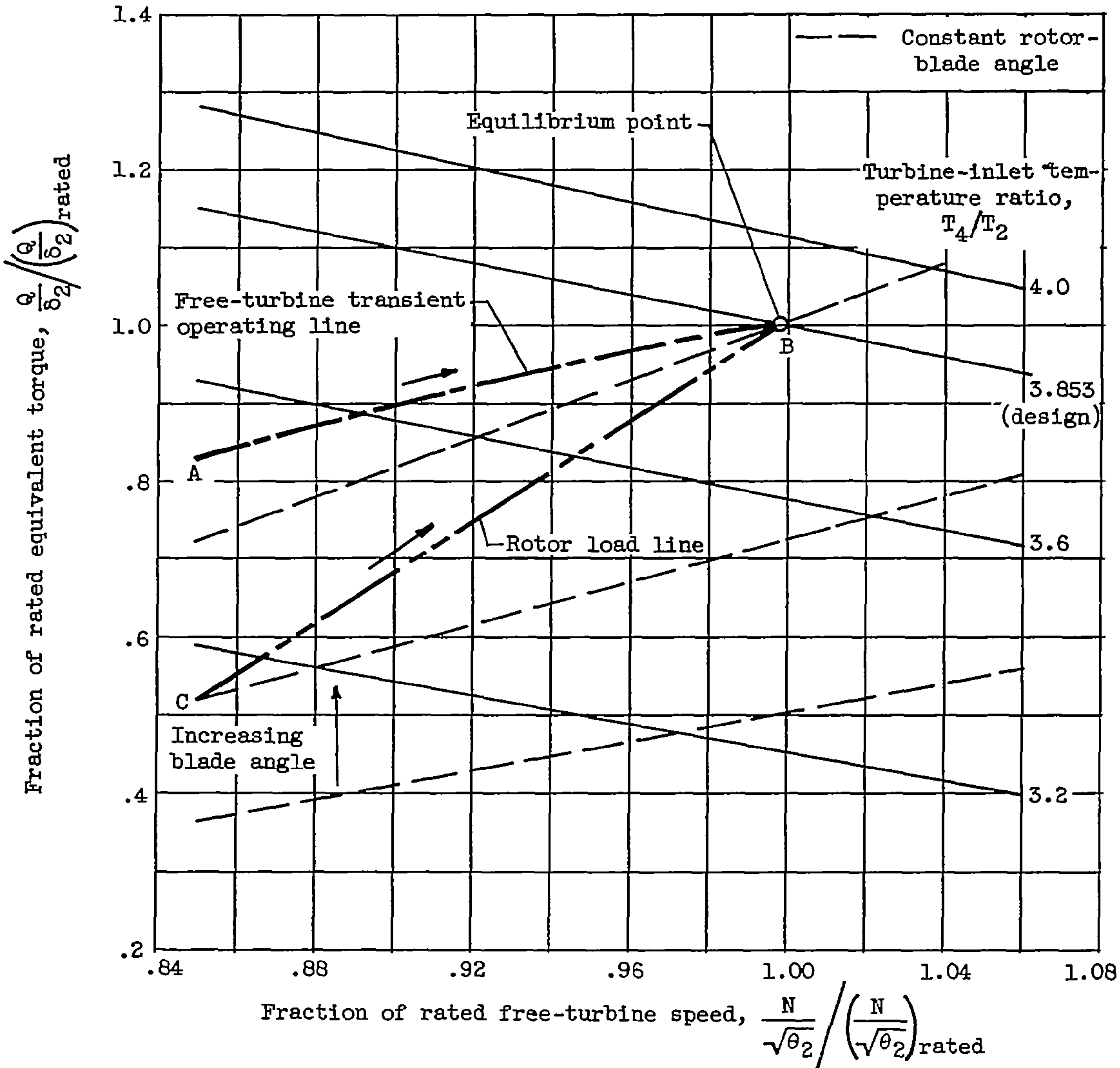


Figure 9. - Gas-generator unbalanced torque for several turbine-inlet temperature ratios.



(a) Fixed-turbine engine and rotor.

Figure 10. - Torque - shaft-speed relation.



(b) Free-turbine engine and rotor.

Figure 10. - Concluded. Torque - shaft-speed relation.

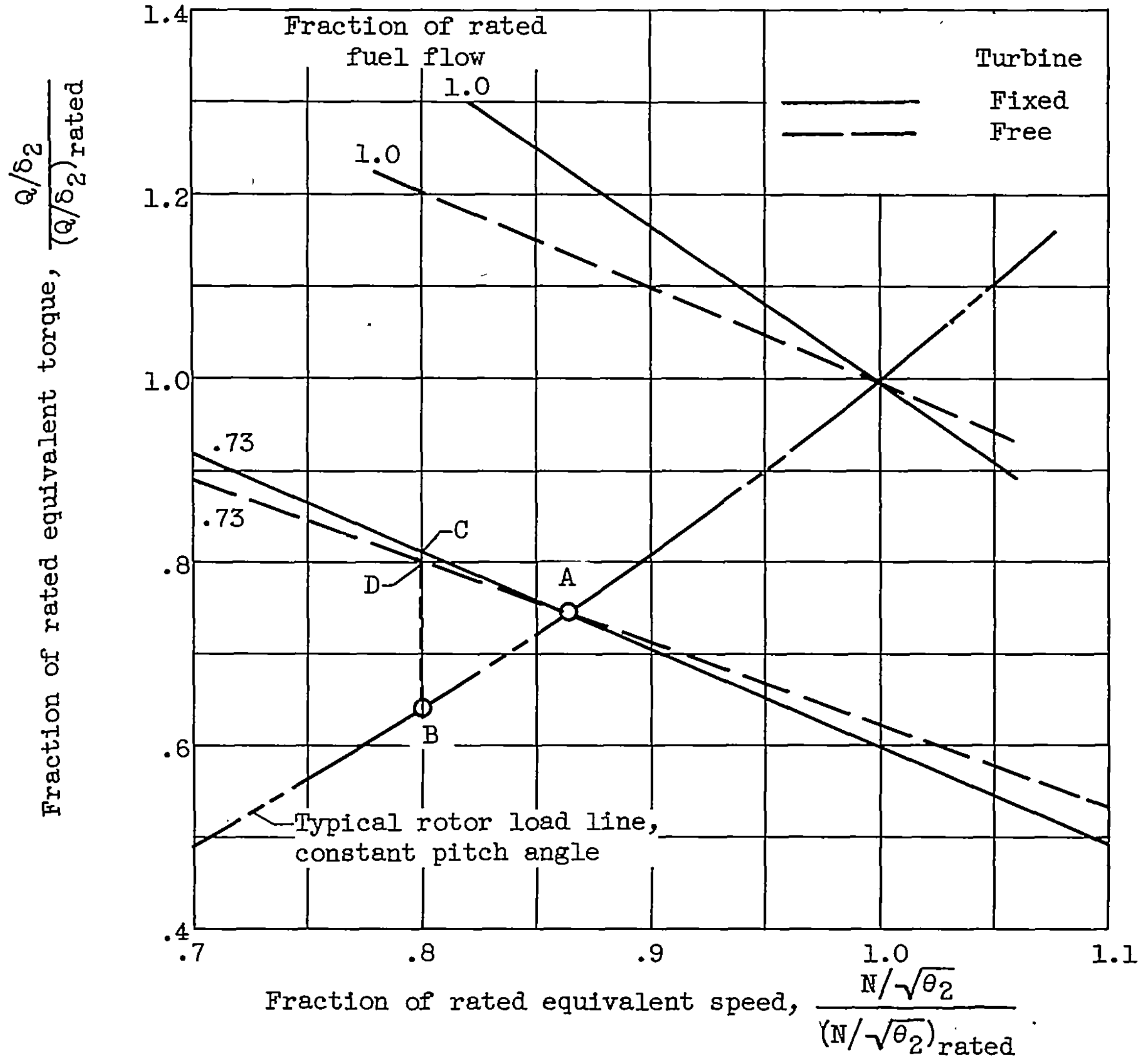
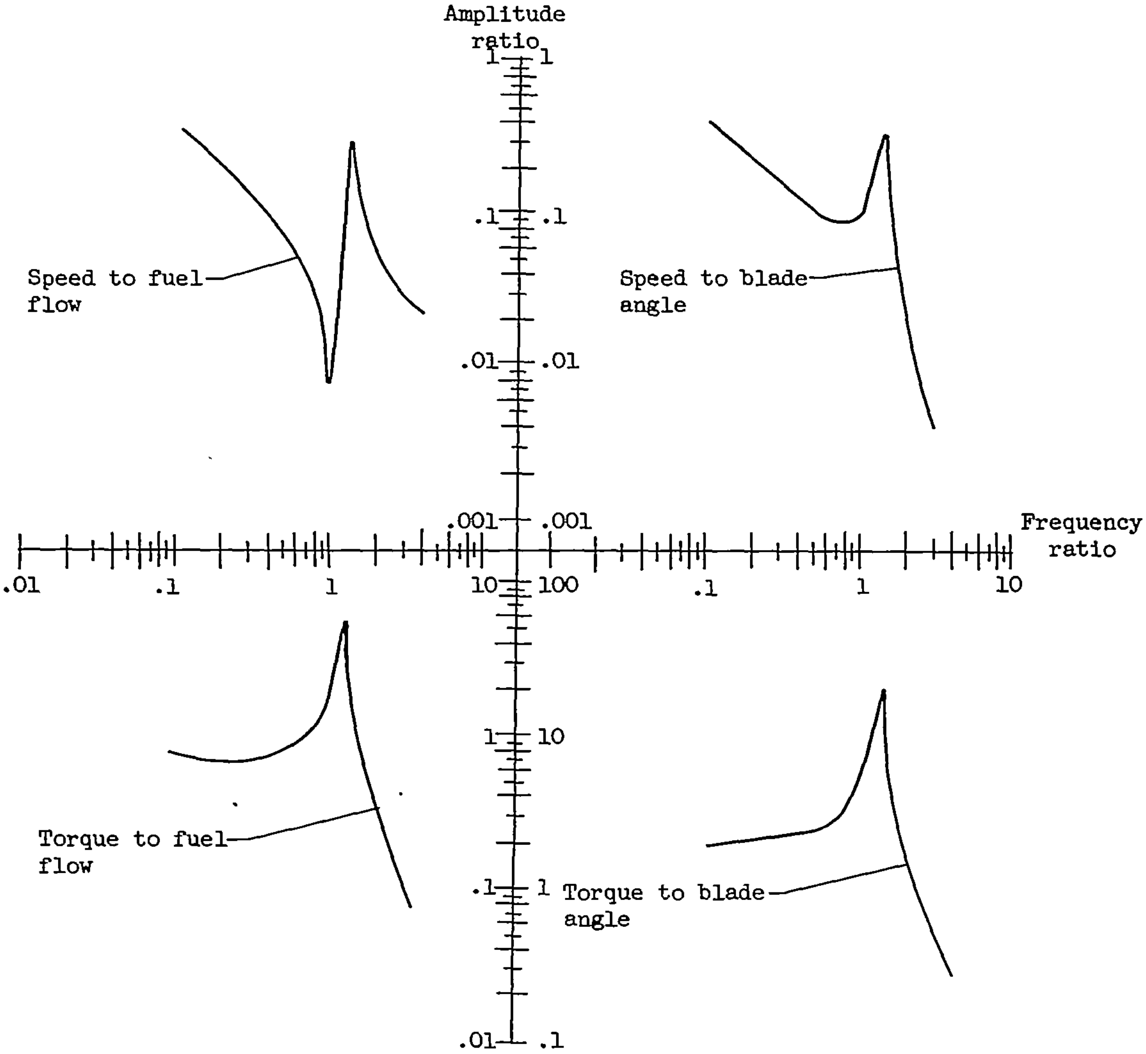
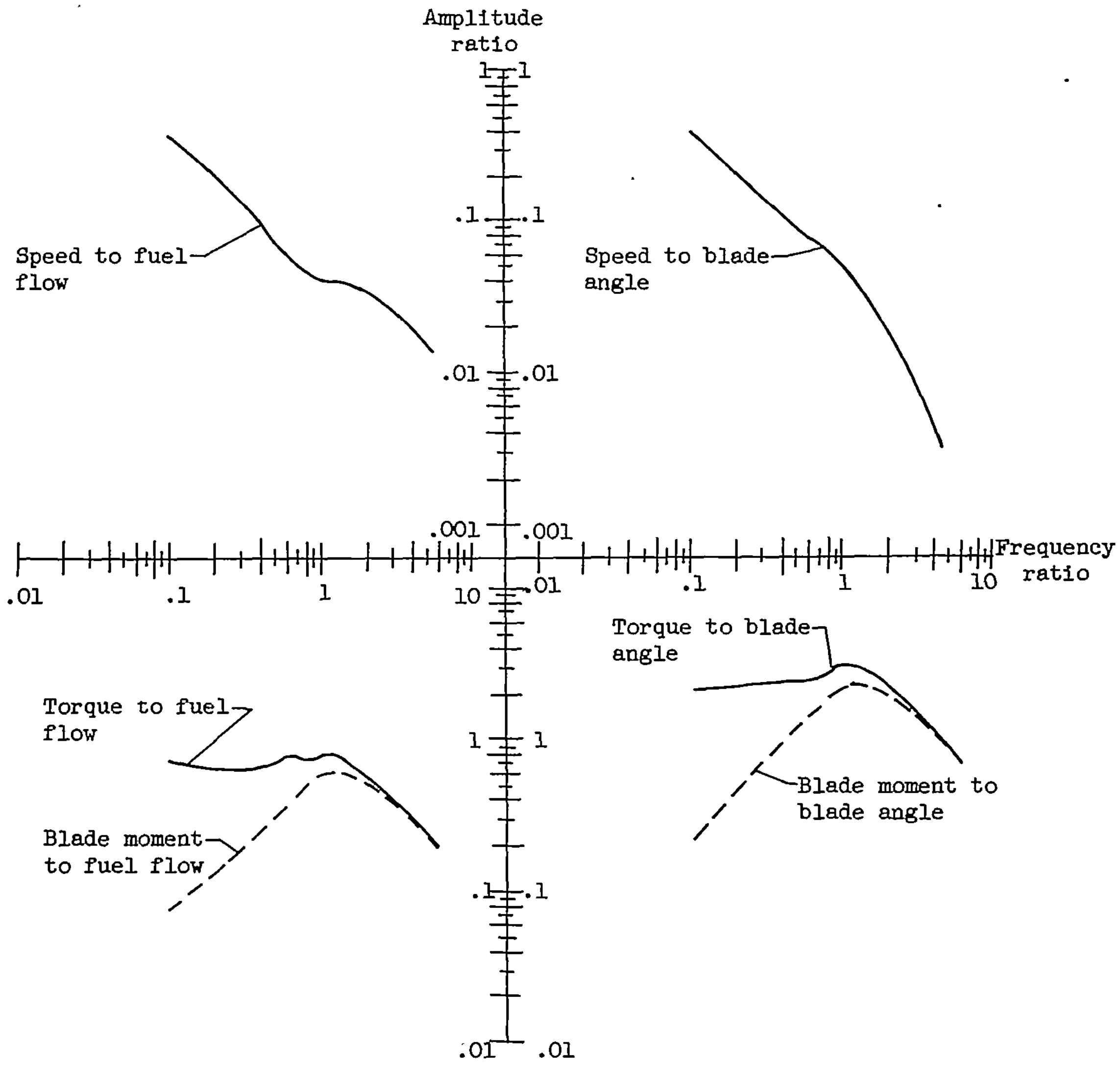


Figure 11. - Torque - shaft-speed characteristics. Constant fuel flow.



(a) No damper on lag hinge.

Figure 12. - Frequency-response characteristics of fixed-turbine engine-rotor combination.



(b) Damper on lag hinge.

Figure 12. - Concluded. Frequency-response characteristics of fixed-turbine engine-rotor combination.

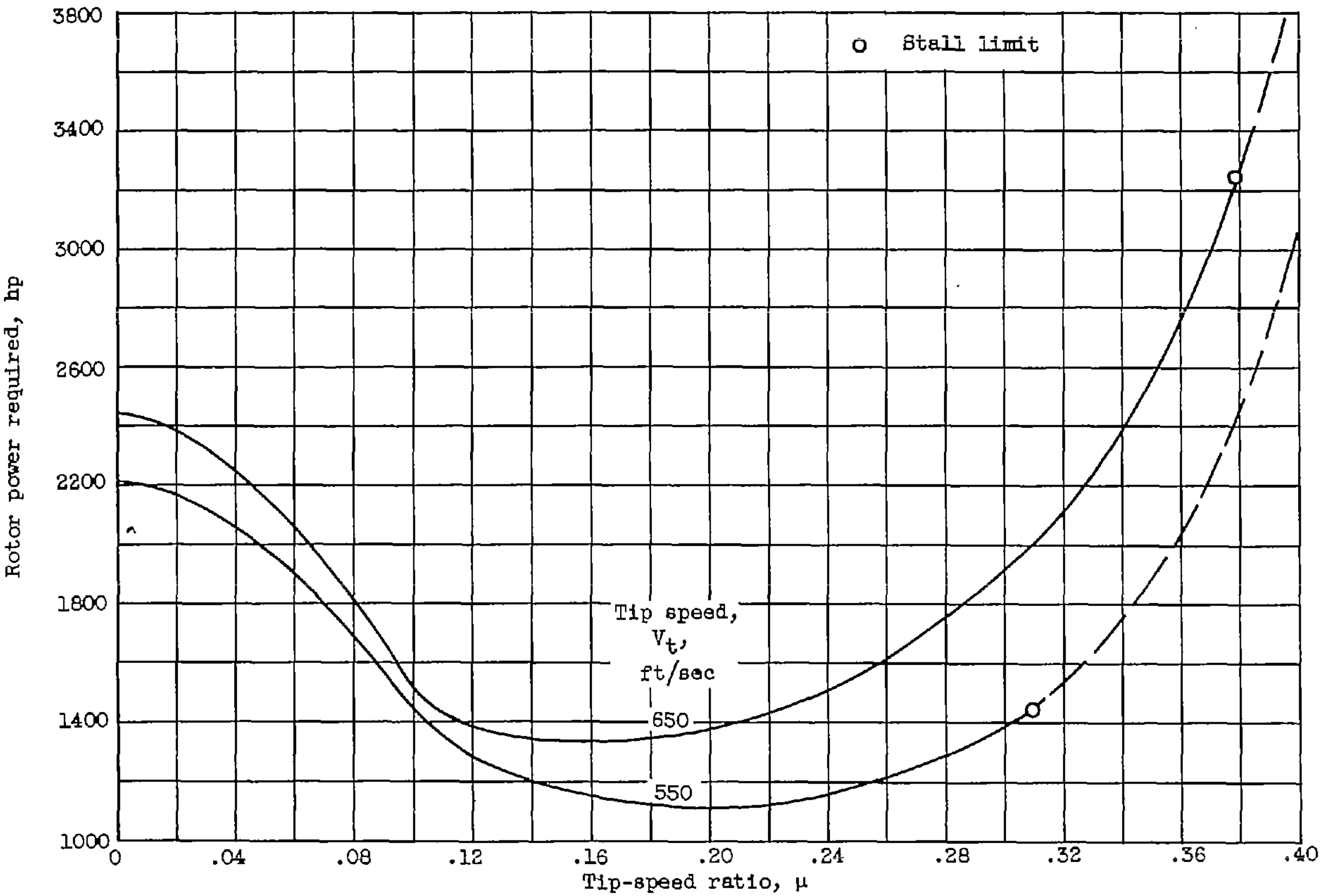


Figure 13. - Rotor power required as function of tip-speed ratio. Rotor solidity, 0.075; rotor disk loading, 4.53 pounds per square foot; helicopter gross weight, 30,000 pounds; sea-level standard conditions.

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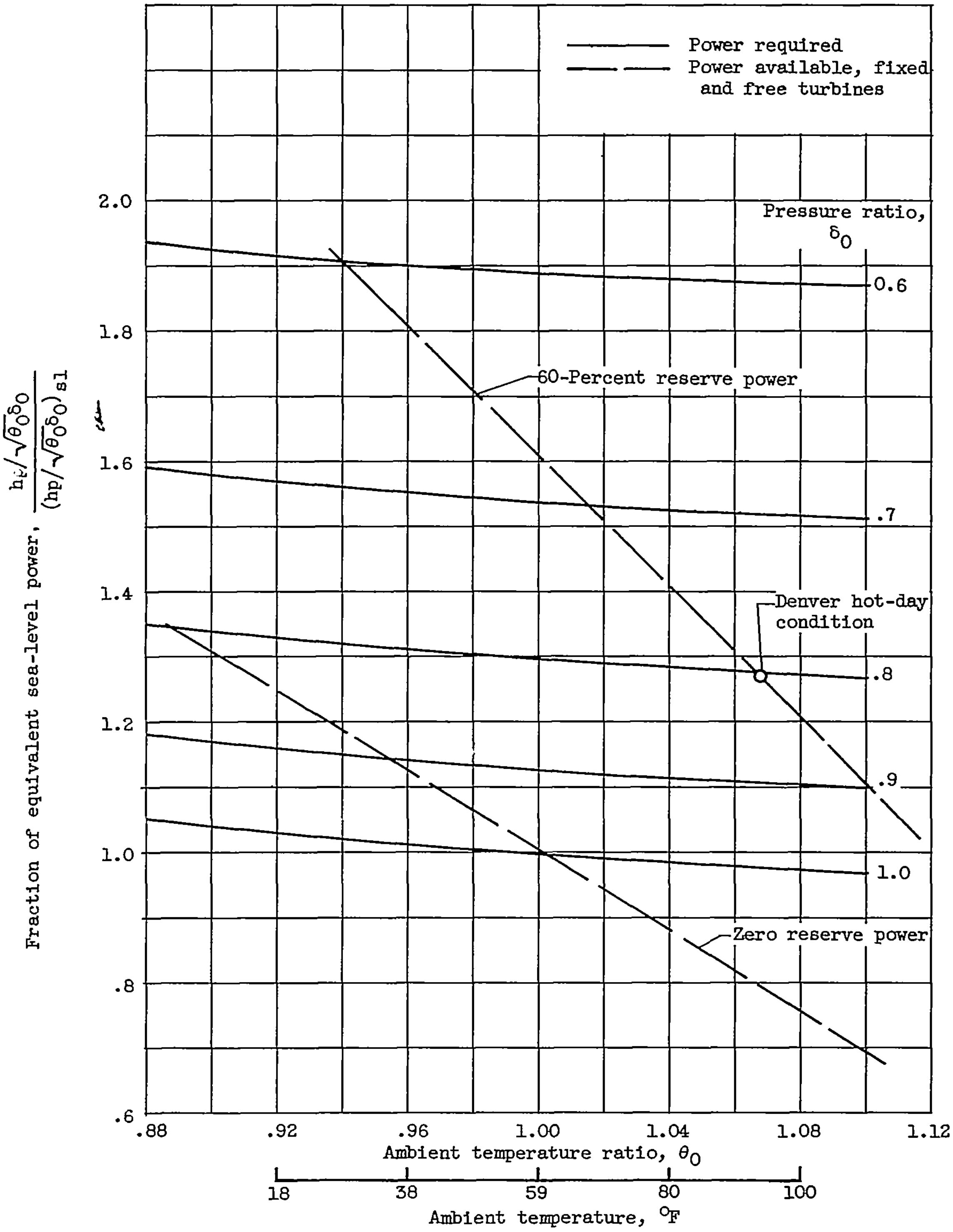
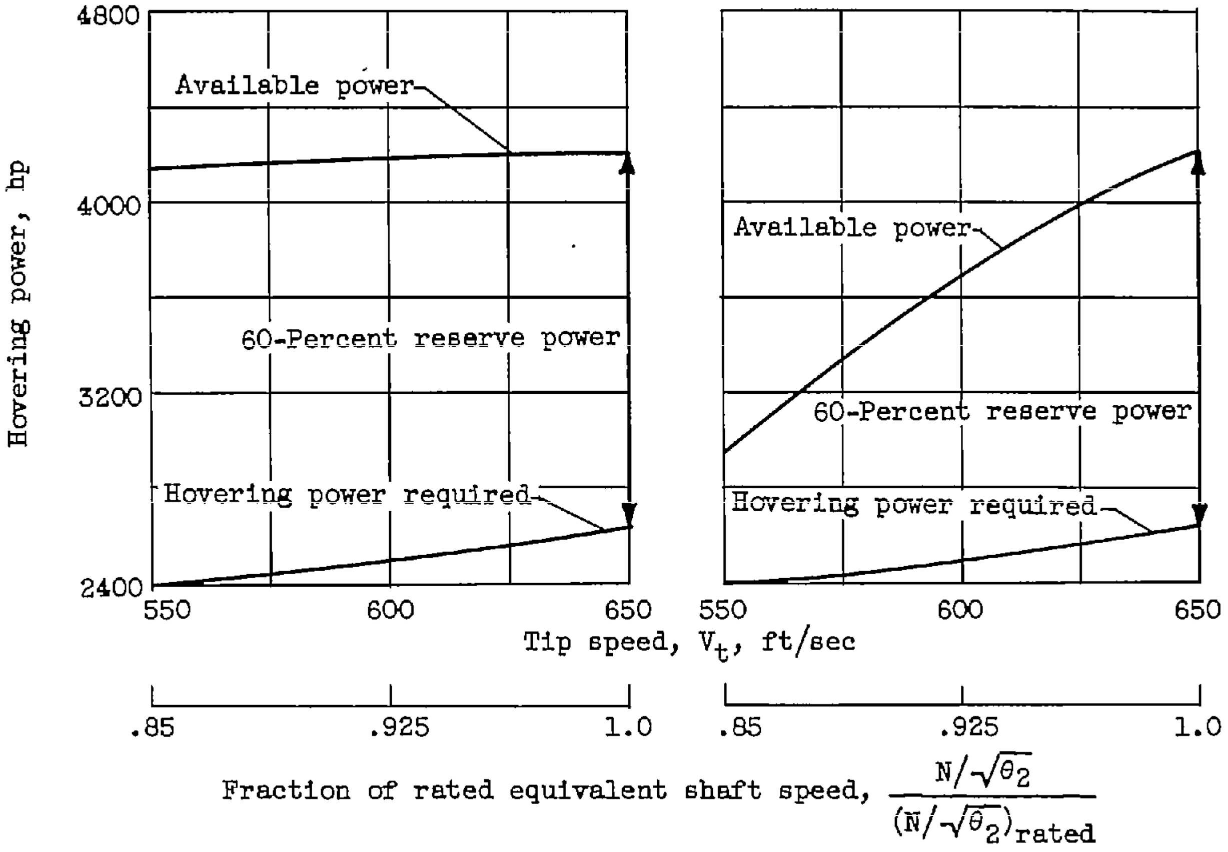


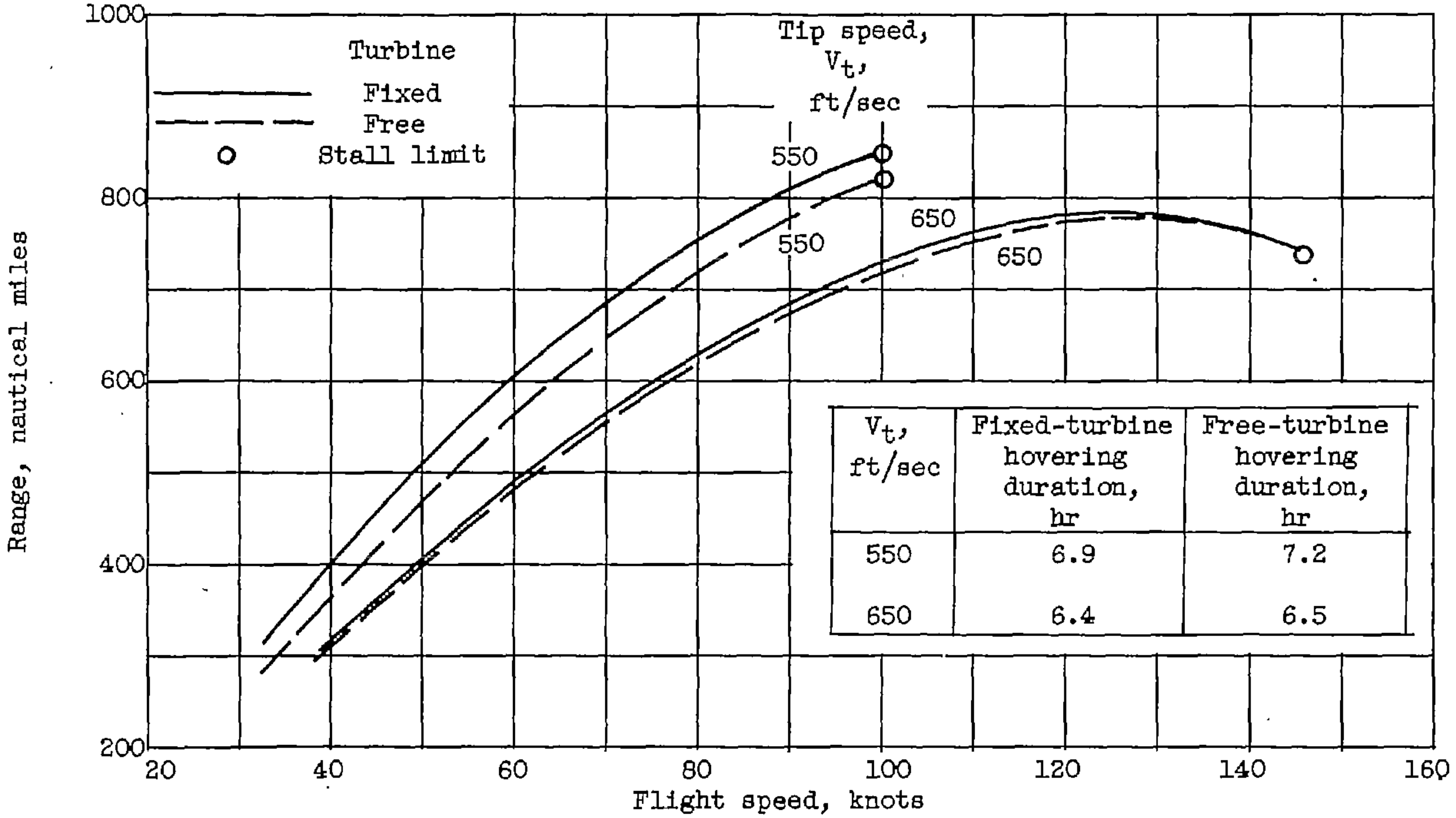
Figure 14. - Required and available power as function of ambient temperature and pressure ratios. Design rotor tip speed, 650 feet per second; rotor solidity, 0.075; rotor disk loading, 4.53 pounds per square foot.



(a) Free turbine.

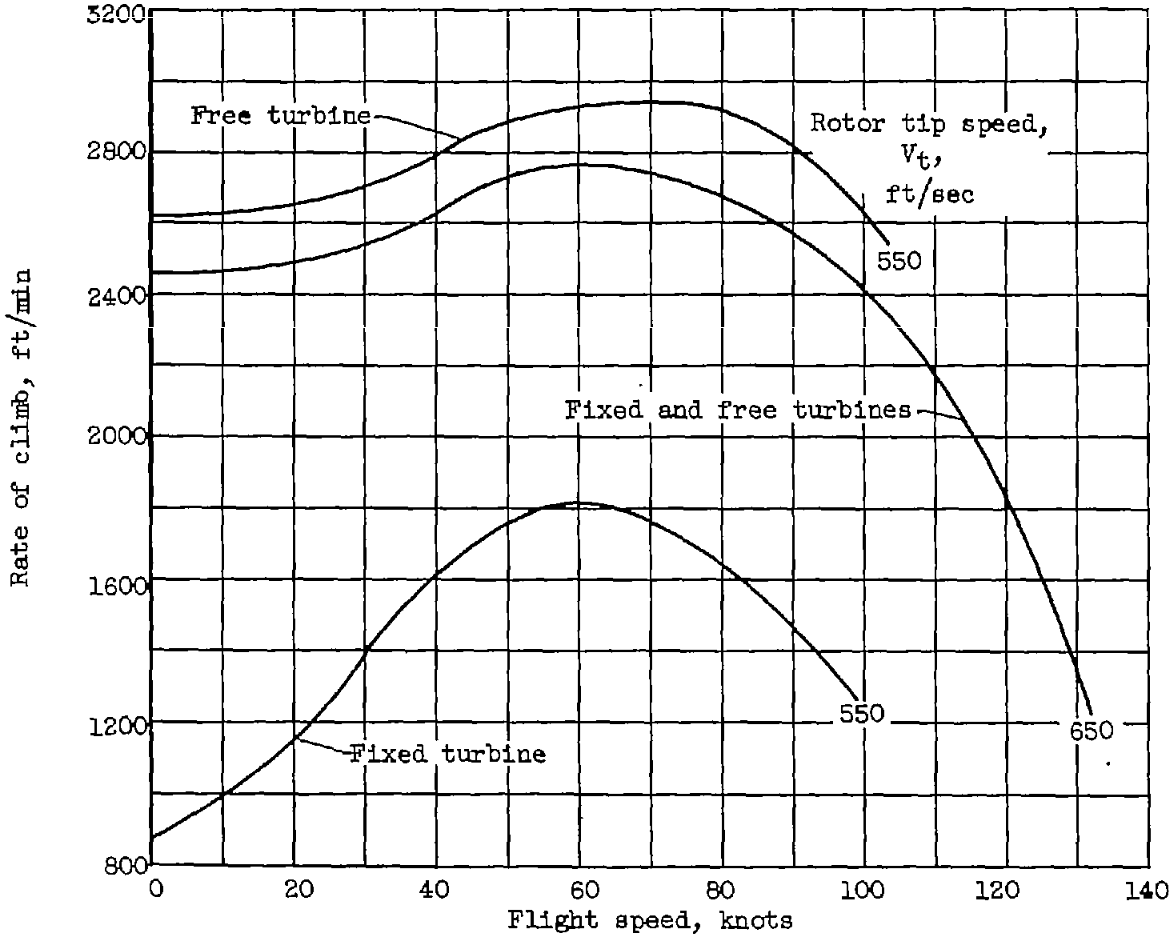
(b) Fixed turbine.

Figure 15. - Effect of variation in operational tip speed on power reserve. Sea-level standard conditions; turbine-inlet temperature ratio, 3.853.



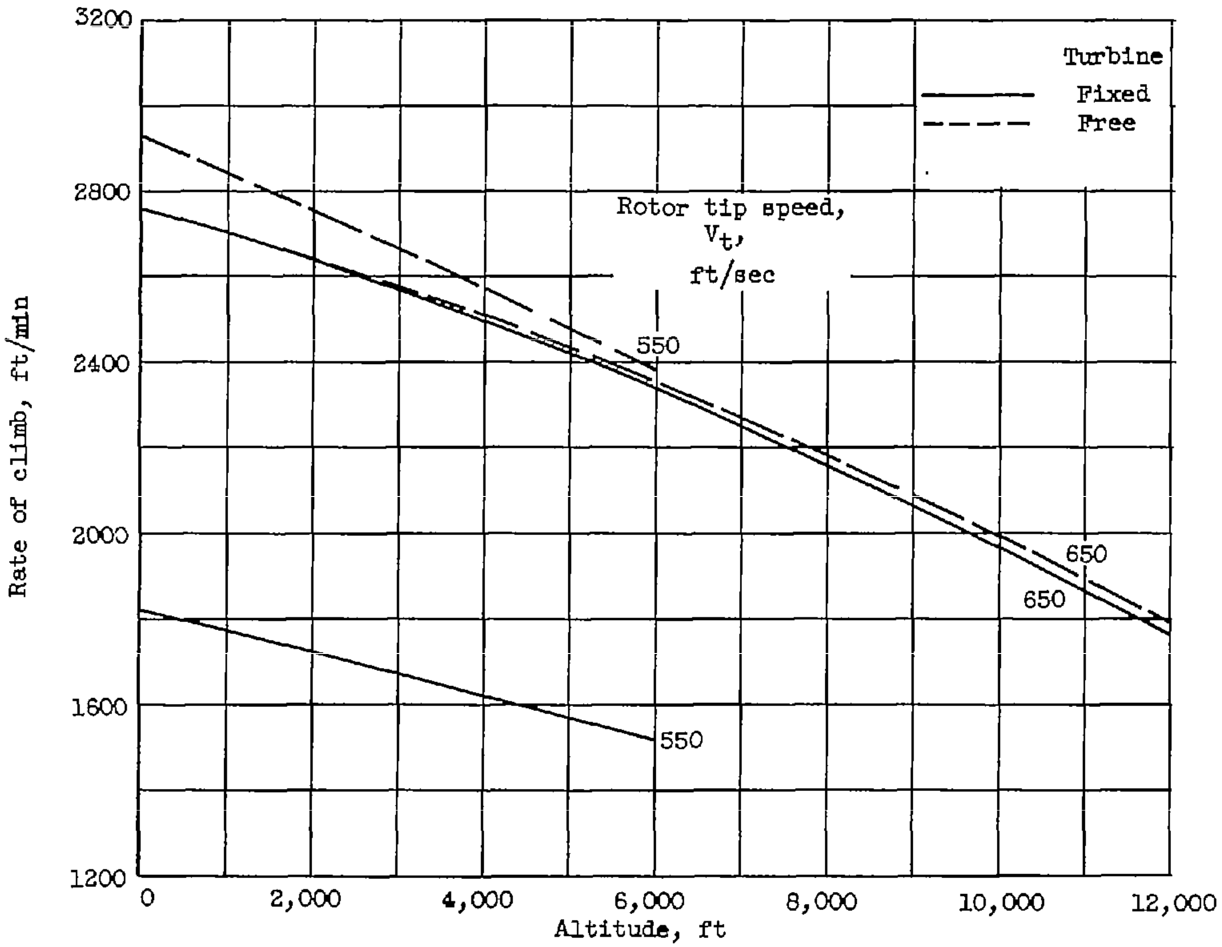
V_t, ft/sec	Fixed-turbine hovering duration, hr	Free-turbine hovering duration, hr
550	6.9	7.2
650	6.4	6.5

Figure 16. - Range and hovering duration at sea-level standard conditions. Helicopter gross weight, 30,000 pounds; design tip speed, 650 feet per second; reserve-power margin, 60 percent at sea level over hovering power.



(a) Flight speed; sea-level standard conditions.

Figure 17. - Rate of climb as function of flight speed and altitude for fixed- and free-turbine helicopters. Helicopter gross weight, 30,000 pounds; rotor solidity, 0.075; reserve power, 60 percent.



(b) Altitude; flight speed, approximately 60 knots.

Figure 17. - Concluded. Rate of climb as function of flight speed and altitude for fixed- and free-turbine helicopters. Helicopter gross weight, 30,000 pounds; rotor solidity, 0.075; reserve power, 60 percent.

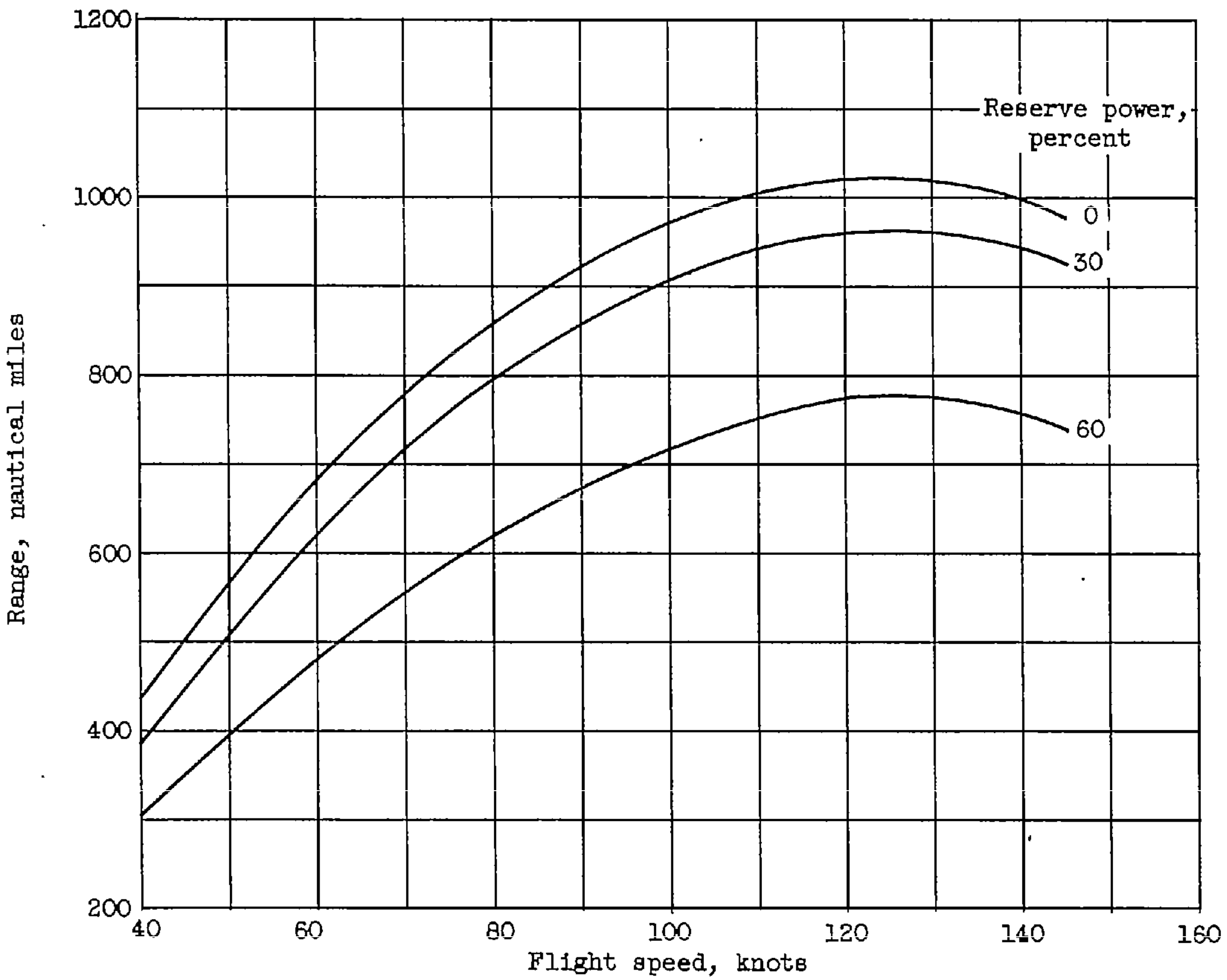


Figure 18. - Effect of reserve power on flight range. Fixed-turbine helicopter; rotor tip speed, 650 feet per second; sea-level conditions.

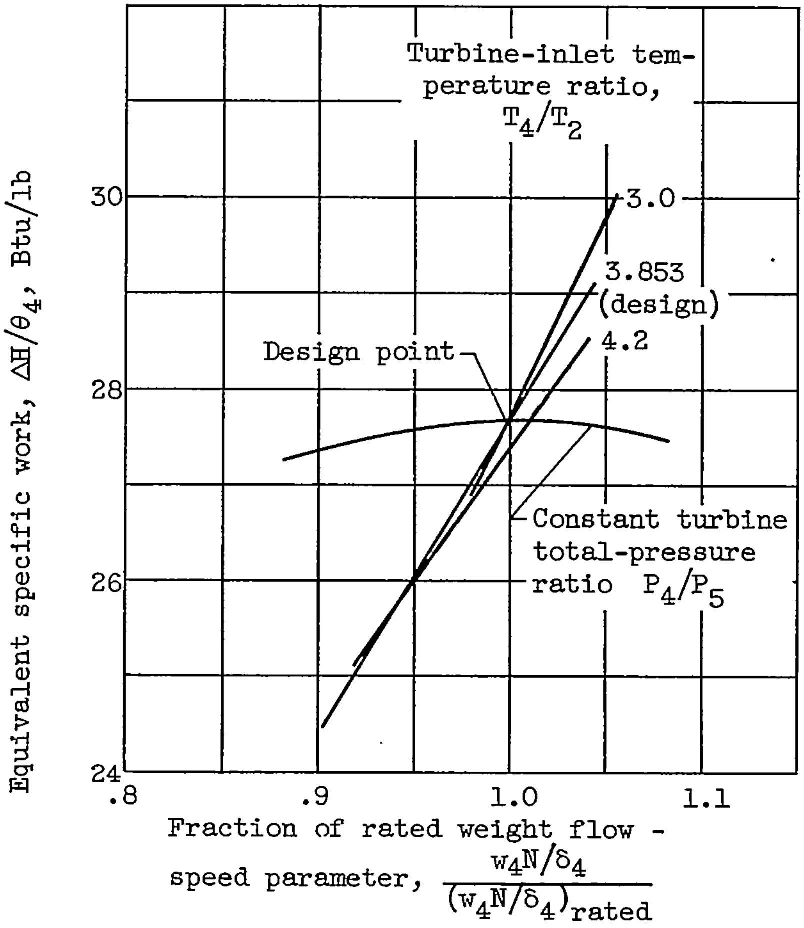


Figure 19. - Determination of gas-generator turbine operating points.