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RESEARCH MEMORANDUM

TURBOPROP-ENGINE DESIGN CONSIDERATIONS

II - DESIGN REQUIREMENTS AND PERFORMANCE OF TURBOPROP ENGINES WITH A SINGLE-SPOOL HIGH-PRESSURE-RATIO COMPRESSOR

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NATIONAL ADVISORY COMMITTEE
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II - DESIGN REQUIREMENTS AND PERFORMANCE OF TURBOPROP ENGINES WITH A SINGLE-SPOOL HIGH-PRESSURE-RATIO COMPRESSOR

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SUMMARY

The effect of mode of engine operation, engine configuration, and airplane flight condition on the performance and design requirements of a turboprop engine with a high-pressure-ratio single-spool compressor is investigated. Both single-spool engines (turbine drives both compressor and propeller) and gas-generating engines (free-turbine drives propeller only) are considered. The analysis uses hypothetical performance characteristics of a single-spool compressor with a design-point pressure ratio of 14.4. The flight conditions investigated range from sea-level take-off to 600 miles per hour at 40,000 feet.

The free-turbine engine appears less versatile than the single-spool engine, because the range of turbine-inlet temperature over which it can operate is restricted. The two engines also differ in turbine requirements, which are more critical for the free-turbine engine. Operation appears more favorable with variable than with constant exhaust-nozzle area, because the turbine can be designed for a much smaller blade stress and frontal area and the other turbine requirements are less critical. Use of a variable exhaust-nozzle area has only a minor effect on specific fuel consumption.

INTRODUCTION

An investigation of the performance and the design problems of turboprop engines has been conducted at the NACA Lewis laboratory. Some of the turbine design problems encountered in a turboprop engine with a single-spool compressor of current pressure ratio (7.32 at design) were investigated in reference 1. The same compressor was used in reference 2 to study the effects of mode of engine operation on engine performance. Other cycle analyses such as references 3 and 4 have shown that lower engine specific fuel consumption can be obtained with engines having higher compressor pressure ratios.

The subject report presents the effects of mode of engine operation, engine configuration, and airplane flight condition on the performance and design requirements of a turboprop engine with a high-pressure-ratio single-spool compressor. A steady-state engine cycle analysis is made for a range of flight conditions. From this cycle analysis, the relative size of different engine components and other design requirements are determined. Both single-spool engines, in which the turbine drives both the compressor and propeller, and gas-generating engines, in which a free-turbine drives only the propeller, are considered. Hypothetical performance characteristics of a single-spool compressor with a design-point 3548
pressure ratio of 14.4 are used in the analysis.

The following three modes of engine operation are considered for flight conditions ranging from take-off to speeds of 600 miles per hour at 40,000 feet:

I. Compressor operating at constant design rotative speed

II. Compressor operating at design equivalent conditions at all times

III. Compressor operating at constant equivalent design rotative speed

For the free-turbine engine configuration, only modes I and III are considered.

The engine parameters investigated are specific fuel consumption, turbine-inlet temperature, turbine pressure ratio, exhaust-nozzle area, turbine frontal area, turbine blade stress, rotative speed, and equivalent weight flow at turbine entrance. The specific fuel consumptions of the engines of this report and those of reference 2 are compared.

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
g	gravitational constant, 32.17 ft/sec^2
P^*	engine power (shaft horsepower plus equivalent shaft horsepower of net thrust), hp
p	pressure, lb/sq ft
S	centrifugal stress, psi
sfc	specific fuel consumption (based on engine power P^*), lb/hp-hr

T temperature, $^{\circ}R$

$U_{T,t}$ turbine tip speed, ft/sec

w weight flow, lb/sec

δ ratio of pressure to 2116 lb/sq ft

η efficiency

θ ratio of temperature to 518.4° R

ρ density, lb/cu ft

ψ stress-reduction factor for tapered blades

ω rotative speed, radians/sec

Subscripts:

b blade

c compressor

p propeller

x annular

1 ambient

2 compressor inlet

3 compressor outlet

4 turbine inlet (fig. 1)

4a exit of gas-generator turbine (fig. 1(b))

5 turbine outlet (fig. 1)

6 exhaust-nozzle outlet

Superscripts:

' total or stagnation state

" total or stagnation state relative to rotor

ANALYSIS

Engine Configurations

Schematic diagrams of the two engine configurations analyzed along with the station designations used in the analysis are shown in figure 1. The engine referred to herein as a single-spool engine (fig. 1(a)) is characterized by one turbine delivering all the power absorbed by the propeller, gearbox, and compressor. In addition, the power obtained from the turbine, and therefore the power that must be absorbed by the propeller, may be varied by changing the exhaust-nozzle area. 3548

The engine referred to herein as a free-turbine engine (fig. 1(b)) is characterized by a gas-generator unit delivering hot-gas to a free-turbine that drives the propeller. Other characteristics of this unit are: (1) the power output of the gas-generator turbine must equal the power absorbed by the compressor, and (2) the power obtained from the free-turbine, and therefore the power that must be absorbed by the propeller, may be varied by changing the exhaust-nozzle area.

Assigned Flight Conditions and Operating Modes

The four flight conditions considered are:

	Flight condition			
	0	A	B	C
Altitude, ft	0	40,000	40,000	19,000
Flight speed, mph	0	600	400	400
Flight Mach number	0	0.906	0.604	0.564

For the single-spool engines over the range of flight conditions investigated, the following three modes of engine operation were considered:

I. Compressor operating at constant design rotative speed

II. Compressor operating at design equivalent conditions at all times. Accomplished by assuming turbine could accommodate resulting variations in turbine-inlet equivalent weight flow by turbine stator adjustment.

III. Compressor operating at constant equivalent design rotative speed

Operation of the gas-generator unit of the free-turbine engine under modes I and III was considered. The more general case was analyzed by assuming the free-turbine could accommodate a variation in inlet equivalent weight flow by turbine stator adjustment. The characteristics of the more specific cases could then be determined by considering the inlet equivalent weight flow to the free-turbine to be constant. Assuming that the turbine-inlet equivalent weight flow is constant implies that the area of the first turbine stator is fixed and that the first stator is choked.

Compressor Performance

3548 The hypothetical performance map of the high-pressure-ratio single-spool compressor used in the analysis is shown in figure 2. These hypothetical performance characteristics were compounded by analytically estimating the change in performance resulting from the addition of several stages to the eight-stage compressor reported in reference 5. At design-point operation the equivalent tip speed of the hypothetical compressor is 1168 feet per second, the pressure ratio is 14.4, the equivalent weight flow per unit compressor frontal area (based on compressor blade tip diameter) is 30.2 pounds per second per square foot, and the compressor is operating near peak efficiency at 83 percent.

Turbine-inlet temperature was related to compressor performance for modes I and III by assigning a turbine-inlet temperature of 2100° R at sea-level static and compressor design-point operation and by assuming constant turbine-inlet equivalent weight flow. As stated previously, assuming that the turbine-inlet equivalent weight flow is constant implies that the area of the first turbine stator is constant and that the first stator is choked. For these assumptions, lines of constant engine temperature ratio (ratio of burner-exit to compressor-inlet total temperature) can be superimposed on the compressor map as shown in figure 2. These temperature-ratio lines do not apply to mode II, for which the compressor equivalent operating conditions remain fixed at the design point. For mode I the compressor operates at a constant rotative speed, or along a different constant equivalent speed line for each flight condition. For mode III the compressor operates along the 100-percent equivalent rotative speed line for all flight conditions.

Cycle Analysis

The assumptions and the manner in which the cycle analysis was carried out for the single-spool engine are the same as in reference 2. The following conditions are assumed:

Ram recovery, percent	100
Propeller efficiency, η_p, percent	80
Gearbox efficiency, η_g, percent	95
Burner total-pressure ratio, p_4'/p_3'	0.95

Burner efficiency, percent	100
Turbine adiabatic efficiency (based on turbine total-pressure ratio), percent	85
Tail-cone total-pressure ratio, p_6'/p_5'	0.95
Exhaust-nozzle efficiency, percent	100
Ratio of specific heats in compressor	1.40
Ratio of specific heats in turbine	1.30
Gas constant, ft-lb/(lb)($^{\circ}$R)	53.4

The jet velocity was calculated from the ratio of exhaust-nozzle total pressure to ambient-air pressure p_6'/p_1, a nozzle efficiency of 100 percent, and the turbine-outlet total temperature T_5'. The turbine-inlet equivalent weight flow $w_4\sqrt{\theta_4'}/\delta_4'$ is assumed to be constant for modes I and III but is allowed to vary for mode II. The air flow through the compressor is assumed equal to the gas flow through the turbine. 3548

The cycle calculations for the free-turbine engine differ from those for the single-spool engine in the following ways:

(1) The inlet equivalent weight flow $w_4\sqrt{\theta_4'}/\delta_4'$ of the gas-generator turbine is assumed constant for both modes I and III, while that of the free-turbine $w_{4a}\sqrt{\theta_{4a}'}/\delta_{4a}'$ is allowed to vary.

(2) For the free-turbine engine, an additional requirement must be met, that the work outputs of the turbine and compressor of the gas-generator unit be equal.

(3) Adiabatic efficiencies of 85 percent are assumed for both gas-generator turbine and free-turbine.

(4) For the free-turbine engine the portion of the pressure ratio p_{4a}'/p_1 taken across the free-turbine at fixed engine operating conditions is varied, as is that for the single-spool engine (p_4'/p_1). Fixed engine operating conditions in this instance mean a given flight condition, mode of operation, and turbine-inlet temperature.

For both engines a range of burner-outlet temperature from 2000° to 2500° R was assigned at flight condition 0 (sea-level static). At altitude the range of temperatures was from 1600° to 3000° R.

The specific-fuel-consumption values obtained in reference 2 by operating with a prescribed exhaust-nozzle area were near the minimum obtainable. This characteristic also holds for the high-pressure-ratio engines analyzed in this report, as can be determined before calculating the sfc values. For this reason, only operation with constant exhaust-nozzle area is considered in calculating sfc. In these calculations, a value of 1.40 is prescribed for the ratio of exhaust-nozzle area to compressor frontal area A_6/A_c. This area ratio represents a good compromise between optimum engine operation at take-off and the other flight conditions considered.

Component Size and Stress

The stress presented herein is the centrifugal stress at the root of a turbine rotor blade. Reference 6 shows that this stress can be determined from the following equation:

$$S_b = \frac{\rho_b \omega^2 A_x}{2\pi g} \psi \qquad (1)$$

Of the modes of engine operation and flight conditions analyzed, only those resulting in the highest blade stress are considered in calculating the stress. However, the effects of other modes of engine operation and flight conditions on turbine stress are discussed. As will be seen, in the single-spool engine the rotative speed and required turbine-outlet annular area are greatest with mode I and constant exhaust-nozzle area, so that the highest stresses are encountered under these conditions (see eq. (1)). The stresses calculated were a minimum for these operating conditions, since the turbine is considered to be at limiting loading at all times. The stresses calculated in this manner are design-point values, which implies that turbines designed for the low-stress conditions would not be suitable for operation at the higher stress conditions if constant exhaust-nozzle area under mode I operation is stipulated.

Limiting loading is assumed to occur at an exit axial Mach number of 0.7 for this analysis. Limiting loading occurs when a further increase in pressure ratio across a turbine does not produce an increase in turbine work output. The exit axial Mach number at which limiting loading occurs is discussed in reference 7. The other assumptions involved in the stress calculation are:

Stress-reduction factor for tapered blades, ψ	0.70
io of exhaust-nozzle area to compressor frontal area, A_6/A_c . .	1.40
Density of blade material, ρ_b, lb/cu ft	500
Compressor blade tip velocity, ft/sec	1168

The turbine was sized with respect to the compressor for the same operating conditions used to calculate turbine blade stress. One additional assumption is made, that the hub-tip radius ratio of the last turbine rotor is 0.6. This assumption is also used to determine the total temperature relative to the last rotor at the hub section. Assuming some value other than 0.6 for the hub-tip radius ratio would change the numerical values obtained from the analysis slightly but not the relative magnitudes on which the conclusions are based.

RESULTS AND DISCUSSION

Single-Spool Engine

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The results of the cycle analysis for the single-spool engine are presented in figures 3 and 4. Figure 3 presents the variation in engine power with exhaust-nozzle area for lines of constant turbine-inlet temperature and turbine total-pressure ratio for the different modes of engine operation and flight conditions considered. The engine power plotted in these figures is the sum of the shaft horsepower delivered to the propeller plus the equivalent shaft horsepower of the net jet thrust. Figure 3 shows the effect of the division of the over-all expansion ratio p_4'/p_1 between the turbine and exhaust nozzle on the engine power. In addition, these figures are used in determining the turbine design requirements for the various operating conditions.

The variations in specific fuel consumption with engine power for various flight conditions and modes of operation are presented in figure 4. The sfc was calculated using reference 8 and figure 3 for a constant ratio of exhaust-nozzle area to compressor frontal area A_6/A_c of 1.40 and various turbine-inlet temperatures. An area ratio of 1.40 represents a good compromise between the optimum engine operating conditions for take-off and the other flight conditions considered, as is apparent upon inspection of figure 3. As in reference 2, slightly lower sfc in some instances could be obtained if the exhaust-nozzle area were varied. Because the improvement in sfc is minor, only curves for constant exhaust-nozzle area are included.

The variations in sfc shown in figure 4 are very similar to those obtained for the low-pressure-ratio engine analyzed in reference 3. Minimum sfc is obtained at flight condition A (600 mph at 40,000 ft). Dropping the flight speed to 400 miles per hour (condition B) in general raises the whole level of the sfc curves, while decreasing the altitude to 19,000 feet (condition C) raises the level of the sfc curves even more. At the higher power outputs, these curves show that there is no marked advantage of one mode of operation over another. The chief differences between the sfc curves of this analysis and those of reference 3 for a low-pressure-ratio engine are:

(1) The minimum sfc for a given flight condition is lower for the high-pressure-ratio engine (about 14 percent less at condition A).

(2) The relative increase in sfc with decreasing altitude and flight speed is less for the high-pressure-ratio engine.

The higher turbine-inlet temperatures obtained with mode II operation were possible because the compressor did not encounter surge. As pointed out previously, mode II complicates the engine design in that adjustable turbine stator areas must be employed in order to achieve this type of operation. From the sfc curves (fig. 4) it appears, as in reference 2, that slightly lower sfc can be obtained under mode III without any added complication to the engine.

Free-Turbine Engine

The results of the cycle analysis for the free-turbine engine are presented in figures 5 and 6. Only the results for mode III are presented, since mode I was very similar. For mode III, constant compressor equivalent rotative speed and adjustable free-turbine stator areas were assumed. Figure 5 presents the effect of flight condition on engine design requirements. For each flight condition the variation in engine power with exhaust-nozzle area is presented for lines of constant gas-generator-turbine inlet temperature and free-turbine total-pressure ratio. In addition, the variation in gas-generator-turbine total-pressure ratio and the variation of the inlet equivalent weight flow to the free-turbine with the gas-generator-turbine inlet temperature are presented. The variation of sfc with engine power of the free-turbine engine for various flight conditions and mode III operation is presented in figure 6. The performance presented is for a ratio of exhaust-nozzle area to compressor frontal area A_6/A_c of 1.40 and a range of gas-generator-turbine inlet temperatures. Similarly to the single-spool engine, the area ratio of 1.40 represents a good compromise between the optimum engine operating conditions for take-off and the other flight conditions considered, as can be noted from figure 5.

The sfc curves for the free-turbine engine differ from those shown for mode III operation of the single-spool engine only as a result of the turbine-efficiency assumptions. Taking part of the over-all expansion ratio p_4'/p_1 across the gas-generator turbine and part across the free-turbine while assuming an adiabatic efficiency of 0.85 for both turbines results in a slightly higher adiabatic efficiency for the over-all turbine expansion process. Thus, for the free-turbine engine, the efficiency for some over-all turbine expansion process would be greater than for a corresponding expansion across the single-spool turbine.

This higher adiabatic efficiency for the over-all turbine expansion process is reflected in lower sfc for the free-turbine engine than for the single-spool engine (cf. figs. 4(c) and 6).

Engine Comparison

The free-turbine and the single-spool engines differ principally in the turbine requirements. Table I(a) shows the variation in turbine requirements for the two engines between flight conditions 0 and A for mode III operation with constant burner-outlet temperature. Table I(b) 3548
shows the variation in turbine requirements for the two engines between burner-outlet temperatures of 1600° and 2600° R for mode III operation at flight condition A. A ratio of exhaust-nozzle area to compressor frontal area A_6/A_c of 1.40 was prescribed in determining the turbine requirements in table I.

High turbine pressure ratios can be obtained without any penalty in turbine efficiency, although these high pressure ratios increase the number of turbine stages required. However, the range of pressure ratio over which a conventional turbine can operate efficiently is limited if the equivalent rotative speed of the turbine does not vary greatly (±15 percent of design). In table I the range of equivalent rotative speed for the gas-generator turbine and the turbine for the single-spool engine is roughly 20 percent of design. No rotative-speed variation was specified for the free-turbine.

The variation in pressure ratio across the free-turbine and the single-spool turbine shown in table I could be reduced by the use of variable exhaust-nozzle area (e.g., fig. 3(b) mode III and fig. 5(b)). However, it is apparent from figure 5(b) that use of a variable exhaust-nozzle area would not aid in reducing the variation in pressure ratio across the gas-generator turbine nor the variation in inlet equivalent weight flow to the free-turbine.

It may not be possible to obtain a high efficiency over the range of rotative speed and pressure ratio shown in table I for the turbine of the single-spool engine. However, the variation in pressure ratio could be reduced, if not eliminated, by use of a variable exhaust-nozzle area, thereby permitting a high turbine efficiency to be maintained over the entire range of engine operation.

In order to obtain the free-turbine pressure ratios shown in table I, multistage turbines would probably have to be employed. Although efficient performance over a wide range of inlet equivalent weight flow has been achieved for a single-stage turbine (ref. 9), no similar performance has been demonstrated for a multistage turbine. Even if a variable exhaust-nozzle area were used to reduce the maximum pressure ratio across the free-turbine and thereby the range of pressure ratio over which it must operate, the turbine would still have to contend with the variation in inlet equivalent weight flow. The task of maintaining high turbine efficiency over the engine operating range would be much more difficult for the free-turbine than for the turbine of the single-spool engine. The task of maintaining high turbine efficiency over the engine operating range would also be more difficult for the gas-generator turbine than for the turbine of the single-spool engine, because, as mentioned previously, the range of pressure ratio imposed across the gas-generator turbine cannot be reduced by using an adjustable exhaust-nozzle area.

Another feature inherent in the free-turbine engine is that the gas-generator turbine and the free-turbine performances must be well matched in order to obtain good over-all performance. It is concluded, then, that the free-turbine engine has more critical turbine requirements than the single-spool engine. If the inlet equivalent weight flow to the free-turbine is not allowed to vary, the free-turbine engine is much less versatile than the single-spool engine. Requiring the inlet equivalent weight flow to the free-turbine to remain constant implies that the first stator is operating in a choked condition with a fixed area.

For the example shown in table II, a turbine-inlet temperature of 2100° R was assigned at the sea-level static condition (0), and constant exhaust-nozzle area was assumed. The values listed for turbine-inlet temperature, free-turbine pressure ratio, power, and sfc are the only ones possible at the other flight conditions if operation is restricted to constant equivalent compressor speed (mode III). These values were obtained from figures 5 and 6 by assuming that the sea-level static value of entrance equivalent weight flow $(w\sqrt{\theta'}/\delta' A_c)_{4a}$ to the free-turbine prevailed at the other flight conditions. If an increase in turbine-inlet temperature is desired at flight condition A in order to obtain more power and lower sfc, it could be obtained by increasing the rotative speed of the engine. However, the increase in turbine-inlet temperature that can be obtained in this manner is restricted by the increasing blade stress and a deterioration of compressor performance. Another alternative would be to design for a high turbine-inlet temperature at flight condition A and then derate the engine at condition 0 by not utilizing the maximum temperature possible. In conclusion, if adjustable-area stators cannot be employed in the free-turbine, the free-turbine engine is restricted in the range of turbine-inlet temperature over which it can operate and is therefore less versatile than the single-spool engine.

Turbine Stress and Frontal Area

The centrifugal stress at the hub of the last turbine rotor for a single-spool engine operating under mode I with constant exhaust-nozzle area (A_6/A_c = 1.40) is presented in figure 7. With respect to stress, these operating conditions and this engine configuration represent the most critical conditions analyzed. However, the stresses calculated were a minimum for these conditions, since the turbine was considered to be at limiting loading at all times.

The left side of figure 7 shows the effect of both flight condition and turbine-inlet temperature on stress. By following the figure to the right side as indicated, total temperature relative to the rotor may be determined for any given flight condition and turbine-inlet temperature. 3548
The total temperature relative to the rotor is, for practical purposes, the blade metal temperature at these conditions. A 100-hour stress-rupture curve for a common high-temperature blade material terminated by the curve for the 0.2-percent offset yield strength of this material is superimposed on the right side of figure 7. Stresses to the left or below these curves are within the material stress limits for a 100-hour life.

For the flight conditions considered in figure 7, turbine-inlet temperatures up to 2600° R can be reached without the exit stress exceeding the 100-hour stress-rupture limits. However, these stresses are a minimum for the flight conditions shown, and no design factor of safety has been employed. The increase in stress with altitude and flight speed results primarily from the increase in turbine-exit annular area required, as reflected by the turbine total-pressure ratio obtained under mode I with constant exhaust-nozzle area (fig. 3). In this case, it is obvious that, at altitude, the blade stress could be greatly reduced by decreasing the exhaust-nozzle area and hence the required turbine pressure ratio. For example, at flight condition A, the stress at a turbine-inlet temperature of 2200° R could be reduced from 70,000 to less than 50,000 pounds per square inch without increasing the specific fuel consumption. However, this would require a large reduction in exhaust-nozzle area, a reduction in the area ratio A_6/A_c from 1.40 to 0.93. The problem could also be alleviated by operating under mode II or III with their reduced rotative speeds at altitude, or by utilizing a free-turbine, the rotative speed of which would be independent of the compressor characteristics. At sea-level flight, however, the stress for modes II and III would be greater than for mode I.

The centrifugal stress at the hub of the first rotor was estimated to be between 10,000 and 12,000 pounds per square inch. The first-rotor stress is assumed to be constant for all flight conditions and turbine-inlet temperatures, because, under mode I for the single-spool engine, the first turbine stator was assumed to be always choked. For mode III the stress would be somewhat less at altitude than for mode I because of the reduced rotative speed - approximately 12 percent at flight condition A. For stresses of the order of 10,000 pounds per square inch, reference 10 indicates that turbine-inlet temperatures as high as 2600° R would require very little cooling-air flow.

The ratio of turbine to compressor frontal area is plotted against turbine-inlet temperature in figure 8 for the various flight conditions. Here again a single-spool engine operating under mode I with constant exhaust-nozzle area ($A_6/A_c = 1.40$) is considered, because it would require the largest turbine frontal areas. Similarly to figure 7, the turbine frontal areas in figure 8 were a minimum for these conditions, since the turbine was considered to be at limiting loading at all times. The turbine blade tip speed is also shown in figure 8 for a compressor blade tip speed of 1168 feet per second.

It would be difficult from the present limited analysis to determine what maximum turbine frontal area could be tolerated. However, it appears from figure 8 that the turbine frontal area at the higher altitudes and speeds may already have exceeded a practical size limit. Areas as small as those shown for the sea-level-static curve (condition 0) could be achieved at the altitude conditions if the required turbine design pressure ratio were reduced by decreasing the exhaust-nozzle area. For the same example used previously to indicate how the exit stress could be reduced without increasing sfc, the ratio of turbine to compressor frontal area could be reduced from 2.14 to 1.51. A variable exhaust-nozzle area would, therefore, be beneficial in reducing both turbine frontal area and turbine stress and, as pointed out in reference 2, would make the other turbine requirements less critical without seriously affecting engine performance.

The turbine tip speeds shown in figure 8 are higher than those normally considered in turbine designs. However, high turbine tip speeds are not a hindrance in designing an efficient turbine if the resulting turbine stress is not a problem. It has been noted that turbine blade stress need not be a problem for these engines.

In converting the net jet thrust into equivalent shaft horsepower, a propeller efficiency of 80 percent was assumed. This assumed propeller efficiency does not influence the values of sfc calculated to any great extent, because the equivalent shaft horsepower of the net thrust is, in general, a small part of the engine power for the conditions considered.

SUMMARY OF RESULTS

The effects of mode of engine operation, engine configuration, and airplane flight condition on the performance of a turboprop engine with a high-pressure-ratio single-spool compressor were investigated. The following results and conclusions were obtained:

1. The lowest specific fuel consumption for an engine with constant exhaust-nozzle area occurred at the highest flight velocity and altitude considered. Either decreasing the flight velocity or decreasing the altitude below the tropopause resulted in higher specific fuel consumption for the engine. Minor improvement in specific fuel consumption at some flight conditions could be obtained by varying the exhaust-nozzle area.

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2. For all flight conditions, the minimum specific-fuel-consumption values of the high-pressure-ratio engine were less than those of the low-pressure-ratio engine previously analyzed. The percentage change in specific fuel consumption with altitude and flight speed for the high-pressure-ratio engine was less than for the low-pressure-ratio engine.

3. The mode of engine operation had little effect on specific fuel consumption for the single-spool engine. However, for mode II (compressor design-point operation), the engine power was not limited by compressor surge. Comparable specific-fuel-consumption values for the free-turbine engine were obtained under mode I (constant compressor mechanical speed) and mode III (constant compressor equivalent speed).

4. The free-turbine and single-spool engines differ mainly in turbine requirements, which are more critical for the free-turbine.

5. If variable-area stators cannot be employed in the free-turbine, the engine is restricted in the range of turbine-inlet temperature over which it can operate and is therefore less versatile than the single-spool engine.

6. For constant-exhaust-nozzle-area operation, turbine blade stress and frontal area become quite large at high flight speed and altitude, being greatest for the single-spool engine operating under mode I. A variable exhaust-nozzle area would therefore make it possible to design for much smaller turbine blade stress and frontal area in addition to making the other turbine requirements less critical. Little, if any, penalty in specific fuel consumption would be incurred from closing down the exhaust nozzle at high flight speed and altitude.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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TABLE I. - EFFECT OF FLIGHT CONDITION AND TURBINE-INLET TEMPERATURE ON TURBINE DESIGN REQUIREMENTS

[Mode III and constant exhaust-nozzle area.]

Flight condition	Turbine-inlet temperature, T_4', °R	Free-turbine engine				Single-spool engine
		Free-turbine total-pressure ratio, p_{4a}'/p_5'	Inlet equivalent weight flow to free-turbine, $\left(\frac{w\sqrt{\theta'}}{\delta' A_c}\right)_{4a}$	Gas-generator-turbine total-pressure ratio, p_4'/p_{4a}'	Over-all turbine total-pressure ratio, p_4'/p_5'	Turbine total-pressure ratio, p_4'/p_5'
(a) Effect of flight condition						
O	2100	2.14	20.5	5.4	11.56	11.6
A	2100	3.90	17.2	4.5	17.55	17.1
(b) Effect of turbine-inlet temperature						
A	1600	2.24	26.0	7.07	15.9	16.0
A	2600	5.25	13.6	3.43	18.0	17.9

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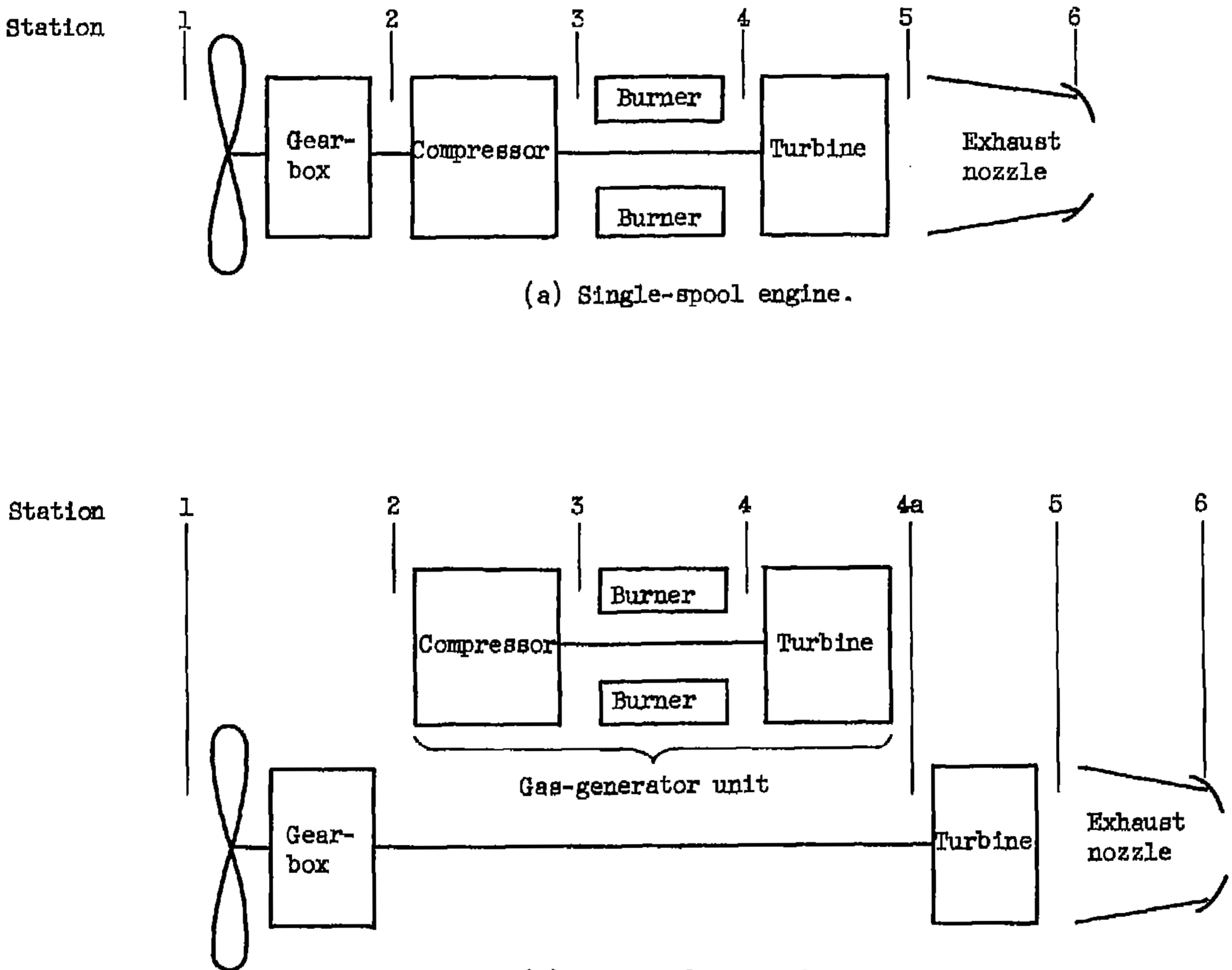
TABLE II. - ENGINE MATCH POINTS AT VARIOUS FLIGHT CONDITIONS FOR CHOKED FREE-TURBINE

[Mode III and constant exhaust-nozzle area.]

Flight condition	Turbine-inlet temperature, T_4', °R	Free-turbine total-pressure ratio, p_{4a}'/p_5'	Inlet equivalent weight flow to free-turbine, $\left(\frac{w\sqrt{\theta'}}{\delta' A_c}\right)_{4a}$	Gas-generator-turbine total-pressure ratio, p_4'/p_{4a}'	Engine power output, P^*/A_c, hp/sq ft	Specific fuel consumption, sfc, lb/hp-hr
O	[a]2100	2.14	20.5	5.42	2720	0.531
A	1850	3.15	↓	↓	1140	.361
B	1700	2.59	↓	↓	710	.409
C	1940	2.55	↓	↓	1894	.425

[a]Assigned.

[redacted]



(a) Single-spool engine.

(b) Free-turbine engine.

Figure 1. - Schematic diagrams of two engines analyzed.

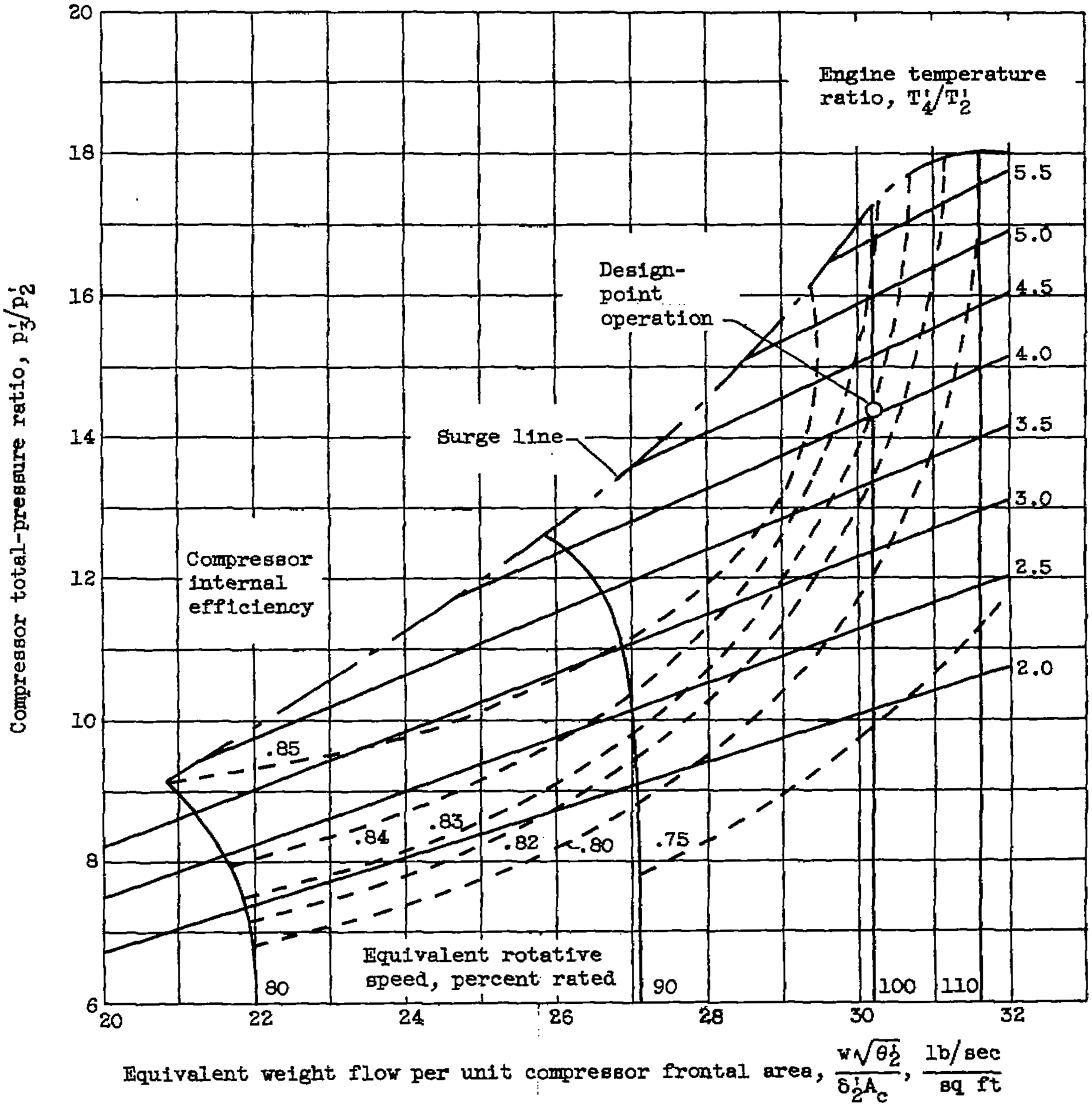


Figure 2. - Compressor map with temperature-ratio lines.

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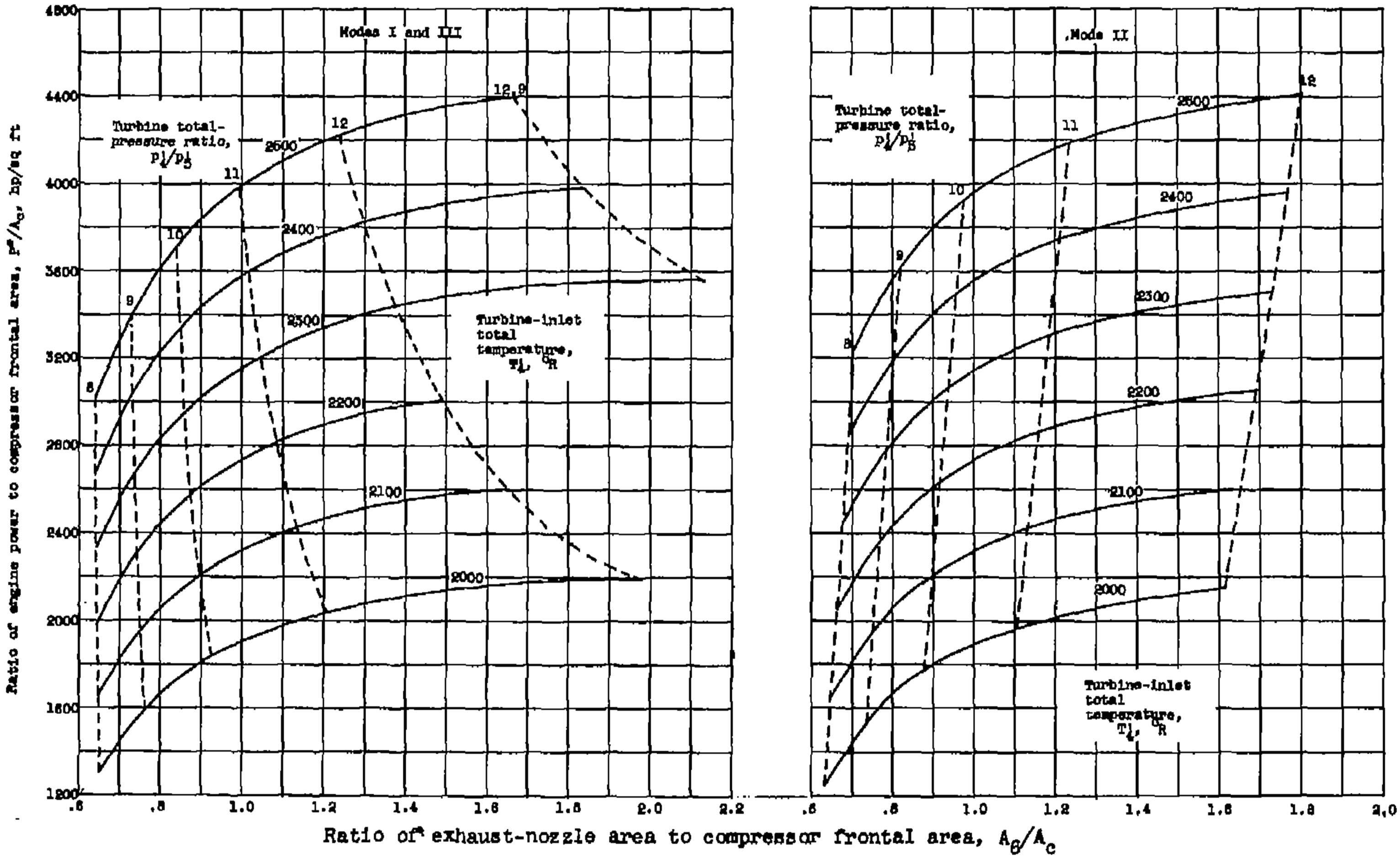
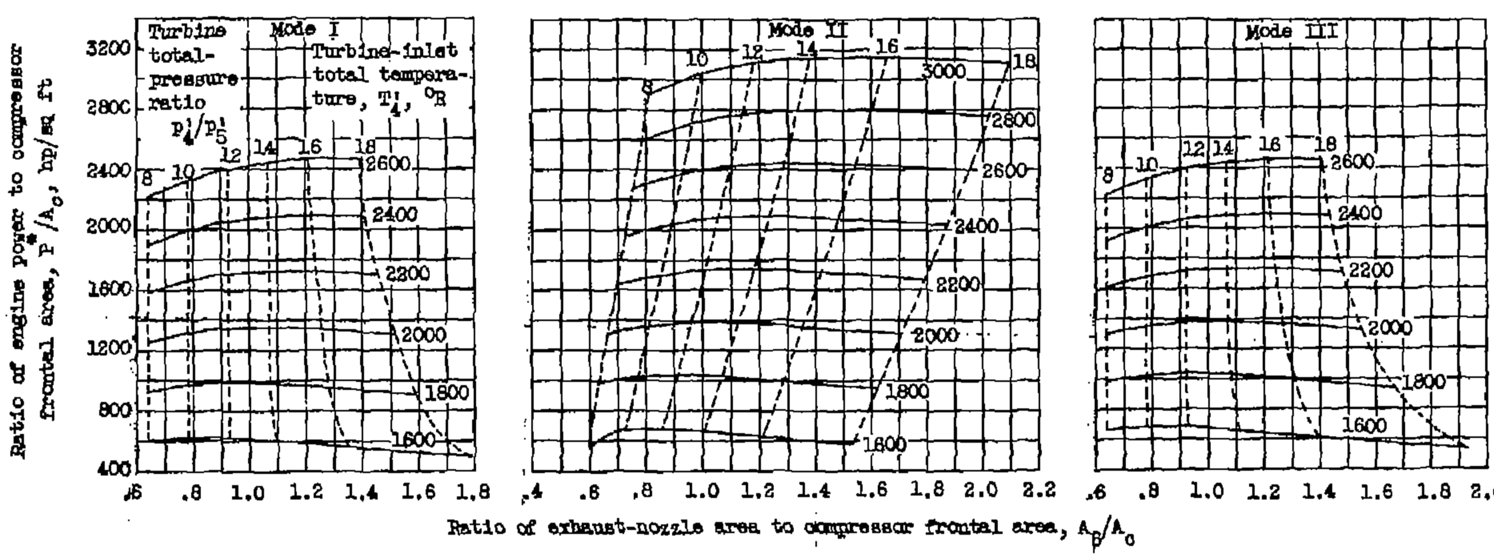


[redacted]

(a) Flight condition 0.

Figure 3. - Effect of flight condition and mode of engine operation on design requirements for single-spool engine.



(b) Flight condition A.

Figure 3. - Continued. Effect of flight condition and mode of engine operation on design requirements for single-spool engine.

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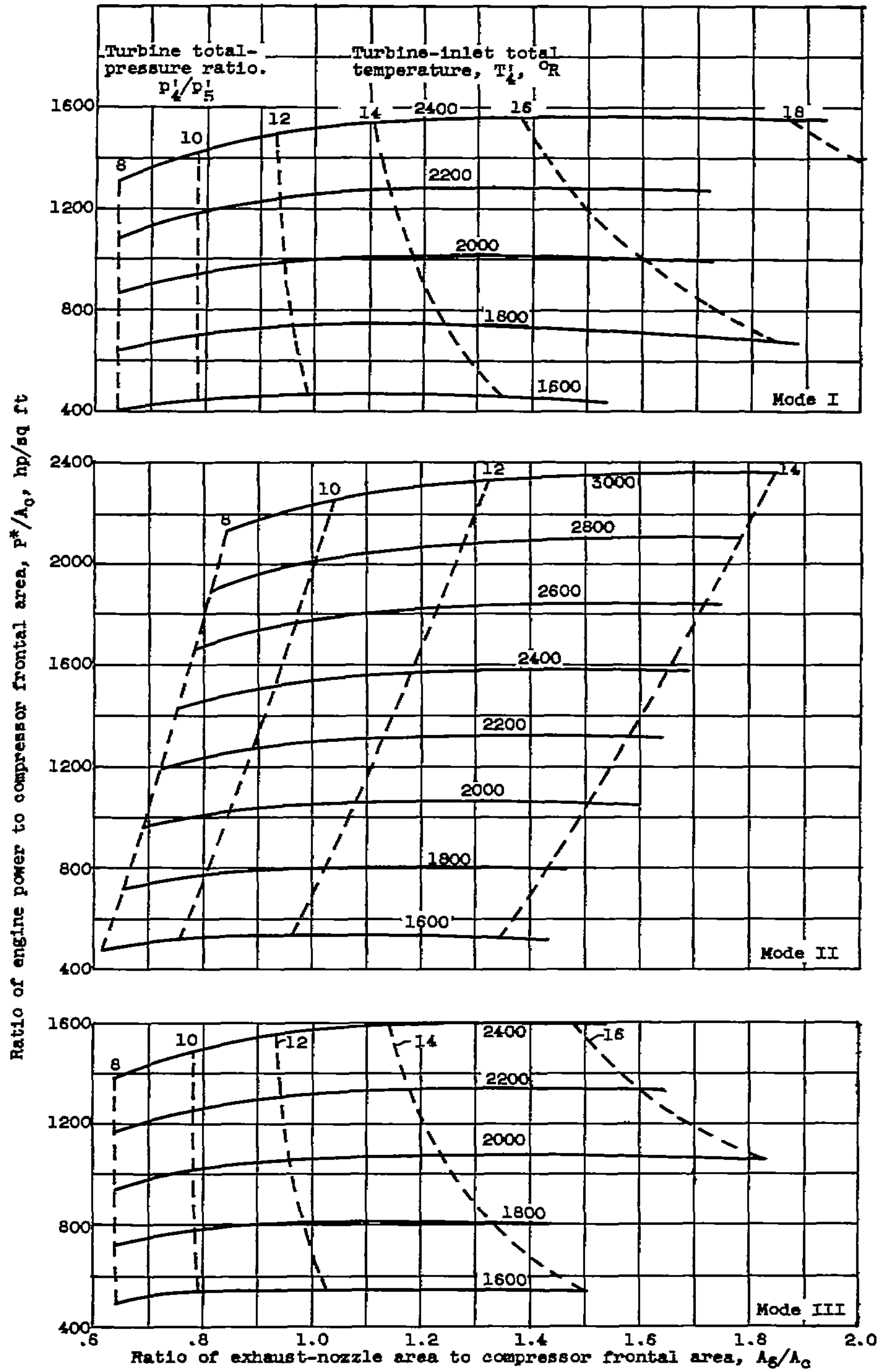
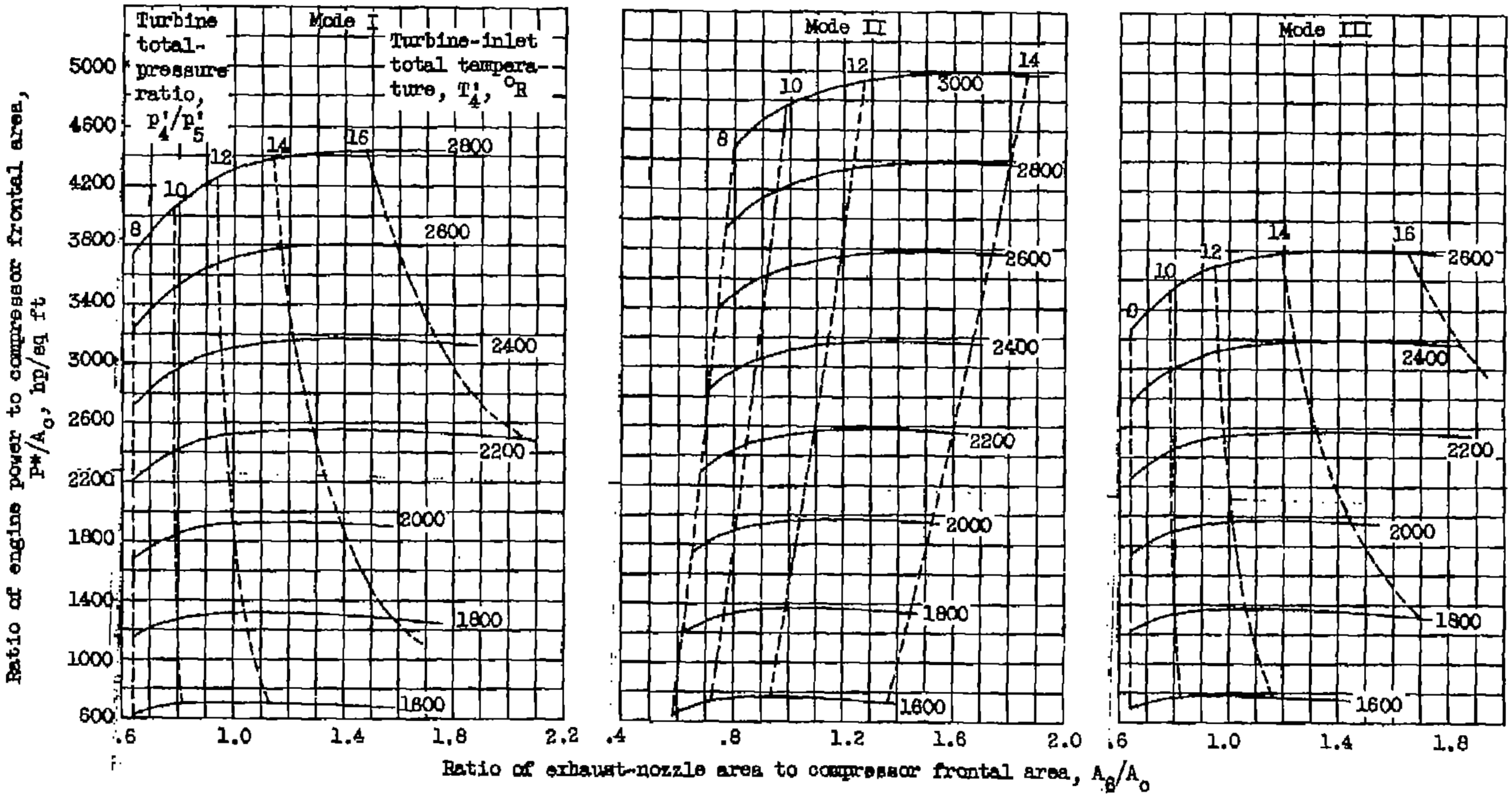


(c) Flight condition B.

Figure 3. - Continued. Effect of flight condition and mode of engine operation on design requirements for single-spool engine.

[redacted]

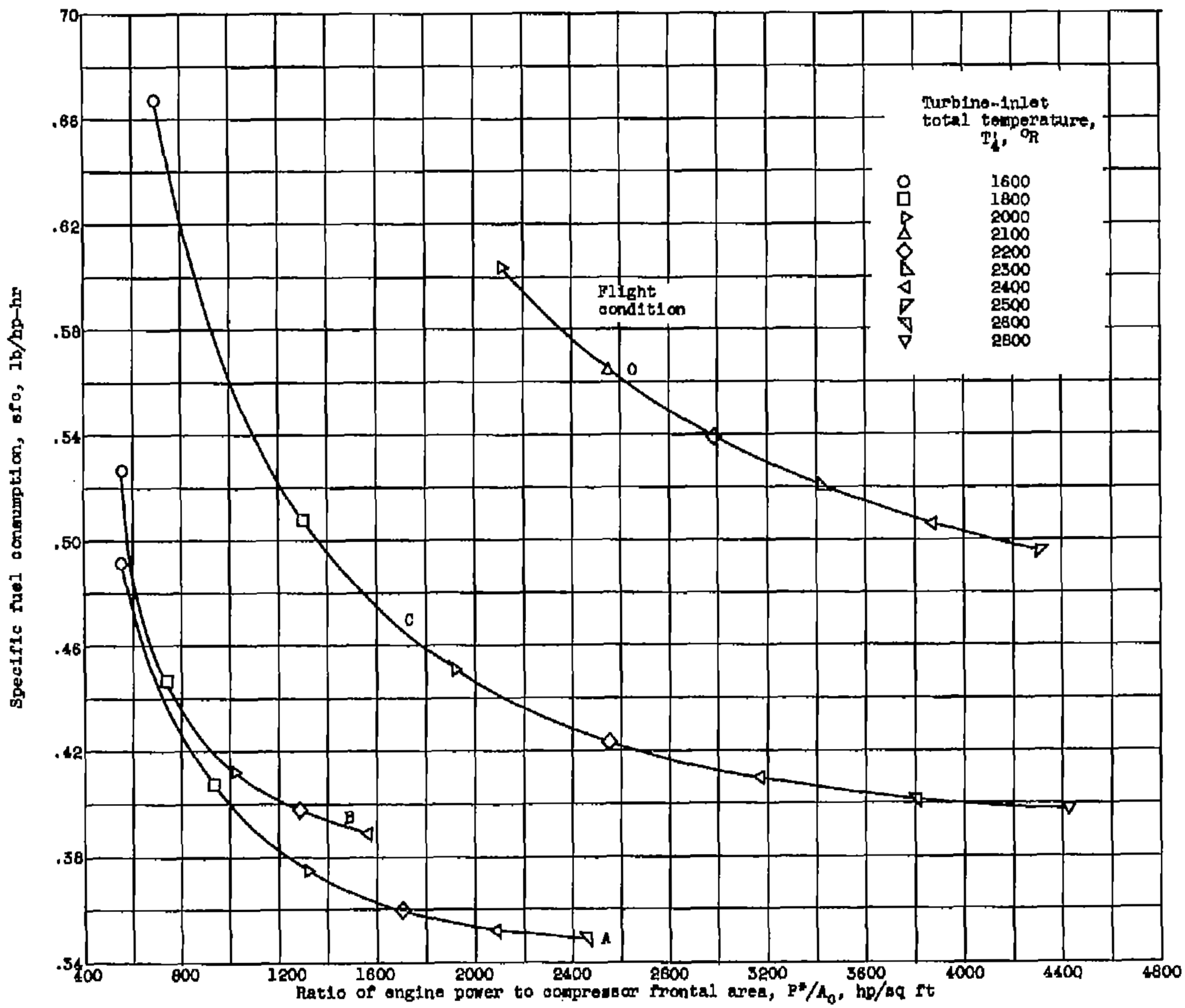
[redacted]



(d) Flight condition C.

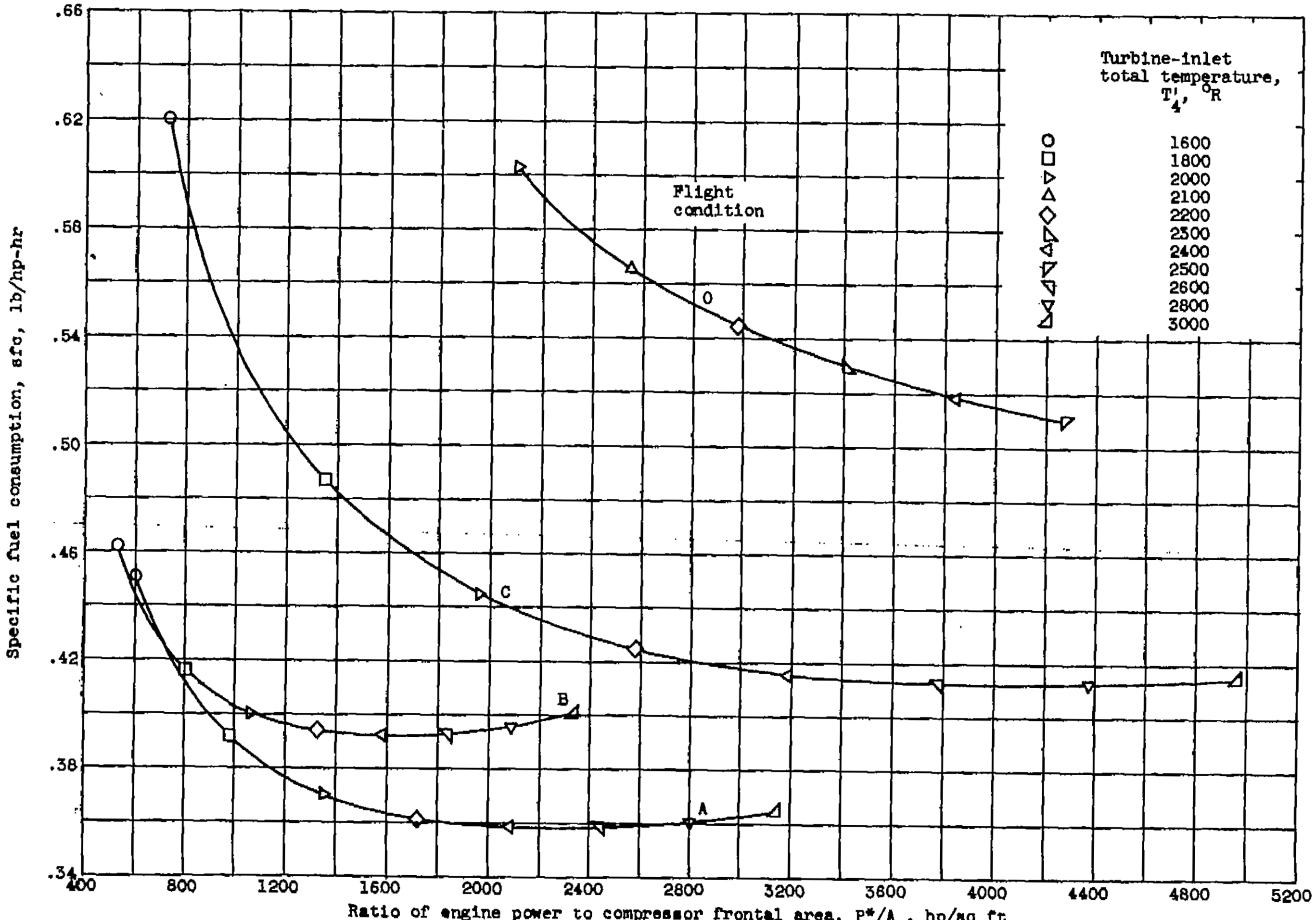
Figure 3. - Concluded. Effect of flight condition and mode of engine operation on design requirements for single-spool engine.

[redacted]



(a) Mode I.

Figure 4. - Variation in specific fuel consumption with engine power for single-spool engine with constant exhaust-nozzle area. Ratio of exhaust-nozzle area to compressor frontal area, 1.4.



(b) Mode II.

Figure 4. - Continued. Variation in specific fuel consumption with engine power for single-spool engine with constant exhaust-nozzle area. Ratio of exhaust-nozzle area to compressor frontal area, 1.4.

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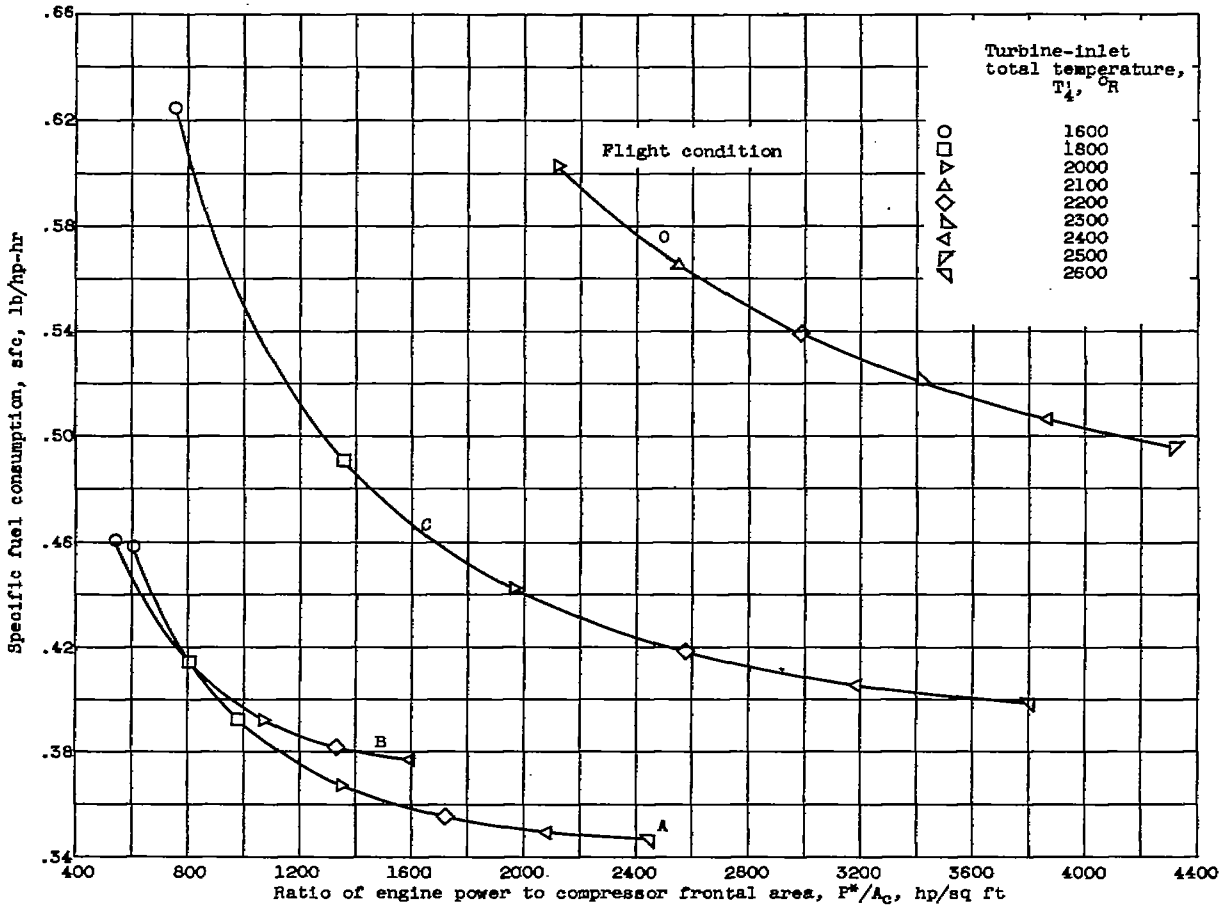
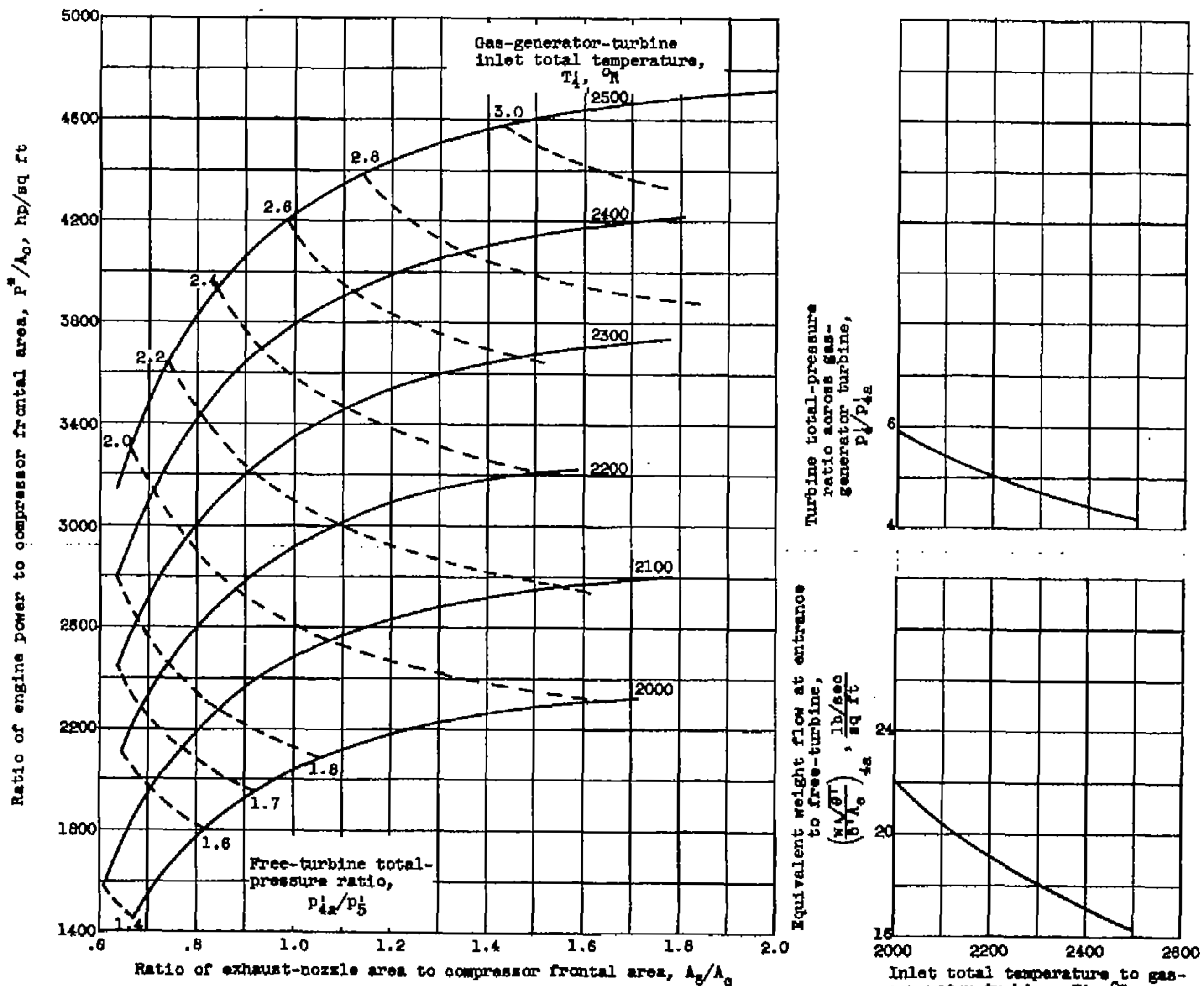


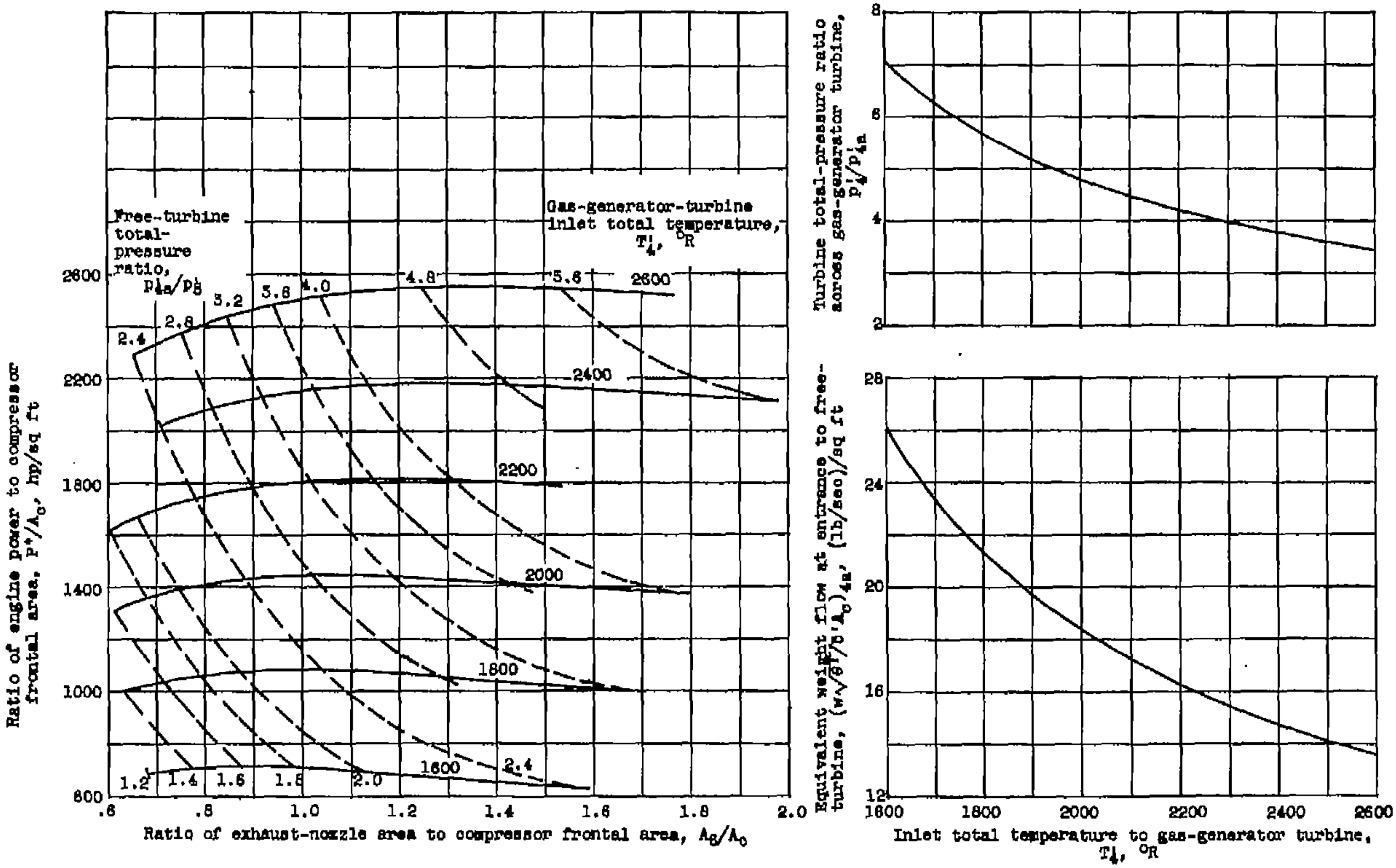
(c) Mode III.

Figure 4. - Concluded. Variation in specific fuel consumption with engine power for single-spool engine with constant exhaust-nozzle area. Ratio of exhaust-nozzle area to compressor frontal area, 1.4.



(a) Flight condition 0.

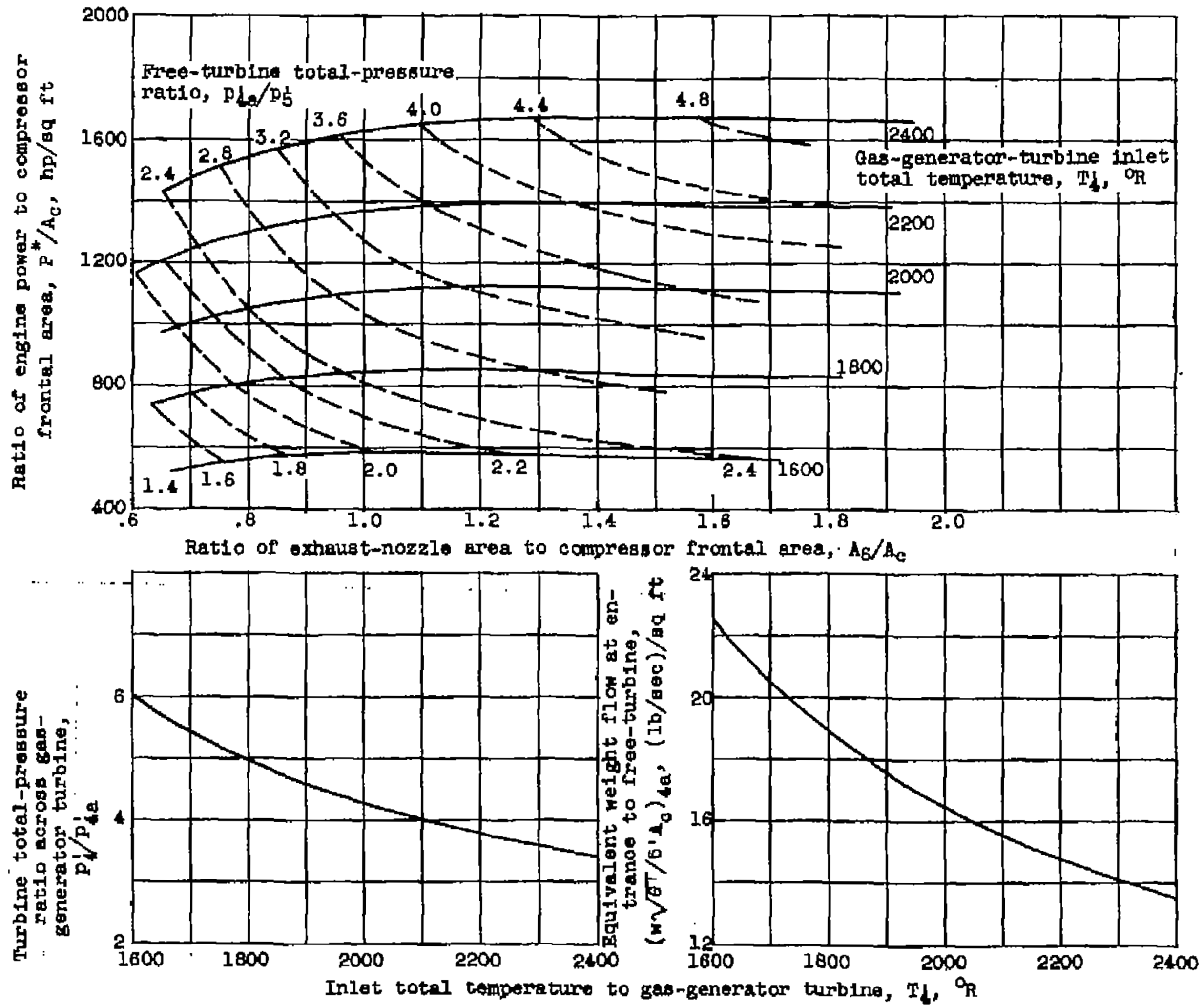
Figure 5. - Effect of flight condition on design requirements for free-turbine engine.



(b) Flight condition A.

Figure 5. - Continued. Effect of flight condition on design requirements for free-turbine engine.

[redacted]

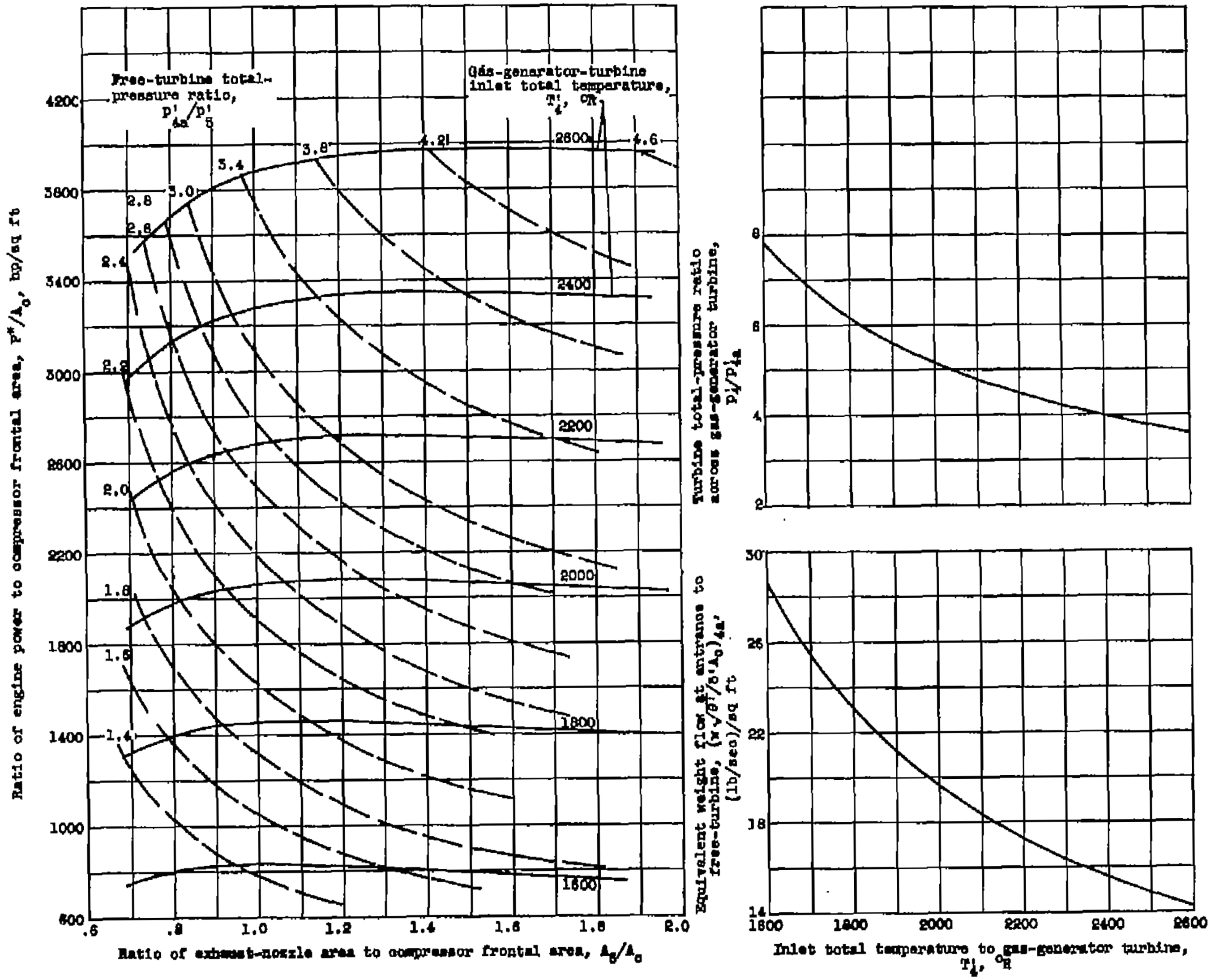


(c) Flight condition B.

Figure 5. - Continued. Effect of flight condition on design requirements for free-turbine engine.

[redacted]

[redacted]



(d) Flight condition C.

Figure 5. - Concluded. Effect of flight condition on design requirements for free-turbine engine.

[redacted]

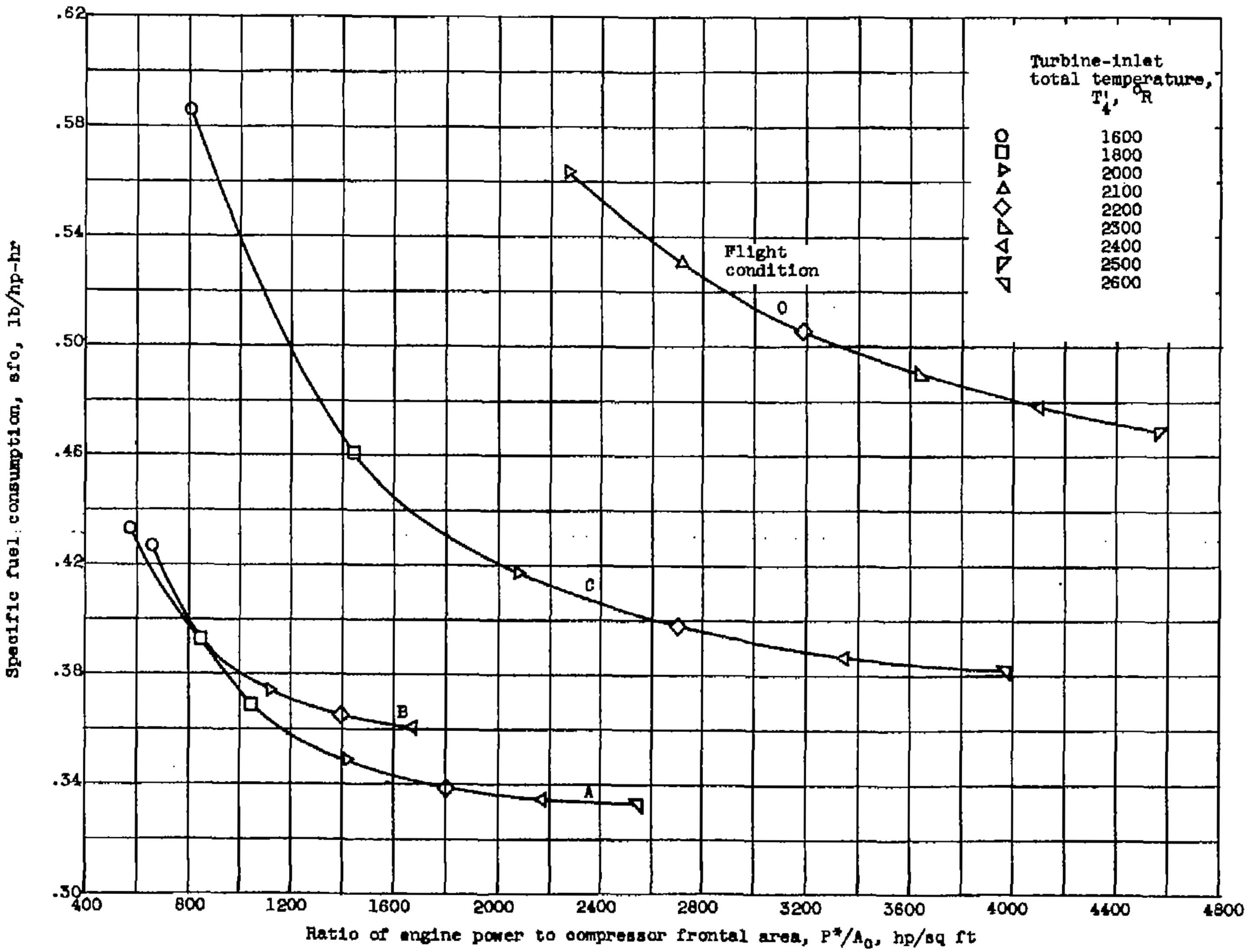


Figure 6. - Variation in specific fuel consumption with engine power for free-turbine engine with constant exhaust-nozzle area. Ratio of exhaust-nozzle area to compressor frontal area, 1.4.

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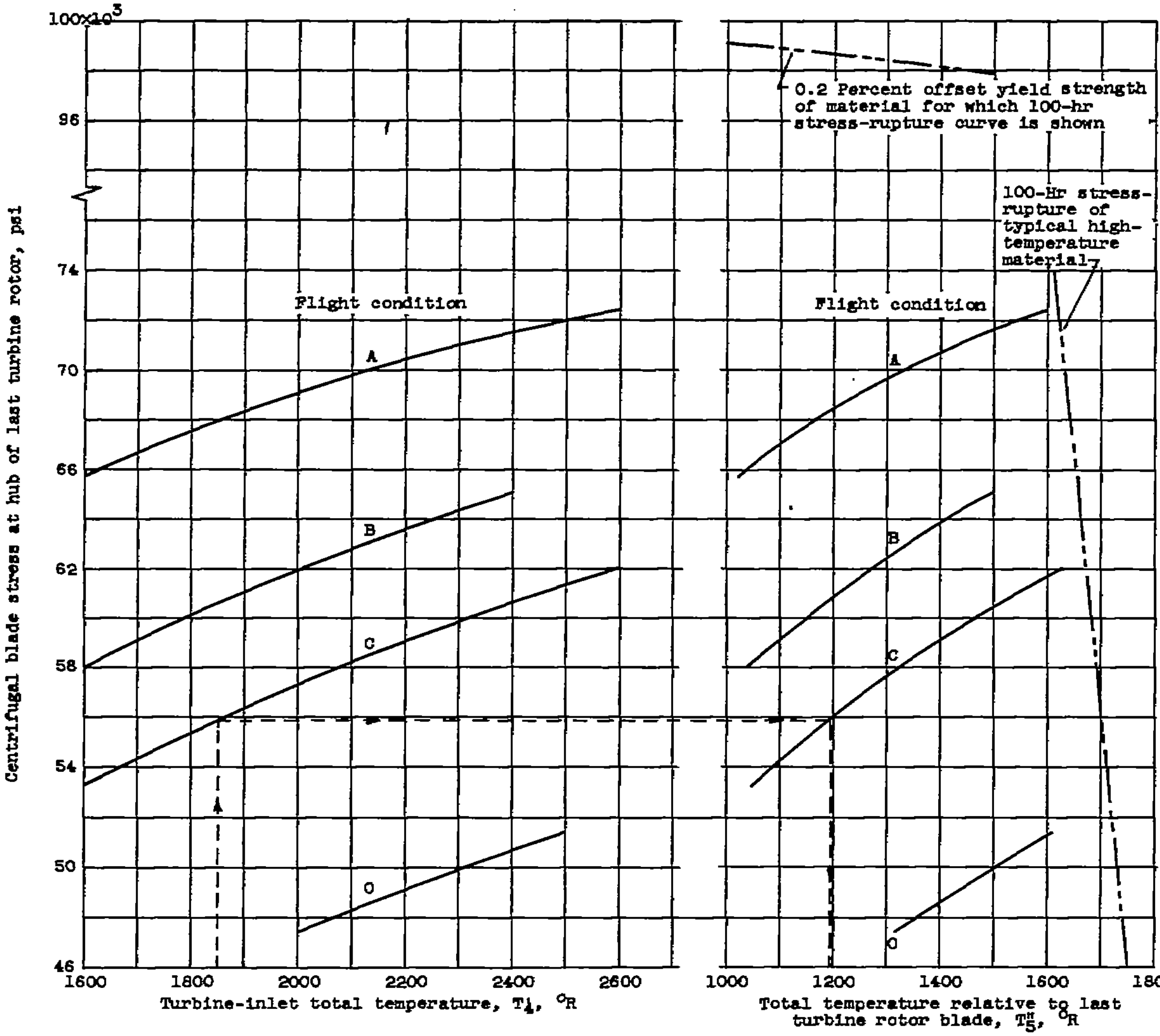

Figure 7. - Effect of turbine-inlet temperature and flight condition on centrifugal blade stress at hub of last rotor. Single-spool engine; mode I operation with constant exhaust-nozzle area.

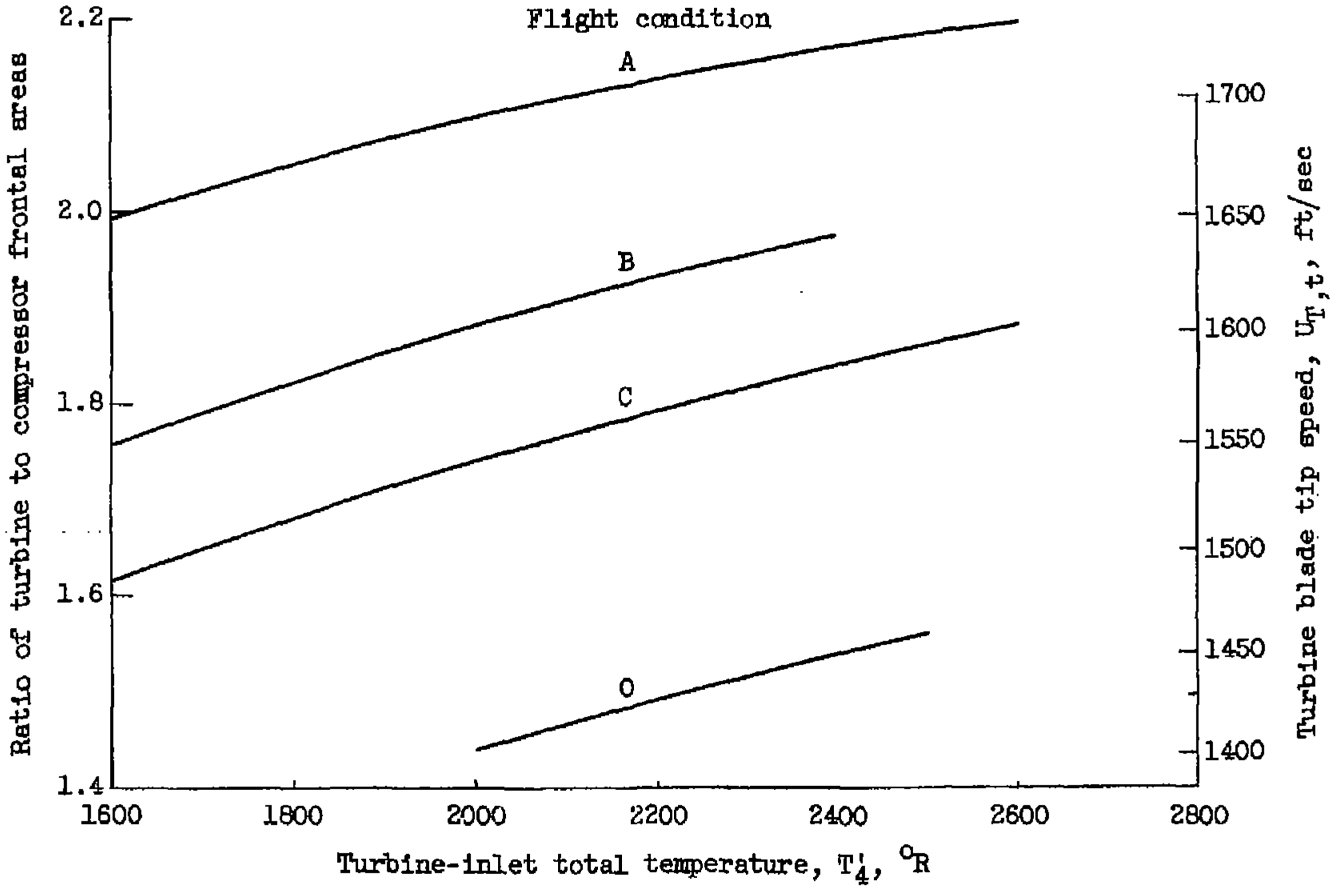

Figure 8. - Effect of turbine-inlet temperature and flight condition on turbine frontal area. Single-spool engine; mode I operation with constant exhaust-nozzle area.

[redacted]

[redacted]