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RESEARCH MEMORANDUM

TURBOPROP-ENGINE DESIGN CONSIDERATIONS

I - EFFECT OF MODE OF ENGINE OPERATION ON PERFORMANCE OF TURBOPROP ENGINE WITH CURRENT COMPRESSOR PRESSURE RATIO

By Elmer H. Davison

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Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
May 23, 1955

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RESEARCH MEMORANDUM

TURBOPROP-ENGINE DESIGN CONSIDERATIONS

I - EFFECT OF MODE OF ENGINE OPERATION ON PERFORMANCE OF TURBOPROP ENGINE WITH CURRENT COMPRESSOR PRESSURE RATIO

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SUMMARY

A cycle analysis was made of a turboprop engine for various modes of operation over a range of flight conditions in order to determine whether one mode of operation has any marked advantages. Operation with constant compressor equivalent design speed, with constant design engine rotative speed, with adjustable turbine stators, and with variable exhaust-nozzle area was considered. The compressor design pressure ratio was 7.32, and the flight conditions investigated ranged from sea-level take-off to 600 miles per hour at 40,000 feet.

It was found that decreasing the flight velocity from the maximum considered or decreasing the altitude below the tropopause increased the specific fuel consumption. At any given flight condition the specific fuel consumption increased rapidly with decreasing power. The method of engine operation had a negligible effect on specific fuel consumption at high power. At low power the specific fuel consumption can be improved by allowing the rotative speed of the engine, the stator areas of the turbine, and the exhaust-nozzle area to vary. The turbine design requirements for an engine operated with a constant exhaust-nozzle area are more severe than for variable exhaust-nozzle area.

INTRODUCTION

The effects of different modes of engine operation on turboprop-engine performance are being studied. The cycle analysis reported herein was made in order to determine if any marked improvement in the performance of a turboprop engine having low compressor pressure ratio could be achieved by operating under one of the various modes of operation considered.

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This investigation, which was conducted at the NACA Lewis laboratory, is a continuation of the investigation reported in reference 1. The performance data of a particular low-pressure-ratio compressor typical of those currently being used in turboprop engines were used in the analysis. At design-point operation the pressure ratio is 7.32, the equivalent weight flow per unit compressor frontal area (based on compressor blade tip diameter) is 26.9 pounds per second per square foot, and the compressor is operating near peak efficiency at 83 percent.

Four modes of engine operation were considered for flight conditions ranging from take-off to speeds of 600 miles per hour at a 40,000-foot altitude. These four modes of operation were:

I. The engine rotative speed remained constant.

II. The compressor was maintained at design equivalent conditions at all times.

III. The compressor was operated at constant equivalent design speed.

IV. The compressor was operated at the fixed equivalent conditions which minimized the specific fuel consumption for 600 miles per hour at 40,000 feet.

The engine parameters investigated were specific fuel consumption, turbine-inlet temperature, turbine pressure ratio, exhaust-nozzle area, rotative speed, and equivalent weight flow at turbine entrance.

SYMBOLS

The following symbols are used in this report:

F	jet thrust, lb
P^*	engine power (shaft horsepower plus equivalent shaft horsepower of net thrust), hp
p	pressure, lb/sq ft
sfc	specific fuel consumption, lb/hp-hr
T	temperature, $^{\circ}R$
V	flight velocity, 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

Subscripts:

c	compressor
n	net
p	propeller
s	sea-level static
t	turbine
1	ambient
2	compressor inlet
3	compressor outlet
4	turbine inlet
5	turbine outlet
6	exhaust-nozzle outlet

Superscript:

'	total or stagnation state

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ANALYSIS

Assigned Flight Conditions and Operating Modes

The four flight conditions considered were:

	Flight condition			
	0	A	B	C
Altitude, ft	0	40,000	40,000	19,000
Flight speed, mph	0	600	400	400
Flight speed, knots	0	521	347	347

Over the range of flight conditions investigated, the following four modes of engine operation were considered:

I. The engine rotative speed remained constant.

II. The compressor was maintained at design equivalent conditions at all times.

III. The compressor was operated at constant equivalent design speed.

IV. The compressor was operated at the fixed equivalent conditions which minimized the specific fuel consumption for 600 miles per hour at 40,000 feet.

Modes II and IV required turbine stator adjustment in order to be realized. The compressor operating point for mode IV was selected after the variations in specific fuel consumption had been calculated for the first three modes.

A take-off (design) turbine-inlet temperature of 2060° R was assigned for modes I to III. The compressor operating conditions for mode IV were different from the other three modes at take-off, which resulted in different engine operating conditions for the same take-off power. For this reason, a range of turbine-inlet temperatures was assigned at take-off for mode IV, which enabled the engine operating conditions for mode IV to be determined when the engine power output was the same as that for the other three modes.

At the altitude of 40,000 feet a range of turbine-inlet temperature from 1600° to 2400° R was assigned for all modes, while at the altitude of 19,000 feet a range of turbine-inlet temperature from 1400° to 2200° R was assigned for all modes.

The compressor performance map used in the cycle analysis is reproduced from reference 1 in figure 1(a). The efficiency contours and rotative speed lines have been extended for this analysis. The compressor operating conditions for the four modes of operation at the four flight conditions considered are shown in figures 1(b) to (e). The lines of constant turbine-inlet temperature shown on the maps apply only to modes I and III and will be discussed later. For modes II and IV, the compressor equivalent conditions remain constant at the values indicated in figures 1(b) to (e). For mode III, the compressor operates along the line of 100-percent equivalent rotative speed. For mode I, the compressor operates at a constant rotative speed, which results in compressor operation along a different constant equivalent speed line for each flight condition.

Cycle Analysis

The cycle analysis for modes I and III was carried out in the same manner as discussed in reference 1. The details of this analysis are discussed in the appendix.

For modes II and IV the continuity equation (A1) of the appendix no longer determines the temperature ratio T_4'/T_2' between the turbine and compressor inlets for a given compressor weight flow $w_2\sqrt{\theta_2'}/\delta_2'$ and pressure ratio p_3'/p_2', because the turbine-inlet equivalent weight flow $w_4\sqrt{\theta_4'}/\delta_4'$ is no longer considered constant. The mass flow through the engine for modes II and IV is determined in these cases by the operating point selected for the compressor and the particular flight condition under consideration. Except for the continuity consideration between the compressor and turbine, the cycle analysis for modes II and IV was also carried through in the same manner as in reference 1.

The cycle analysis of reference 1 was extended, in that the specific fuel consumption was calculated for the different modes of engine operation and flight conditions. These calculated values were based on the total power output of the engine P^*. Curves of specific fuel consumption were calculated for the following two engine configurations at each turbine-inlet temperature:

(1) The exhaust-nozzle area was selected so that the minimum specific fuel consumption was obtained for any given turbine-inlet temperature, flight condition, and mode of engine operation. At take-off an exception was made, because the exhaust-nozzle area required for minimum specific fuel consumption would be unreasonably large. The exhaust-nozzle area selected for this flight condition resulted in an area ratio A_6/A_c of 1.40, which represents a good compromise between exhaust-nozzle area and specific fuel consumption.

(2) The engine was considered to operate with a fixed exhaust-nozzle area. For the analysis reported herein, the exhaust-nozzle area selected was such that the ratio A_6/A_c was 1.40. This area ratio represents a good compromise between optimum conditions at take-off and the other flight conditions considered.

The following conditions were assumed for the analysis:

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 turbines	1.30
Gas constant, ft-lb/(lb)($^{\circ}$R)	53.4

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The turbine-inlet equivalent weight flow $w_4\sqrt{\theta_4'}/\delta_4'$ was assumed to be constant for operating modes I and III, which implies that the first turbine stator is choked for all conditions analyzed. The turbine-inlet equivalent weight flow $w_4\sqrt{\theta_4'}/\delta_4'$ was allowed to vary for operating modes II and IV, which implies that the turbine stator areas are adjustable in order to accommodate the variation in turbine equivalent weight flow. The air flow through the compressor was assumed equal to the gas flow through the turbine. 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.

RESULTS AND DISCUSSION

The results of the cycle analysis are presented in figures 2 to 7. Figures 2 to 5 present the variations 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. Figures 2 to 5 show the effect of the division of the over-all expansion ratio p_4'/p_1 between the turbine and the exhaust nozzle on the engine power. In addition, they are used in determining the turbine design requirements for the various operating conditions.

Figure 6, which shows the variation in specific fuel consumption with engine power for various flight conditions, was constructed by calculating the specific fuel consumption for those points from figures 3 to 5 where the power output of the engine reaches a maximum for any given turbine-inlet temperature. Reference 2 was used for these specific-fuel-consumption calculations. As a result of the manner in which figure 6 was constructed, it represents the minimum specific fuel consumption that can be obtained from the engine at any given power level, flight condition, and mode of engine operation. The achievement of these values of specific fuel consumption requires the use of an adjustable exhaust-nozzle area.

The variation in specific fuel consumption with engine power for various flight conditions is also presented in figure 7. Figure 7, however, was constructed by calculating the specific fuel consumption from figures 3 to 5 for a constant value of the ratio of exhaust-nozzle area to compressor frontal area A_6/A_c of 1.40 and various turbine-inlet temperatures. Figure 7 represents the specific fuel consumption obtainable from the engine at any given power level for operation with constant exhaust-nozzle area. The value of 1.40 for A_6/A_c represents a good compromise between the optimum engine operating conditions for take-off and the other flight conditions considered.

Figure 6(a) shows that the compressor operating point selected for mode IV did not, as intended, give the lowest specific fuel consumption at all power levels. The choice of the compressor operating conditions for mode IV was based on the trends of the curves of specific fuel consumption for the other three modes of operation. Increasing power output for mode III results in increasing compressor pressure ratio and moves the compressor toward surge. If the compressor could be operated at these high pressure ratios, a curve of specific fuel consumption similar to that for mode II could be obtained that would have lower sfc over the entire power range than the other modes. A slight variation in the compressor operating point selected for mode IV would have given a lower specific fuel consumption at all power levels than the other three modes considered. The difference in specific fuel consumption between modes III and IV at the higher power ratings is a measure of the calculation accuracy maintained in the analysis.

Figures 6 and 7 show that the minimum specific fuel consumption is obtained at flight condition A (600 mph at 40,000 ft). Dropping the flight speed to 400 miles per hour (condition B) raises the whole level of the specific-fuel-consumption curves, while decreasing the altitude to 19,000 feet (condition C) further raises the specific fuel consumption. At any given flight condition, the specific fuel consumption increases rapidly with decreasing power. At the higher powers these curves show that there is no marked advantage of one mode of operation over another. It is only in the low-power range that there is any marked advantage of one mode of operation over another.

At high power (figs. 6 and 7) there is little difference in specific fuel consumption between operation with constant and with variable exhaust-nozzle area. However, at the lower end of the power range some improvement in specific fuel consumption may be achieved by adjusting the exhaust-nozzle area.

The maximum pressure ratio for which the turbine must be designed and the range of pressure ratio over which it must operate can be reduced by adjusting the exhaust-nozzle area. This is apparent, for example, from figure 3(a). Thus, even though the specific fuel consumption is not improved to any great extent by adjusting the exhaust-nozzle area, the turbine requirements could be made less critical. The turbine pressure ratios obtained for the different modes of operation were comparable.

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 specific fuel consumption 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.

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CONCLUSIONS

The effect of different modes of operation on the performance of a low-compressor-pressure-ratio turboprop engine was analyzed. The following conclusions were reached:

1. The lowest specific fuel consumption for the engine 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 values for the engine.

2. At any given flight condition the specific fuel consumption increases rapidly with decreasing power. The difference in specific fuel consumption at high power between operation with constant and with variable exhaust-nozzle area and between the different modes of operation is negligible. At low power the specific fuel consumption can be improved by allowing the rotative speed of the engine, the stator areas of the turbine, and the exhaust-nozzle area to vary.

3. The turbine requirements for an engine operated with a constant exhaust-nozzle area are more severe than for variable exhaust-nozzle area. For constant exhaust-nozzle area, the turbine must operate over a greater range of turbine total-pressure ratio and at a higher maximum turbine total-pressure ratio.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 19, 1954

APPENDIX - CYCLE ANALYSIS

Compressor performance. - With the use of the over-all compressor characteristics shown in figure 1, a cycle analysis was made of equilibrium engine operation.

The continuity requirements between the turbine and compressor are given by equation (1) of reference 1 as follows:

$$\frac{w_2\sqrt{\theta_2'}}{\delta_2'} = \frac{p_3'}{p_2'}\sqrt{\frac{T_2'}{T_4'}}\left(\frac{w_4\sqrt{\theta_4'}}{\delta_4'} \times \frac{p_4'}{p_3'}\right) \qquad (A1)$$

For modes I and III it is assumed that the turbine-inlet equivalent weight flow $w_4\sqrt{\theta_4'}/\delta_4'$ is constant. This assumption implies that the first turbine stator is choked for all the operating conditions considered. With these assumptions it is possible to construct the lines of constant turbine-inlet temperature on the compressor performance maps shown in figures 1(b) to (e). These lines were constructed for an assigned turbine-inlet temperature of 2060° R at sea-level static and compressor design-point operation. Thus, for modes I and III it is possible to determine the compressor operating conditions from figure 1 for any given turbine-inlet temperature and flight condition.

For modes II and IV the compressor equivalent operating conditions were fixed for all flight conditions and turbine-inlet temperatures. For these conditions the turbine-inlet equivalent weight flow in equation (A1) is no longer constant. This implies that the turbine stator area must be varied in order to accommodate the variations in turbine-inlet equivalent weight flow. The lines of constant turbine-inlet temperature shown in figures 1(b) to (e) are, therefore, not applicable to modes II and IV.

Fuel consumption. - The fuel consumption was calculated by the method given in reference 2 for an assumed combustion efficiency of 100 percent.

Turbine performance. - In calculating turbine performance, a constant turbine adiabatic efficiency of 85 percent based on the turbine total-pressure ratio was assumed. The basis of this assumption is that the range of turbine pressure ratio and equivalent rotative speed over which the turbine operates is not unduly large.

Exhaust-nozzle area. - For any flight condition in which the pressure ratio across the exhaust nozzle was equal to or greater than that required for choking, the choking exhaust-nozzle area was used. When the pressure ratio was not great enough to choke the exhaust nozzle, ambient-air pressure was assumed at the exit of the exhaust nozzle in order to calculate the exhaust-nozzle area.

Engine power. - In order to determine the variations in engine power output at a given flight condition for varying amounts of the over-all expansion ratio p_4'/p_1 taken across the turbine, the net jet thrust was converted into an equivalent shaft horsepower by using the assumed propeller efficiency of 80 percent. That is,

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$$P^* = \eta_g (P_t - P_c) + \frac{F_n V}{550\eta_p} \tag{A2}$$

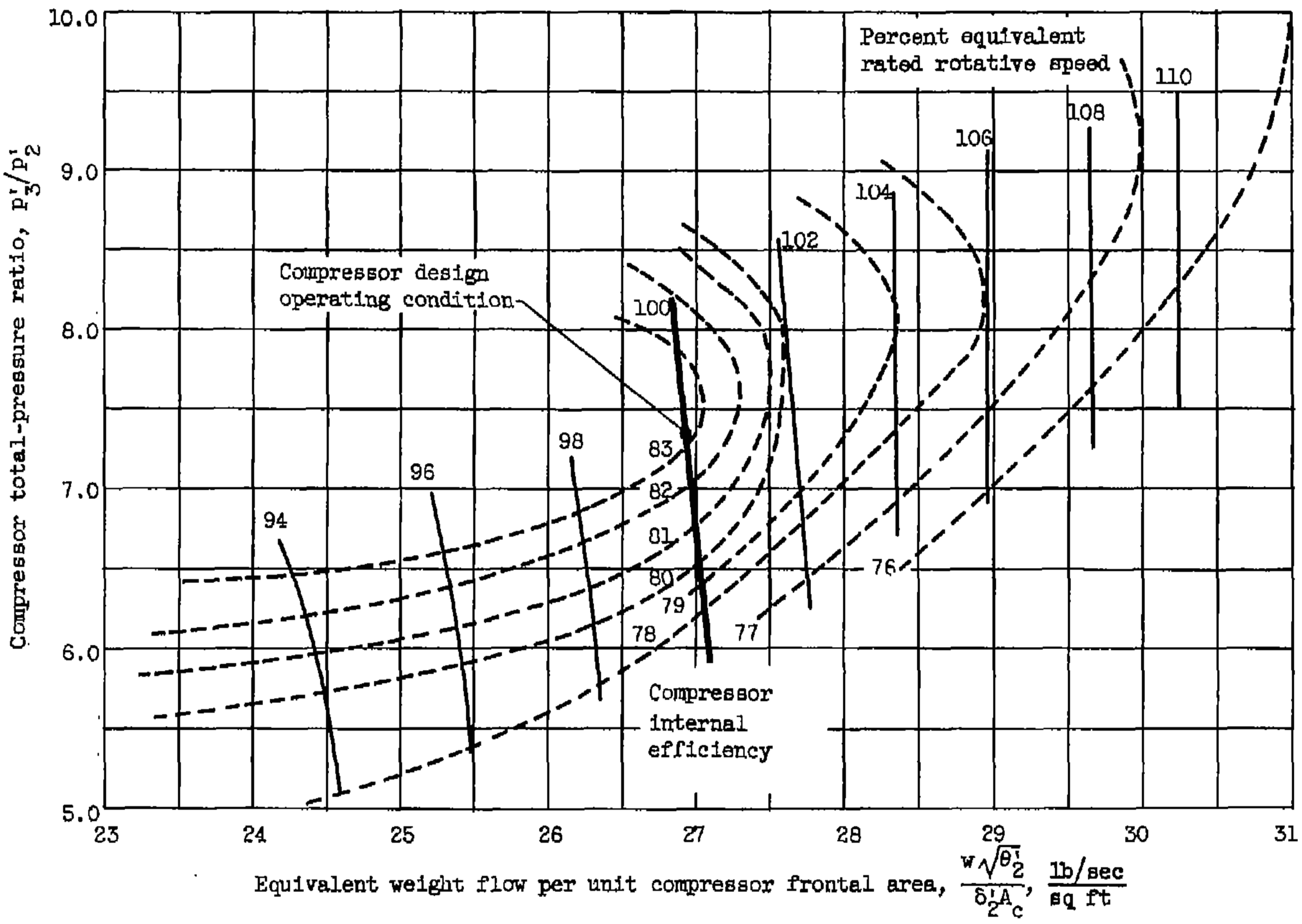
Because the jet thrust cannot be converted into an equivalent shaft horsepower in the previously mentioned manner at the static sea-level condition, a conversion factor between shaft horsepower and static thrust must be assumed. For this analysis the conversion factor assumed was 3.62; thus, for sea-level static conditions,

$$P^* = \eta_g (P_t - P_c) + \frac{F_s}{3.62} \tag{A3}$$

REFERENCES

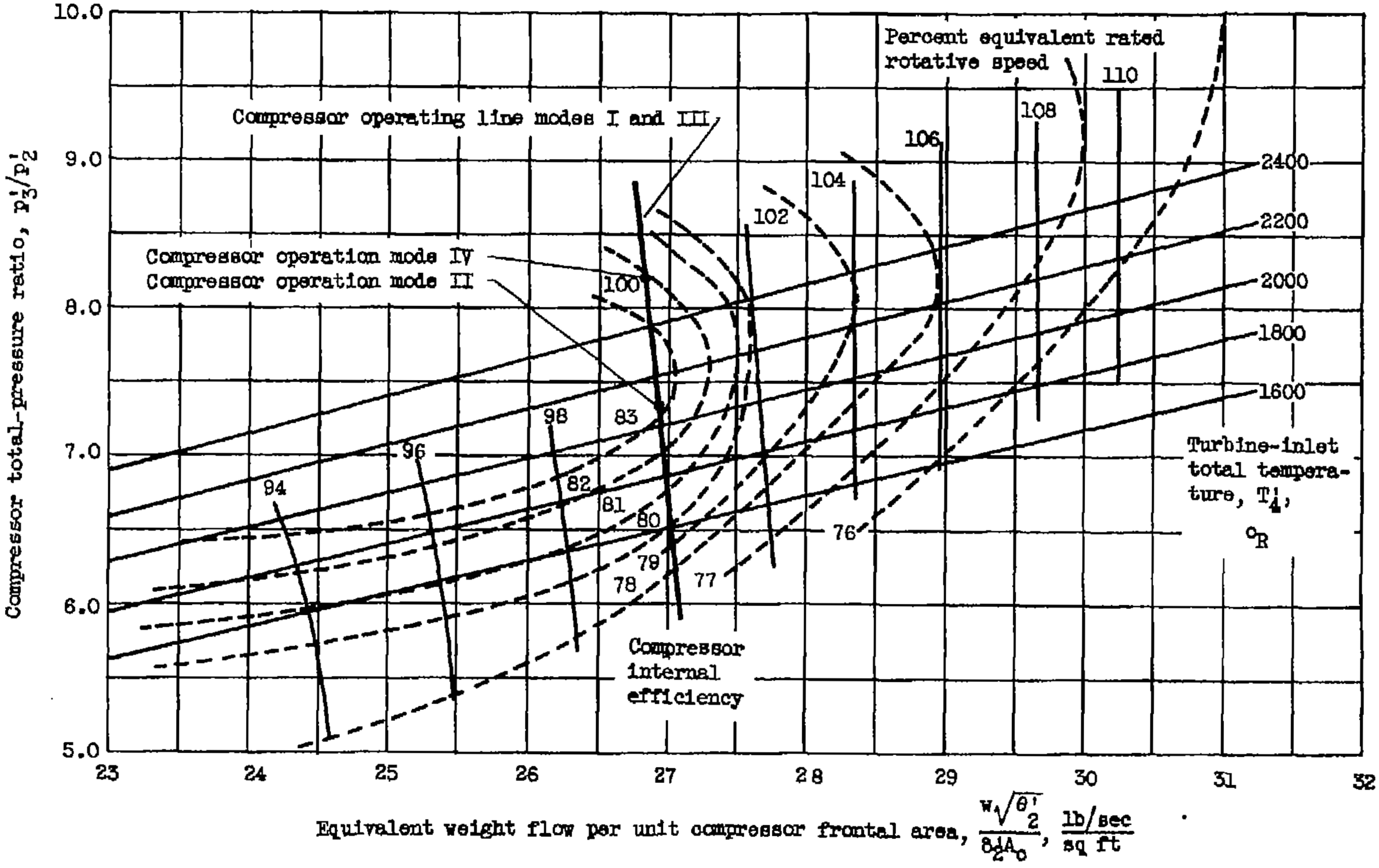
1. Davison, Elmer H.: Turbine Design Considerations for Turbine-Propeller Engine Operating over a Range of Flight Conditions. NACA RM E53D16, 1953.

2. English, Robert E., and Wachtl, William W.: Charts of Thermodynamic Properties of Air and Combustion Products from 300° to 3500° R. NACA TN 2071, 1950.



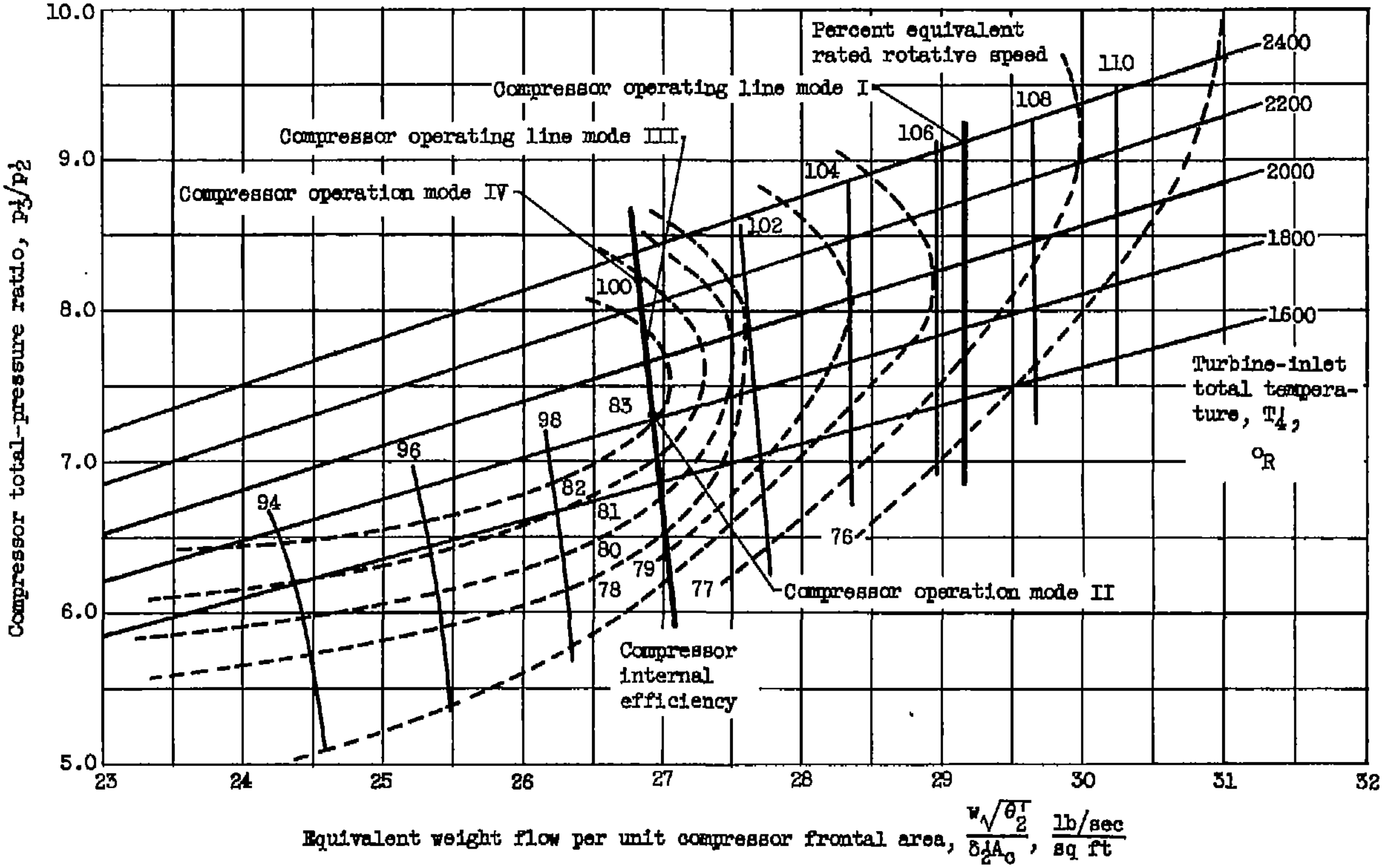
(a) Compressor performance map (ref. 1).

Figure 1. - Effect of flight condition and mode of engine operation on compressor performance.



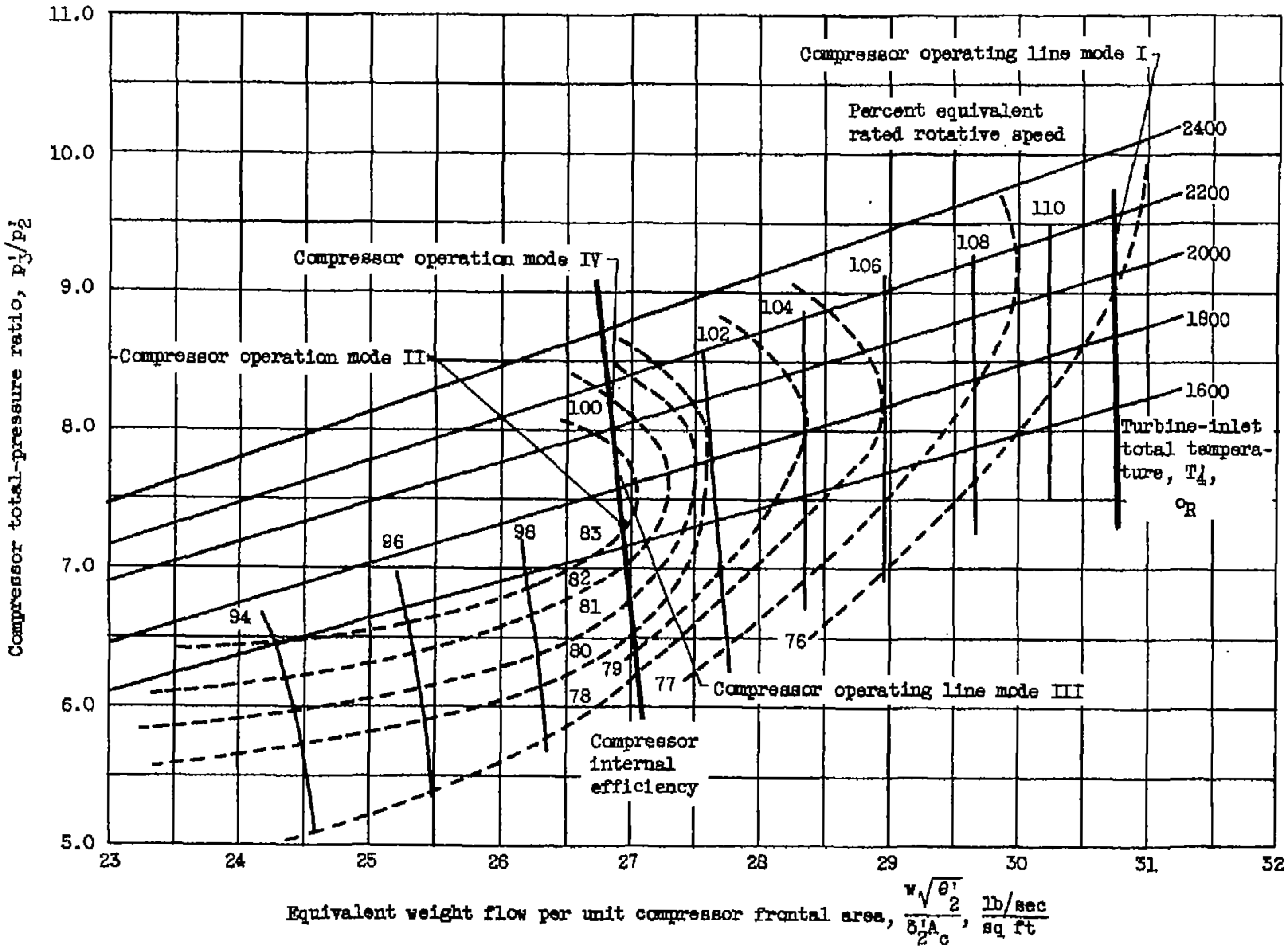
(b) Compressor performance for sea-level static flight condition (condition 0).

Figure 1. - Continued. Effect of flight condition and mode of engine operation on compressor performance.



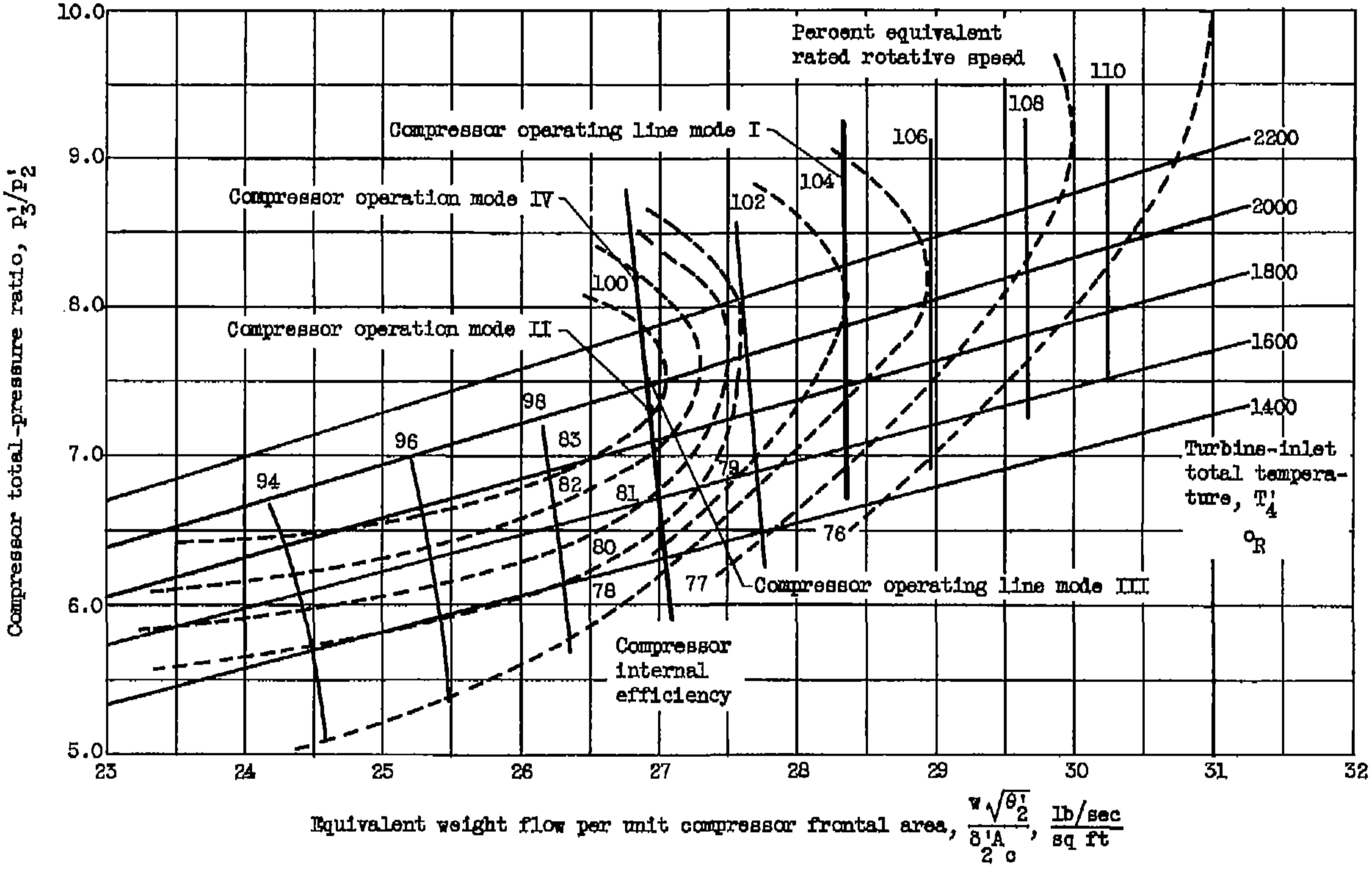
(c) Compressor performance for 600 mph at 40,000 feet (condition A).

Figure 1. - Continued. Effect of flight condition and mode of engine operation on compressor performance.



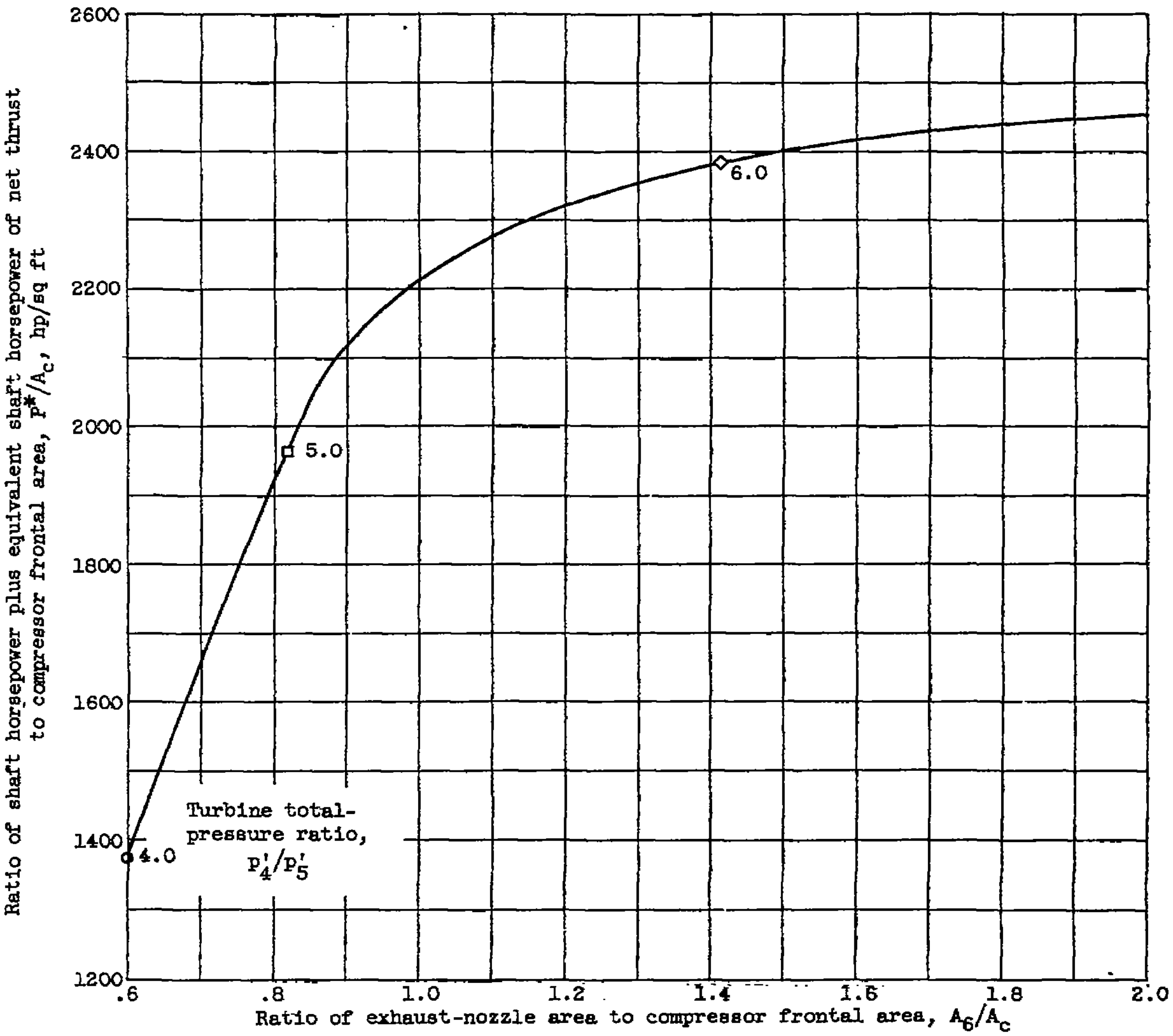
(d) Compressor performance for 400 mph at 40,000 feet (condition B).

Figure 1. - Continued. Effect of flight condition and mode of engine operation on compressor performance.



(e) Compressor performance for 400 mph at 19,000 feet (condition C).

Figure 1. - Concluded. Effect of flight condition and mode of engine operation on compressor performance.



(a) Modes I to III. Turbine-inlet total temperature, 2060° R.

Figure 2. - Effect of flight condition and mode of engine operation on engine design requirements. Flight condition 0 (sea-level static or take-off).

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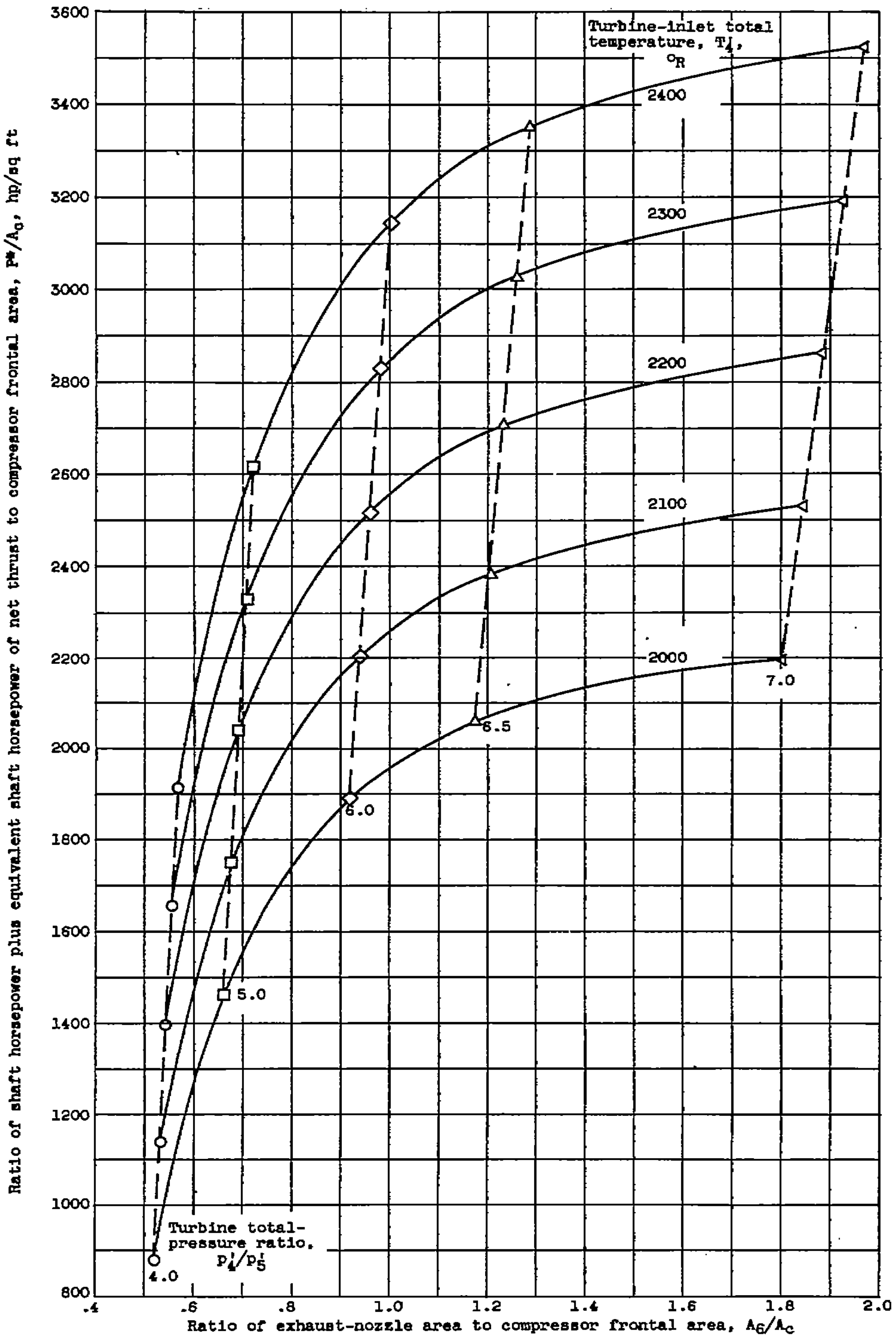
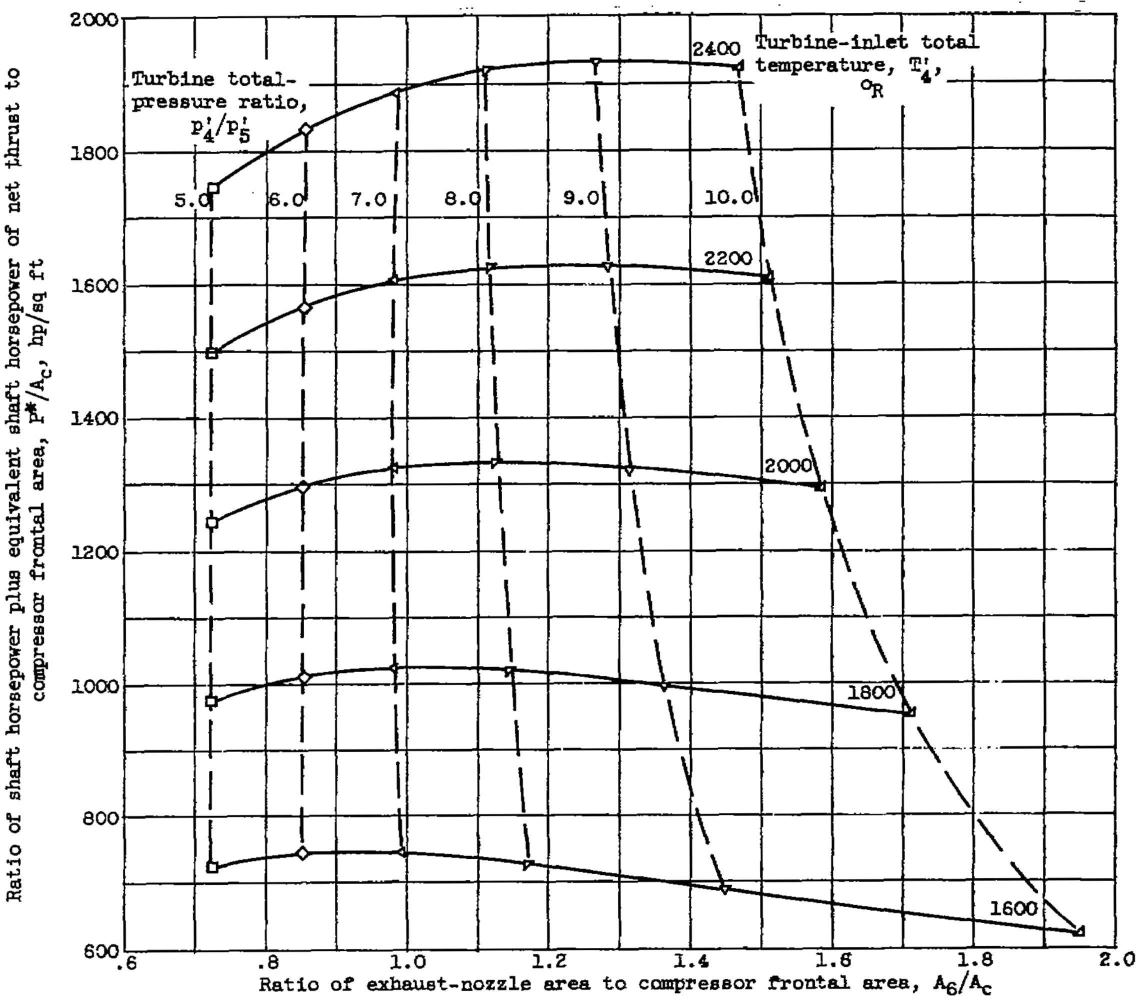


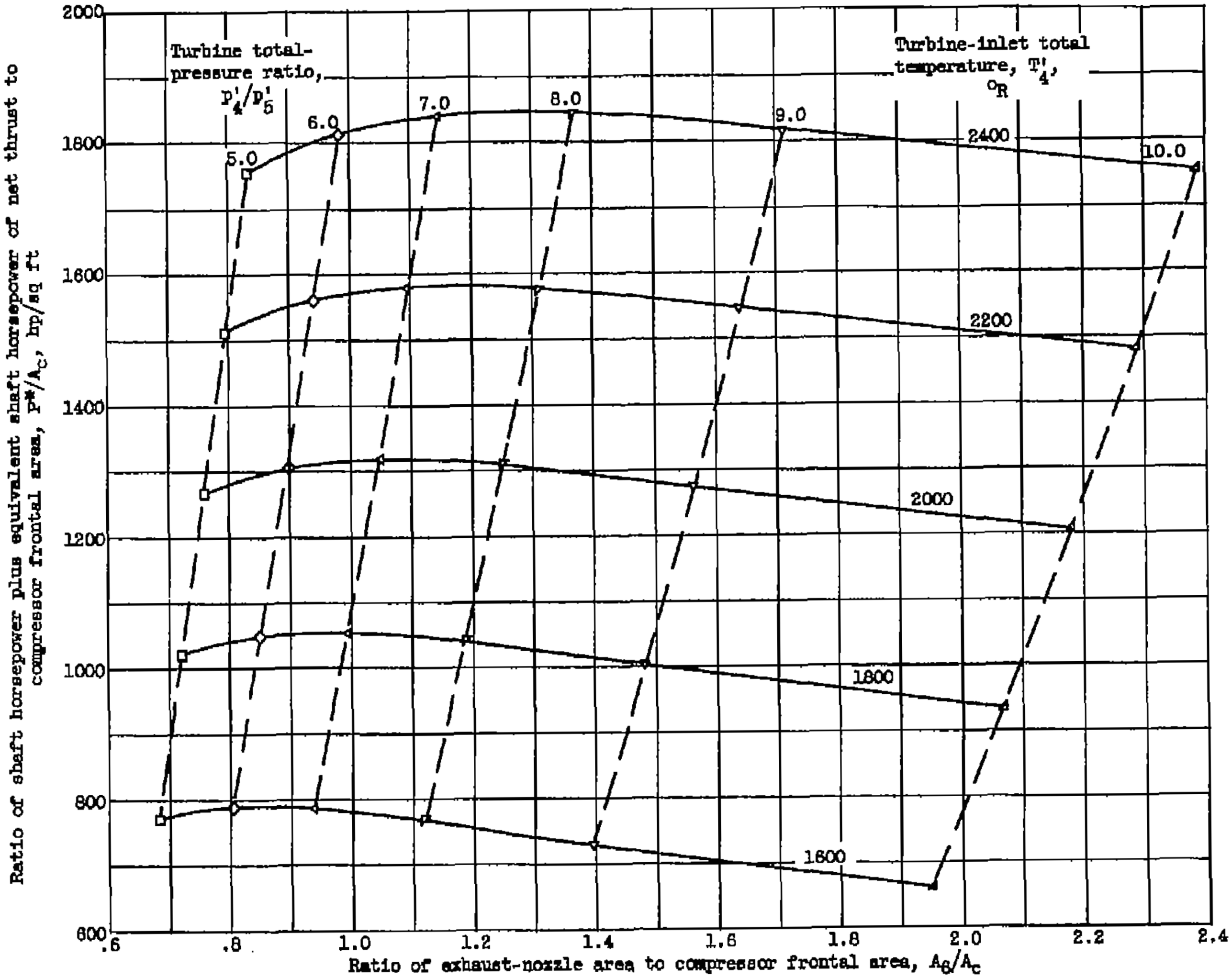
(b) Mode IV.

Figure 2. - Concluded. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition 0 (sea-level static or take-off).



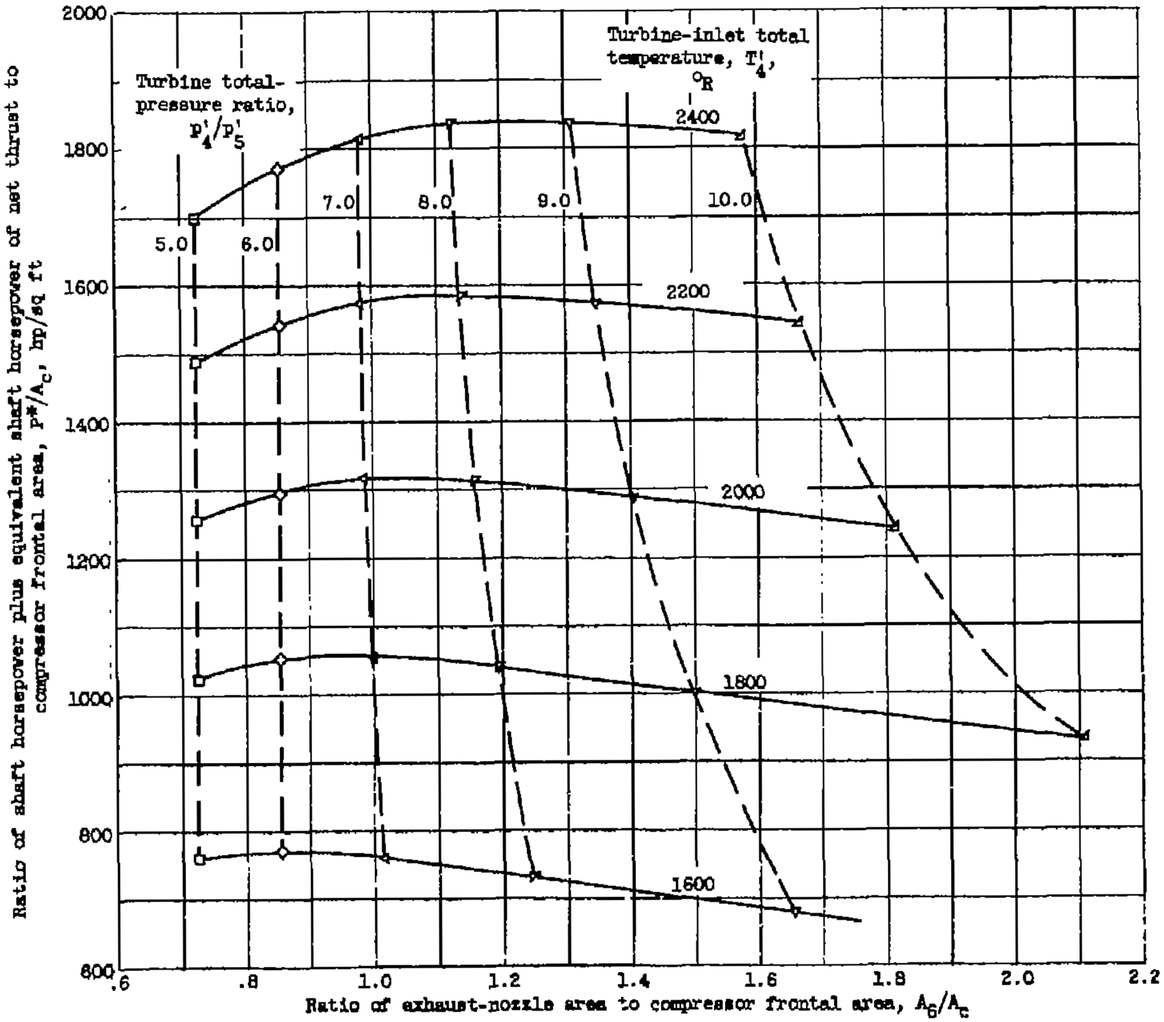
(a) Mode I.

Figure 3. - Effect of flight condition and mode of engine operation on engine design requirements. Flight condition A (600 mph at 40,000 ft).



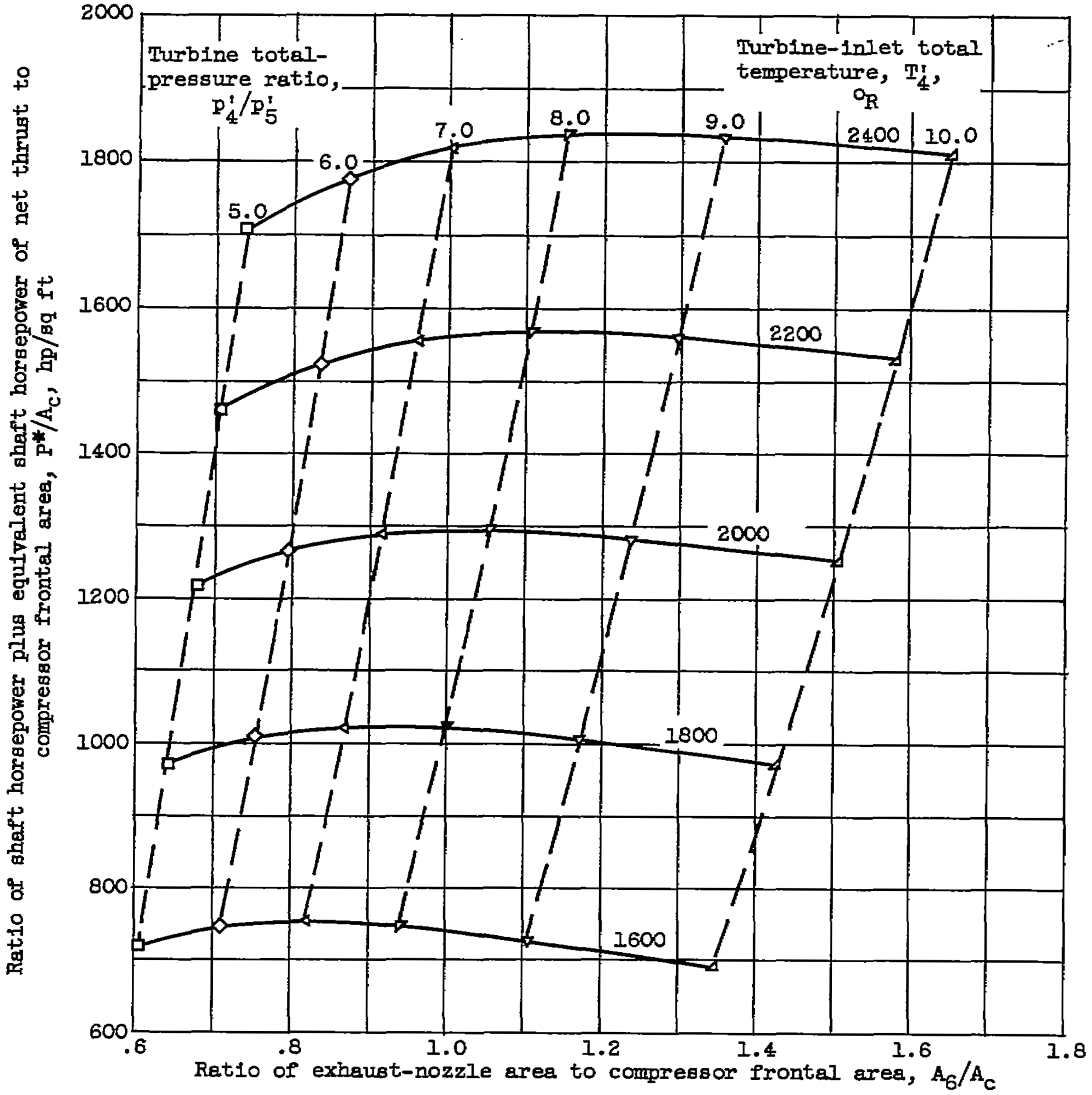
(b) Mode II.

Figure 3. - Continued. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition A (600 mph at 40,000 ft).



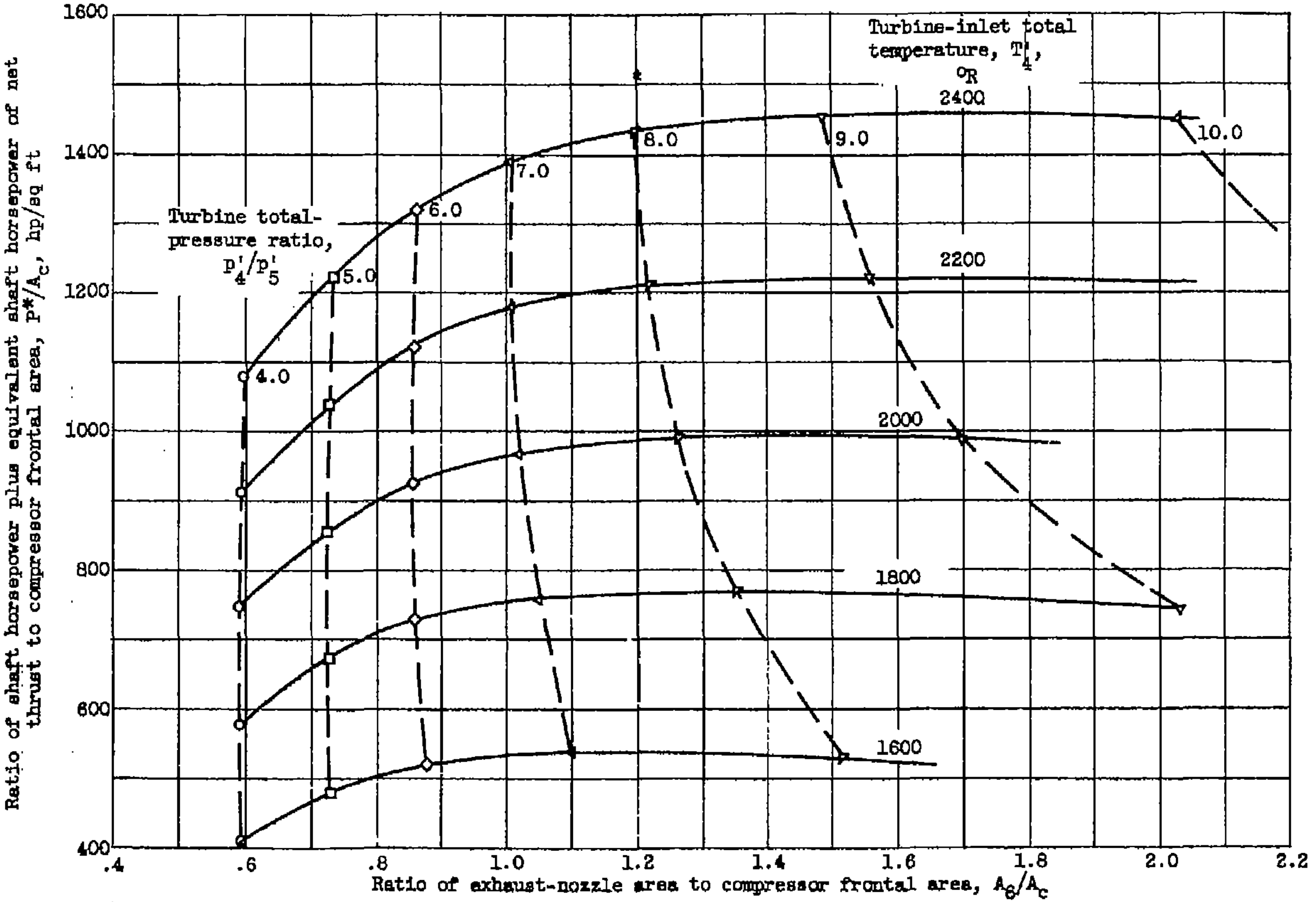
(c) Mode III.

Figure 3. - Continued. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition A (600 mph at 40,000 ft).



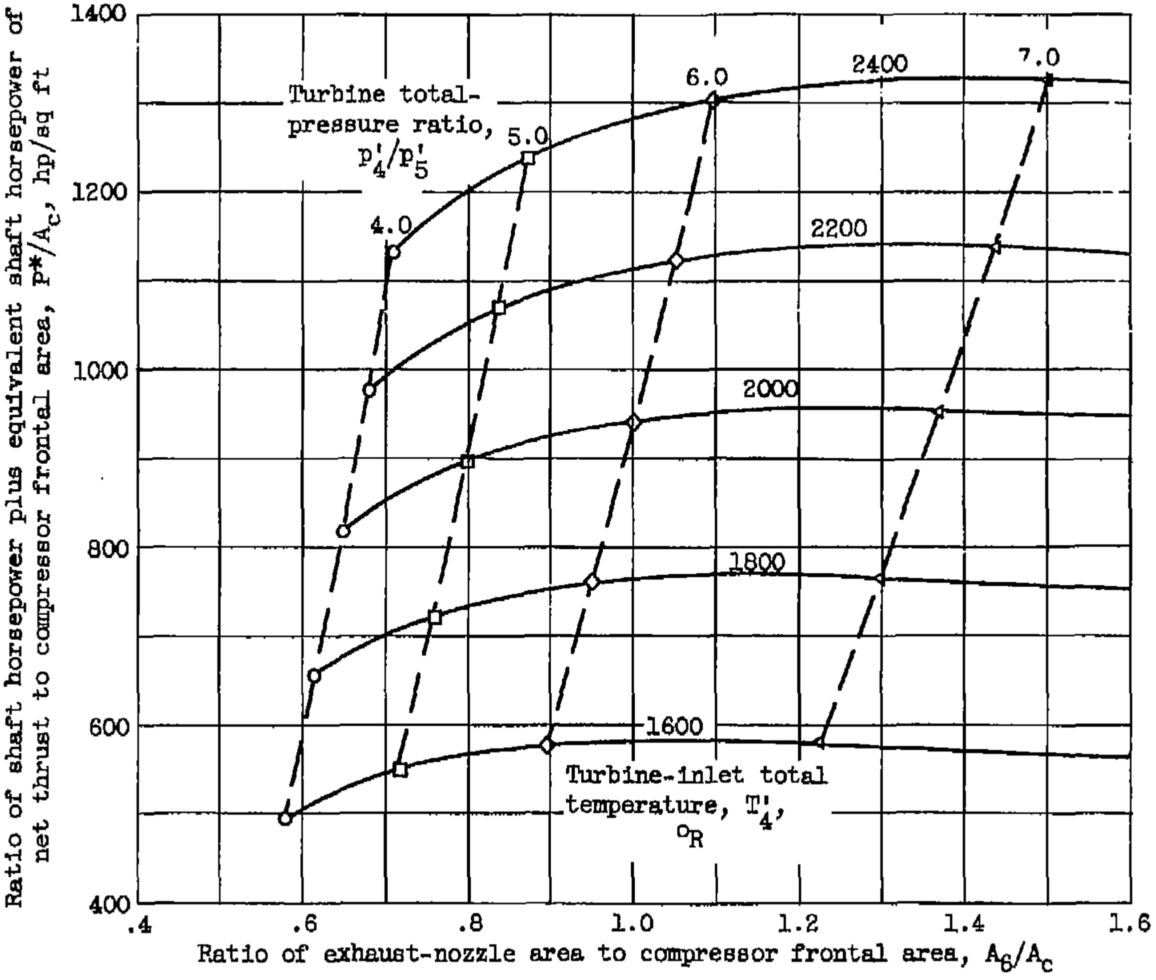
(d) Mode IV.

Figure 3. - Concluded. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition A (600 mph at 40,000 ft).



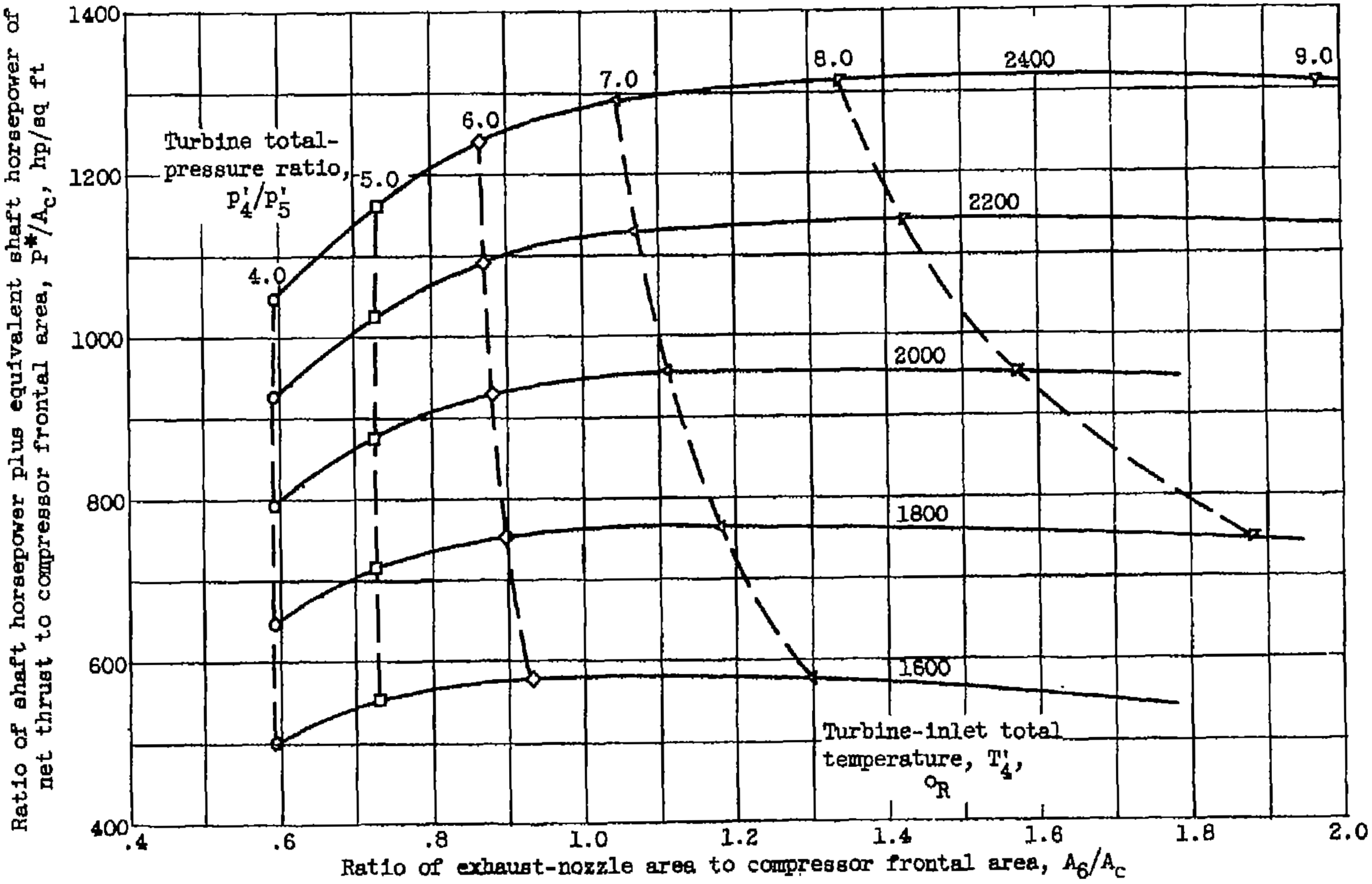
(a) Mode I.

Figure 4. - Effect of flight condition and mode of engine operation on engine design requirements. Flight condition B (400 mph at 40,000 ft).



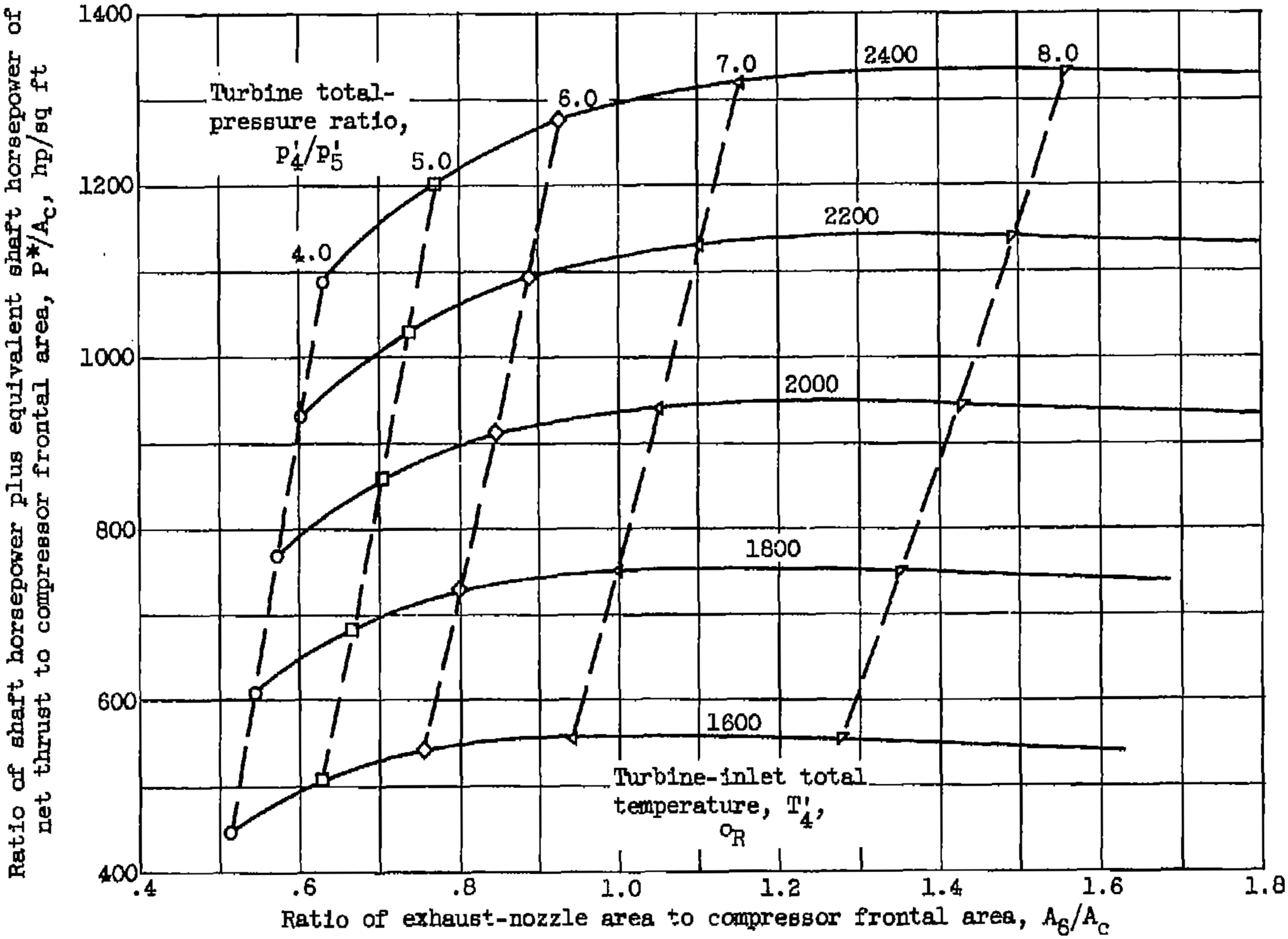
(b) Mode II.

Figure 4. - Continued. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition B (400 mph at 40,000 ft).



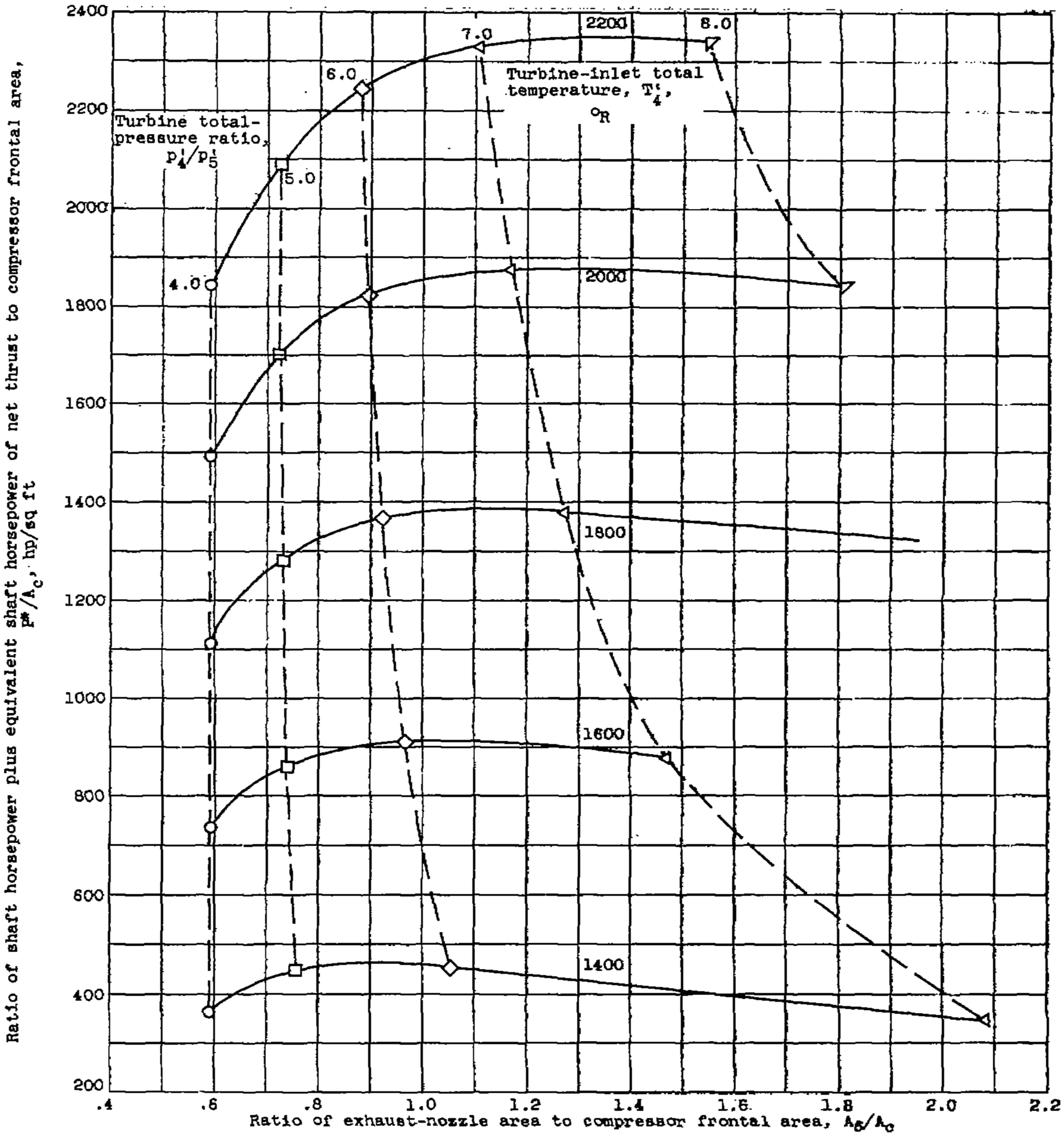
(c) Mode III.

Figure 4. - Continued. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition B (400 mph at 40,000 ft).



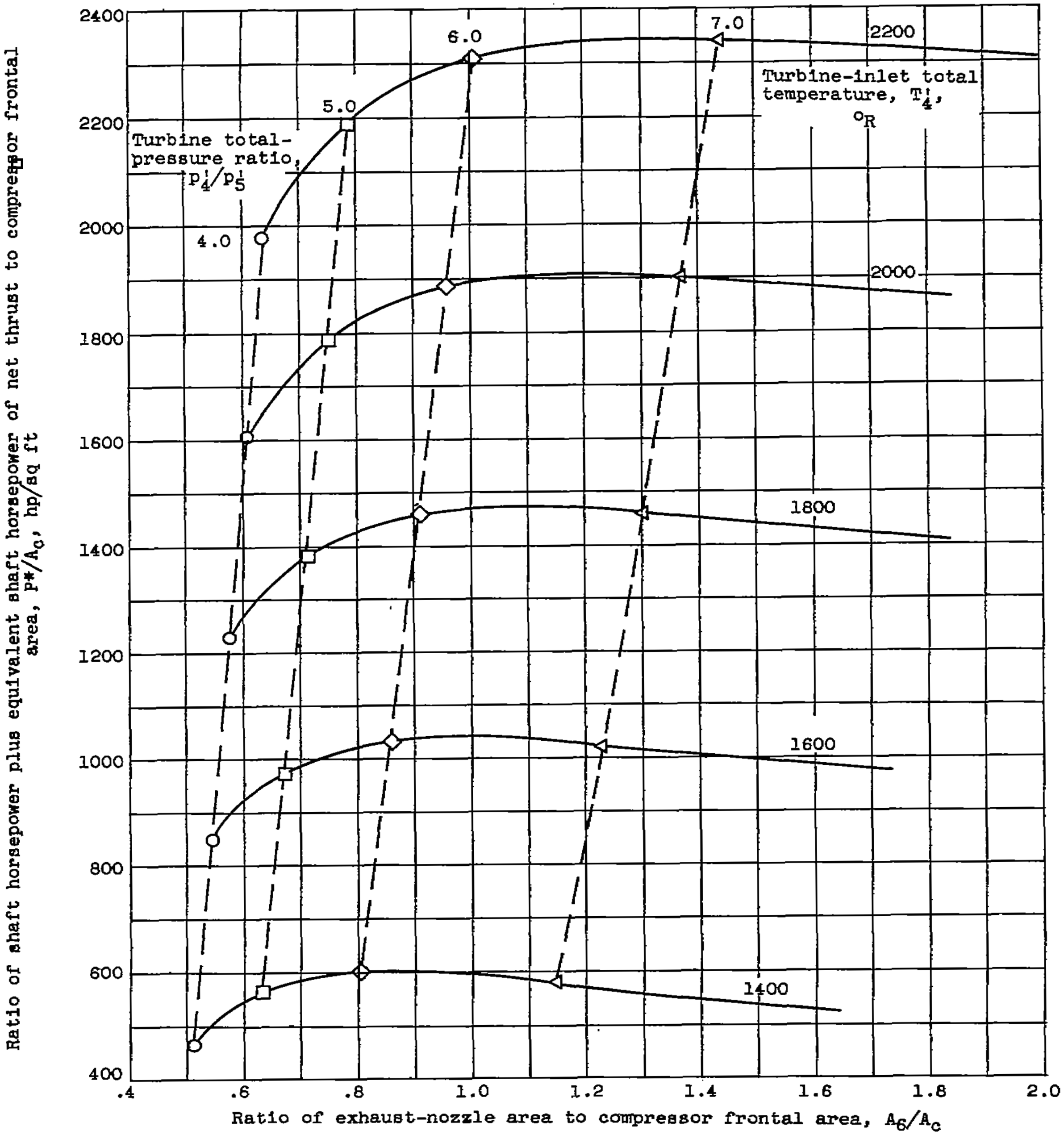
(d) Mode IV.

Figure 4. - Concluded. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition B (400 mph at 40,000 ft).



(a) Mode I.

Figure 5. - Effect of flight condition and mode of engine operation on engine design requirements. Flight condition C (400 mph at 19,000 ft).



(b) Mode II.

Figure 5. - Continued. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition C (400 mph at 19,000 ft).

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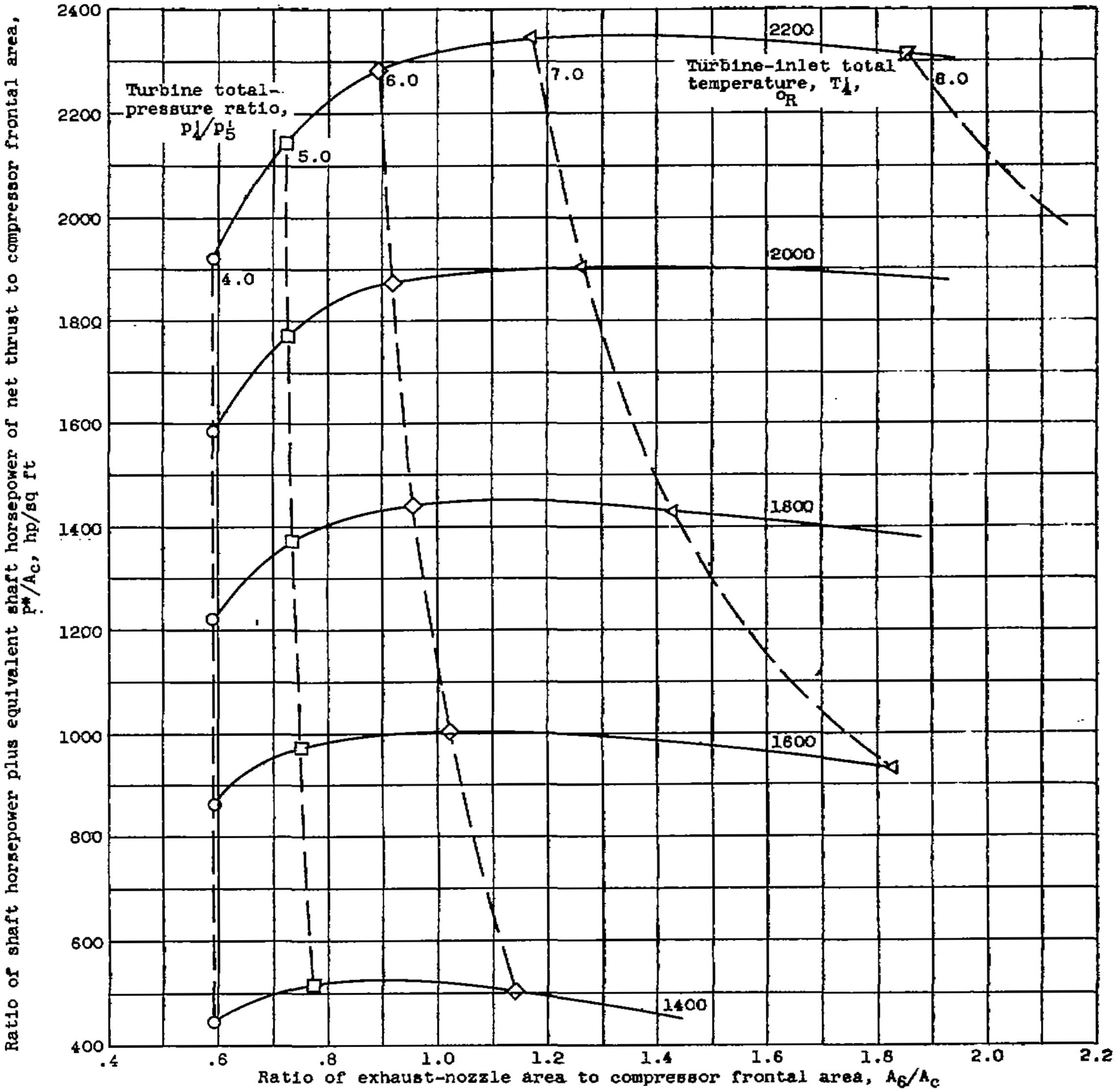

(c) Mode III.

Figure 5. - Continued. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition C (400 mph at 19,000 ft).

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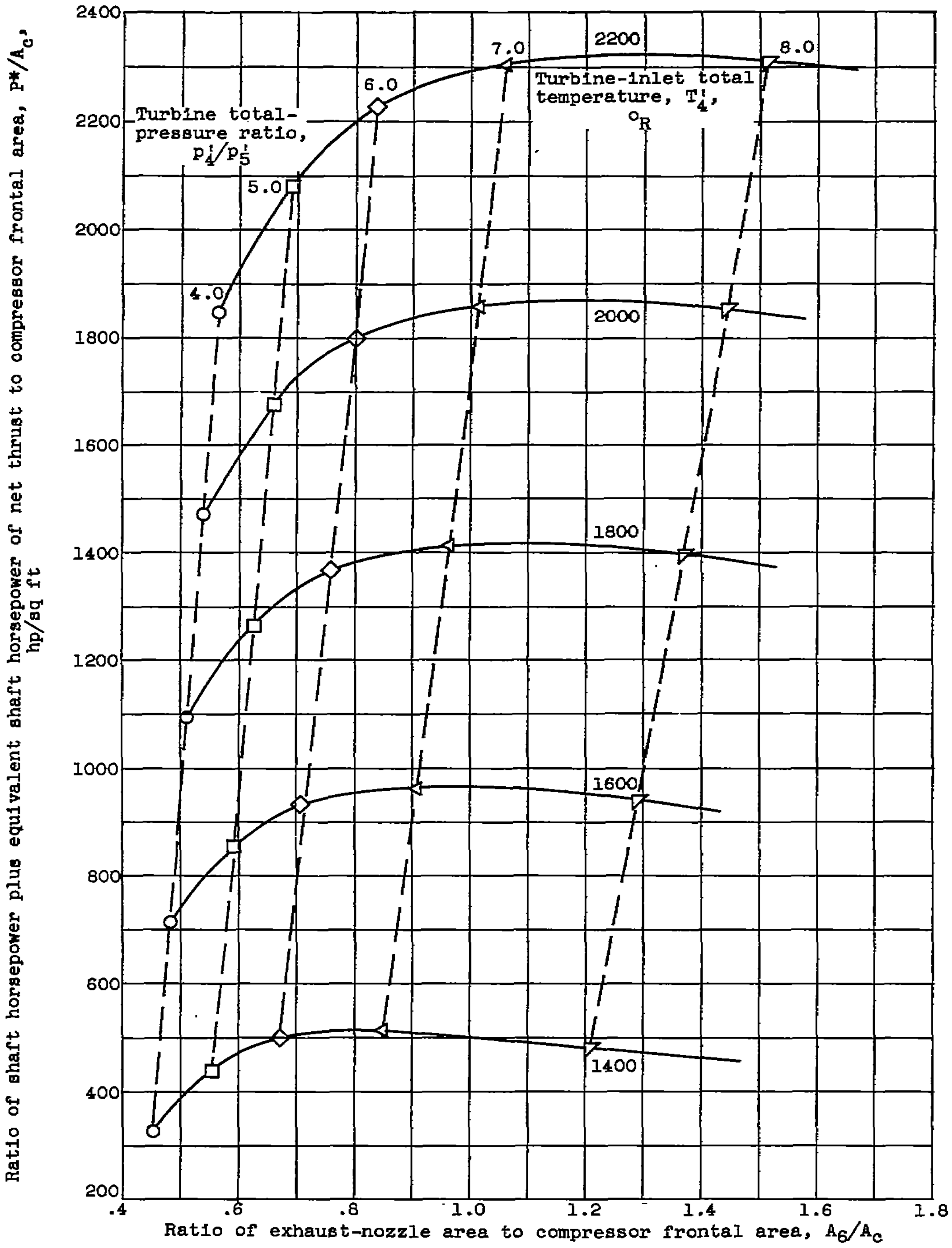

(d) Mode IV.

Figure 5. - Concluded. Effect of flight condition and mode of engine operation on engine design requirements. Flight condition C (400 mph at 19,000 ft).

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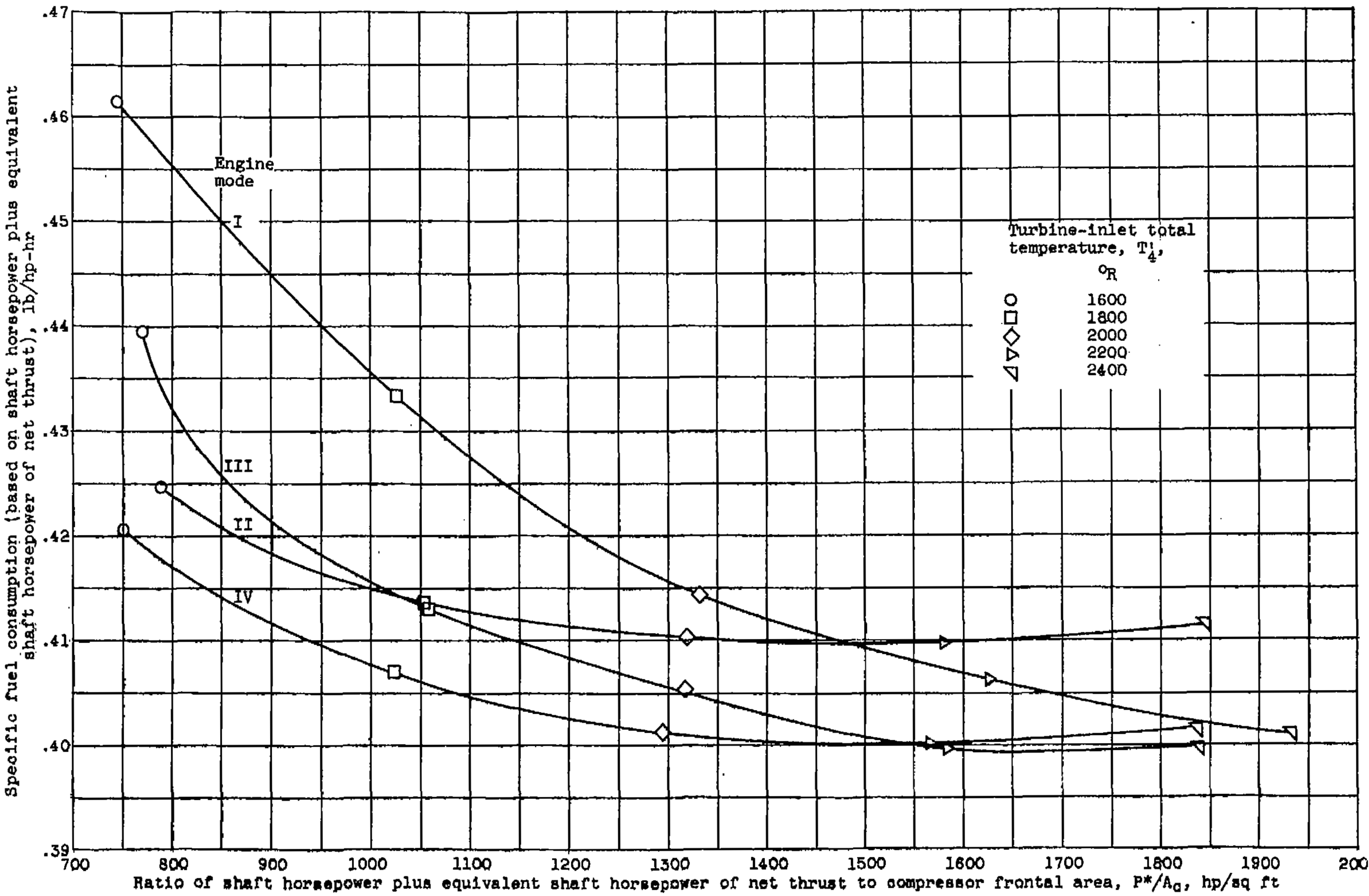
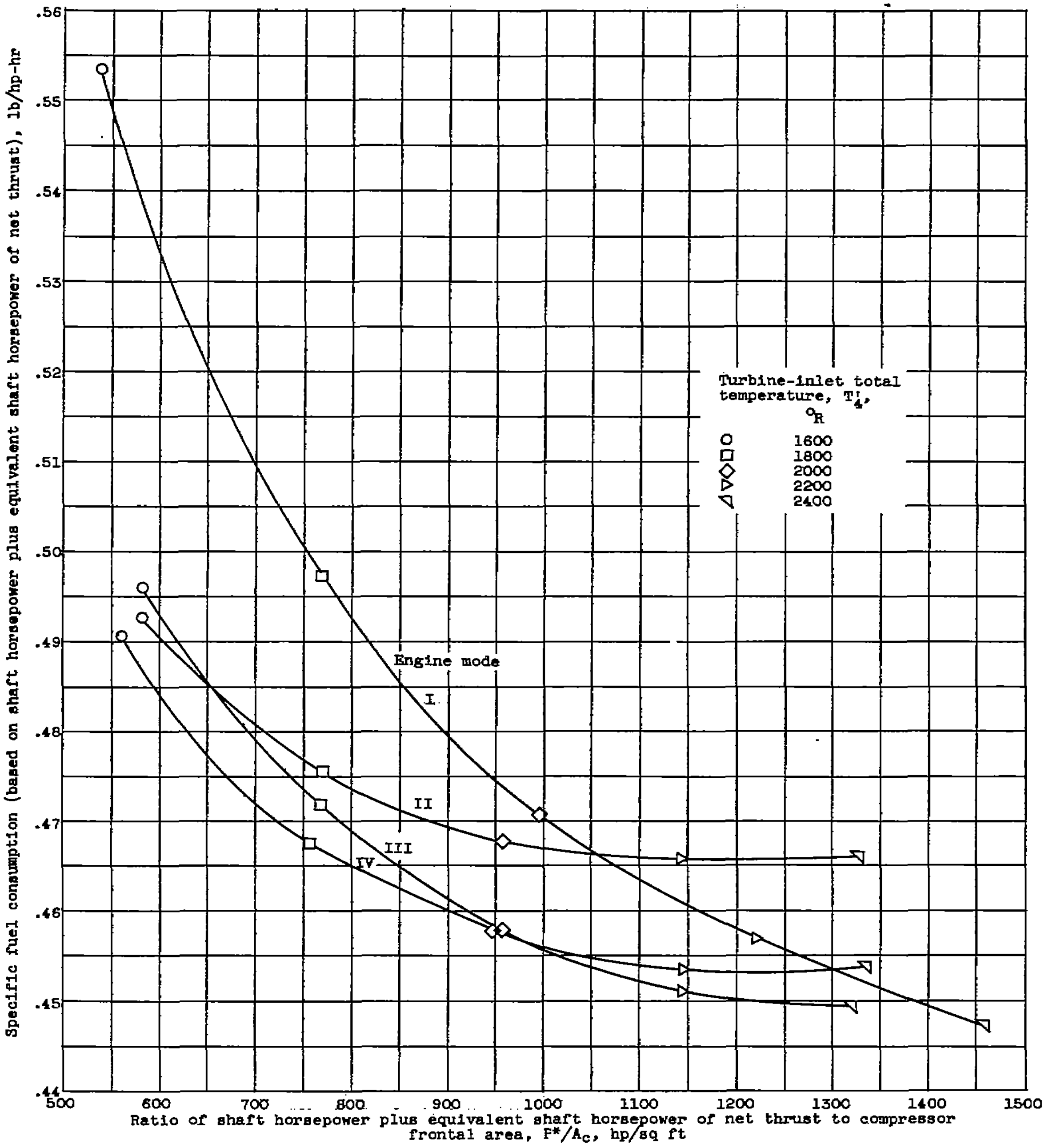


(a) Flight condition A.

Figure 6. - Variation of specific fuel consumption with power output for variable exhaust-nozzle area. Minimum specific fuel consumption.



(b) Flight condition B.

Figure 6. - Continued. Variation of specific fuel consumption with power output for variable exhaust-nozzle area. Minimum specific fuel consumption.

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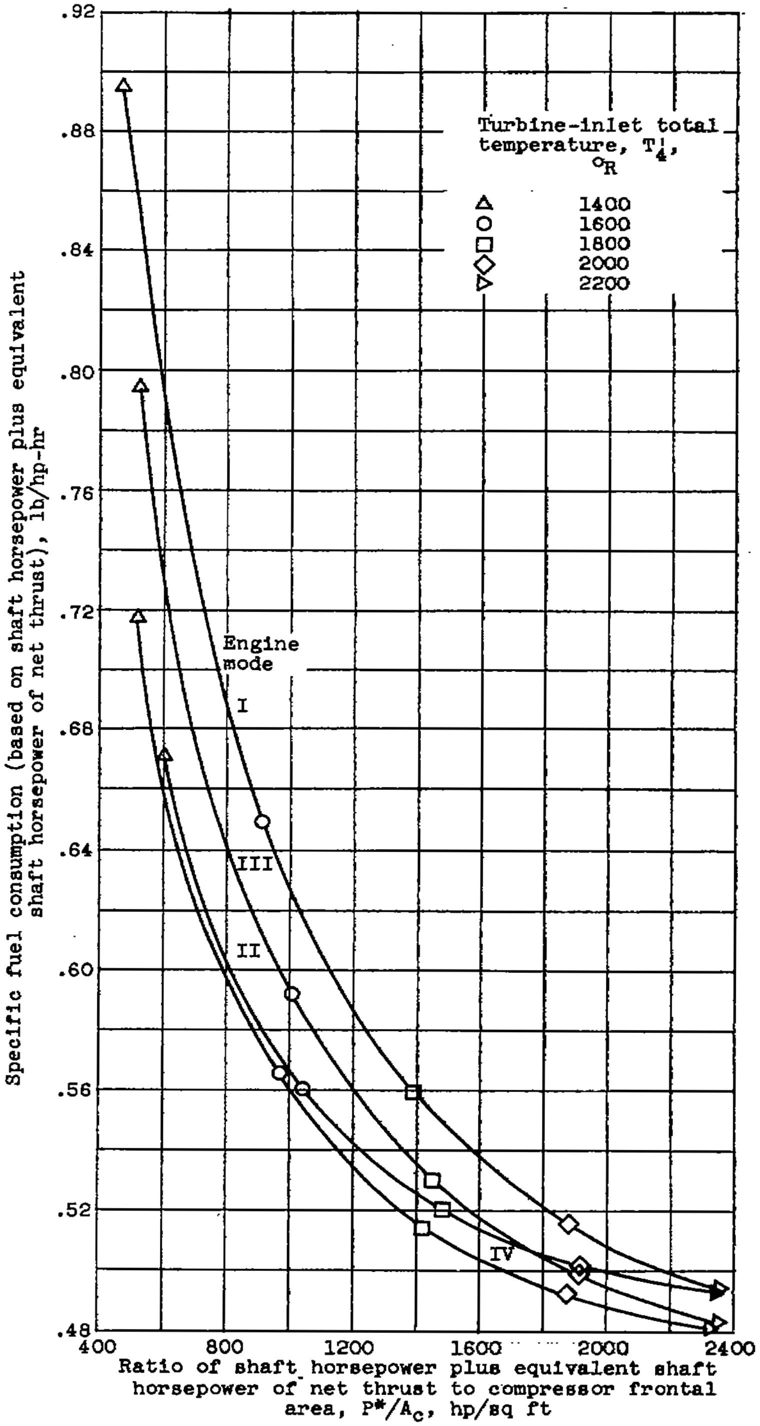
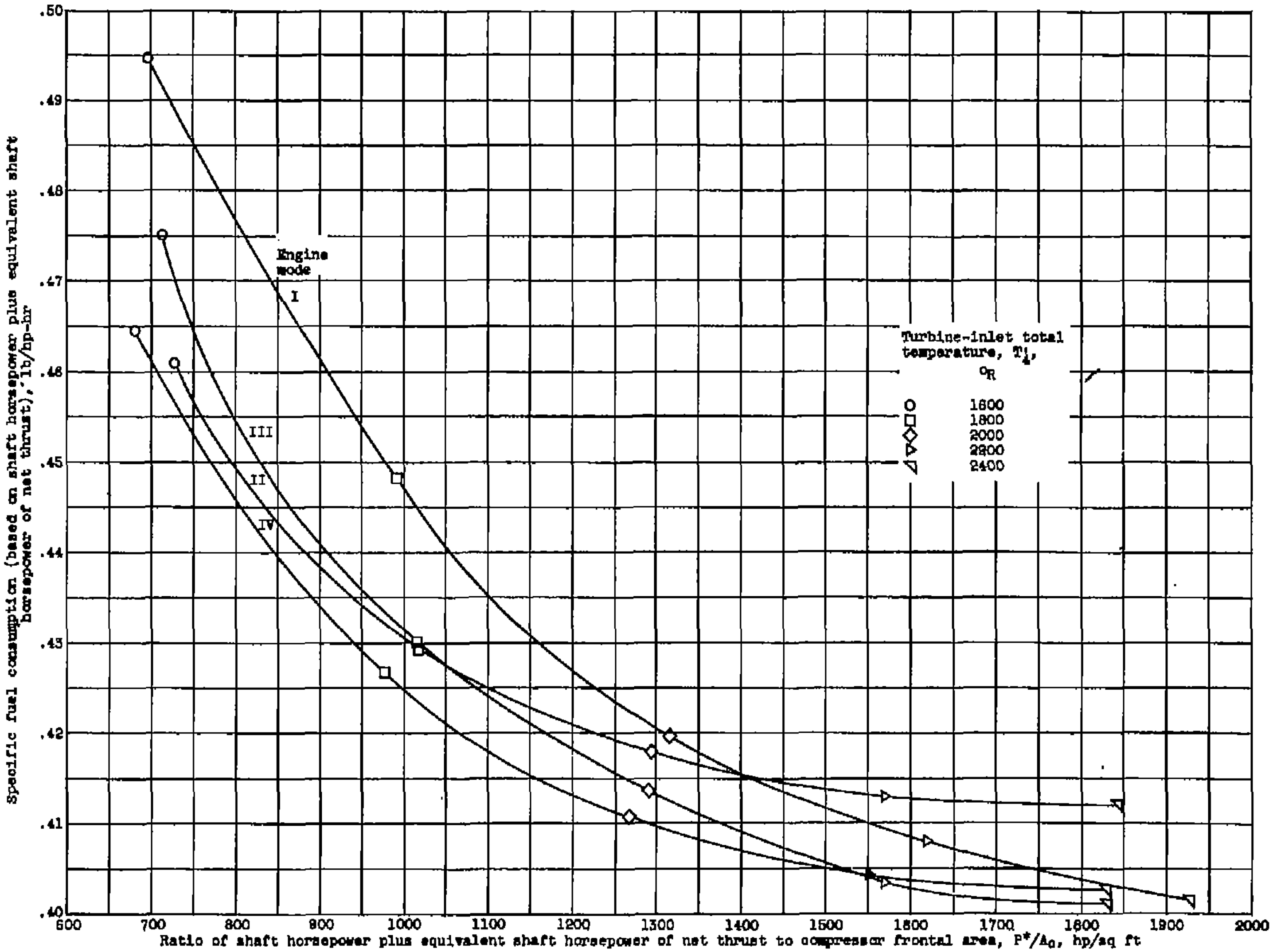


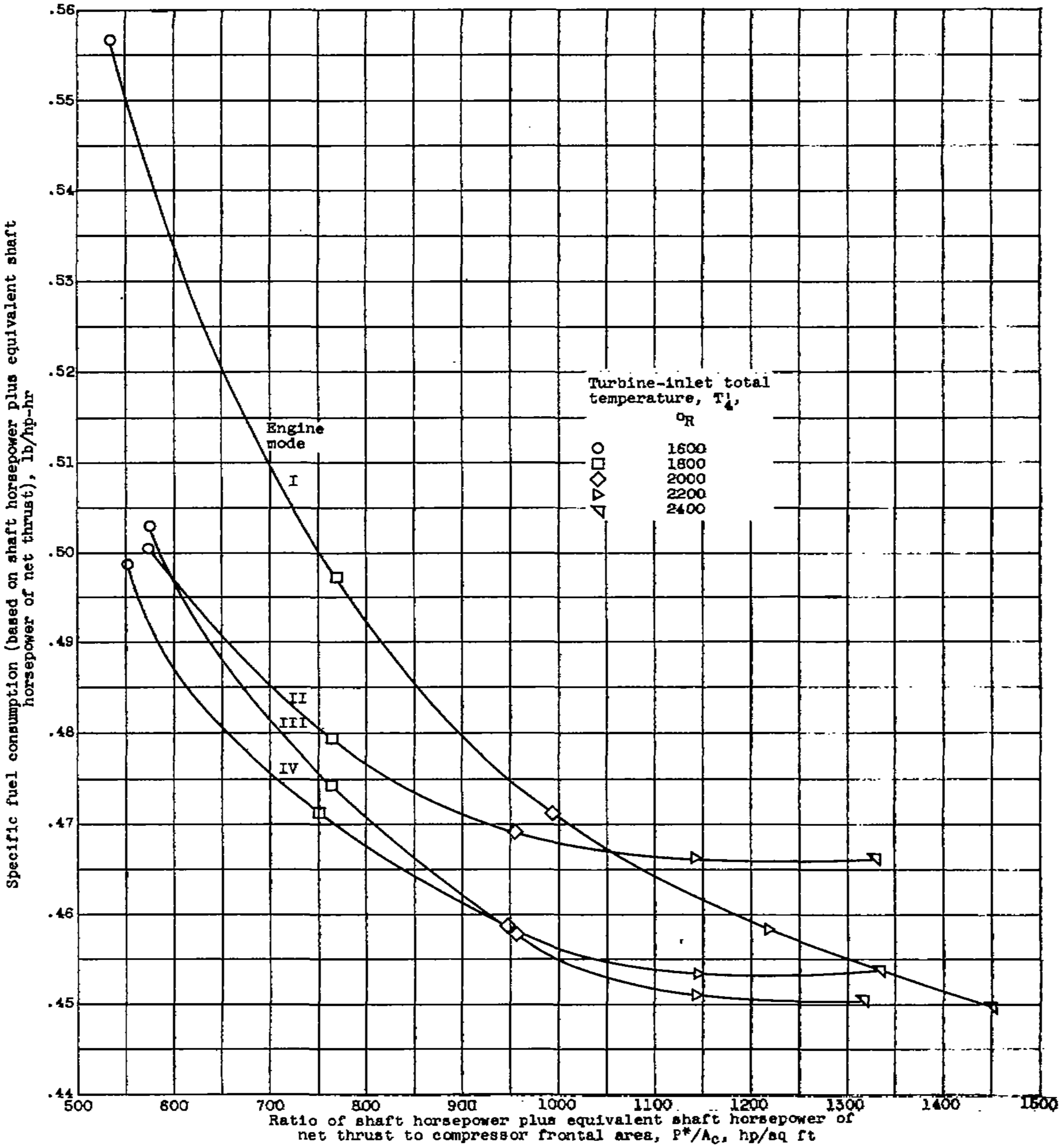
(c) Flight condition C.

Figure 6. - Concluded. Variation of specific fuel consumption with power output for variable exhaust-nozzle area. Minimum specific fuel consumption.



(a) Flight condition A.

Figure 7. - Variation of specific fuel consumption with power output for constant exhaust-nozzle area. Ratio of exhaust-nozzle area to compressor frontal area, 1.40.



(b) Flight condition B.

Figure 7. - Concluded. Variation of specific fuel consumption with power output for constant exhaust-nozzle area. Ratio of exhaust-nozzle area to compressor frontal area, 1.40.

[redacted]