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RESEARCH MEMORANDUM

MATCHING CHARACTERISTICS OF J35-A-23 COMPRESSOR AND TWO-STAGE TURBINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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SUMMARY

Component data on the J35-A-23 compressor and two-stage turbine were used to determine the problems encountered in matching the two units for operation in a turbojet engine. Possible operating regions and an equilibrium operating line for the assumed conditions of zero flight speed and a jet nozzle area approximately $5\frac{1}{2}$ percent greater than the wide-open nozzle area were determined. The compressor surge line, the turbine power limit line, and the design turbine inlet to compressor inlet total-temperature ratio line severely restricted the possible operating regions above 65 percent of compressor equivalent design speed.

Engine operation at design speed required a ratio of turbine inlet to compressor inlet total temperature approximately 22 percent higher than the design value which was 4.04. An even higher temperature ratio was required to obtain maximum thrust at design speed by closing the jet nozzle. If no auxiliary means, such as air bleed, were used, no stable operating region existed for a speed range between approximately 76 and 83 percent of compressor equivalent design speed. The equilibrium operating line for zero flight speed and a jet nozzle area $5\frac{1}{2}$ percent greater than the engine-wide-open nozzle area entered the compressor surge region at approximately 65 percent equivalent design speed and re-entered the stable region at approximately 83 percent equivalent design speed.

INTRODUCTION

As part of a study of high-power multistage axial-flow compressors and turbines, investigations are being conducted at the NACA Lewis laboratory to determine the performance characteristics of the 16-stage compressor and two-stage turbine of the J35-A-23 turbojet engine. The performances of the compressor and turbine as determined from component investigations over a wide range of operating conditions are presented in references 1 and 2, respectively. The problems encountered in matching these two components for engine operation from approximately 50 percent of design speed to design speed and maximum thrust are investigated herein. Changes which must be made to obtain design performance and to improve acceleration to design speed are noted.

The matching method of reference 3 was used in determining operating points which were possible when the units were directly coupled together. An equilibrium compressor operating line was obtained from the component performance characteristics for the assumed engine operating conditions of zero flight speed and a jet nozzle area approximately $5\frac{1}{2}$ percent greater than the wide-open nozzle condition. Acceleration of the engine from 50-percent design speed to design speed was investigated along this line. Operation along the design speed line to obtain maximum thrust was then investigated. The matching method was based on the assumption that values of fuel-air ratio, burner total-pressure ratio, and auxiliary torque parameter remained constant over the entire operating range.

SYMBOLS

The following symbols are used in this report:

f	ratio of fuel flow to air flow
ΔH	stagnation enthalpy change, Btu/lb
J	mechanical equivalent of heat, 778 ft-lb/Btu
K	$\frac{60J}{2\pi}$, sec (ft-lb)/min Btu
N	rotative speed, rpm
P	total pressure, lb/sq ft
P_a	power for accessories and friction losses, ft-lb/min
p	static pressure, lb/sq ft
T	total temperature, $^{\circ}R$
W	weight flow, lb/sec
δ	ratio of total pressure to NACA standard sea-level pressure (2116 lb/sq ft)

θ ratio of total temperature to NACA standard sea-level temperature (518.4° R)

Subscripts:

t turbine

c compressor

0 ambient conditions

1 compressor inlet

2 compressor outlet

3 turbine inlet

4 turbine outlet

5 tail-pipe measuring station

METHODS AND PROCEDURE

Equilibrium operation of a compressor and turbine as a directly coupled unit requires that three conditions be satisfied; the compressor rotative speed must equal the turbine speed, the air weight flow into the compressor plus the fuel weight flow added in the burners must equal the weight flow into the turbine when no air is bled from the engine, and the turbine power or torque output must equal the power or torque required to drive the compressor plus the power required to drive auxiliary equipment and to overcome mechanical losses. A fourth condition must be satisfied to obtain an operating line when the components are installed in an engine. The over-all pressure ratio resulting from ram, compressor compression, and pressure loss in the burners must equal that resulting from expansion in the turbine, tail pipe, and jet nozzle.

These requirements are restated in the following equations, which are used to determine engine operating points by the method of reference 3

$$\frac{W_c N}{60\delta_2}\left[\frac{\delta_2}{\delta_3}(1+f)\right] = \frac{W_t N}{60\delta_3} \tag{1}$$

$$K\,\frac{W_c \Delta H_c}{N\delta_2}\left(\frac{\delta_2}{\delta_3}\right) + \frac{P_a}{N\delta_3} = K\,\frac{W_t \Delta H_t}{N\delta_3} \tag{2}$$

$$\frac{T_3}{T_1} = \left(\frac{\frac{N_c}{\sqrt{\theta_1}}}{\frac{N_t}{\sqrt{\theta_3}}}\right)^2 \tag{3}$$

$$\frac{P_1}{p_0}\left(\frac{P_2}{P_1}\right)\frac{P_3}{P_2} = \frac{P_3}{P_4}\left(\frac{P_4}{p_5}\right)\frac{p_5}{p_0} \tag{4}$$

The weight flow and torque requirements are satisfied by plotting compressor and turbine performance as a torque parameter (equation 2) against a flow parameter (equation 1) for constant percentages of design equivalent compressor and turbine speed. Intersections of the compressor and turbine speed lines give possible operating points. The ratio of turbine inlet to compressor inlet temperature required to satisfy the speed condition $N_c = N_t$ is calculated for each of these intersection points from equation 3. The engine operating line is determined by superimposing the compressor plot of the torque parameter against flow parameter for constant values of ram-compressor-burner pressure ratio (left side of equation 4) on the turbine plot of the torque parameter against the flow parameter for constant values of the turbine-tail-pipe-nozzle pressure ratio (right side of equation 4). Intersections of equal-pressure-ratio lines give points which define the equilibrium operating line.

The assumptions made in the analysis to determine the matching characteristics of the J35-A-23 compressor and two-stage turbine are: (1) the ratio of total pressure at the compressor outlet to total pressure at the turbine inlet is a constant, $\delta_2/\delta_3 = 1.03$; (2) the ratio of fuel flow to air flow is a constant, $f = 0.02$; (3) the torque required to drive the accessories and to overcome mechanical losses is a constant, $P_a/N\delta_3 = 3.0$ lb-ft. The engine operating line in this analysis is determined for the assumed conditions of zero flight speed $(P_1/p_0 = 1.0)$ and a jet nozzle area equal to 485 square inches (approximately $5\frac{1}{2}$ percent greater than the engine-wide-open nozzle area). The assumed nozzle area is equal to the area at a station in the turbine tail pipe at which performance data were obtained during the investigation of reference 2. The jet nozzle pressure ratio p_5/p_0 is assumed equal to 1.0.

The compressor performance is presented in figure 1(a) as a plot of the torque parameter (the left side of equation 2) against the flow parameter (the left side of equation 1) for constant speeds of 50 to 100 percent of the compressor equivalent design speed of 6100 rpm. The data used were obtained from unpublished results determined in the investigation of a compressor differing from the compressor of reference 1 only with respect to blade tip clearance. The same parameters are presented in figure 1(b) for constant values of turbine inlet to compressor inlet total-pressure ratio. The two-stage turbine performance determined in the investigation of reference 2 is presented in figure 2 as a plot of the torque parameter against the weight-flow parameter for constant speeds of 60 to 130 percent of the turbine equivalent design speed of 3035 rpm. Also shown are contours of constant ratios of turbine inlet total pressure to tail-cone exit static pressure and the envelope of the constant speed lines which represents the turbine power limit (reference 2).

Superposition of figures 1 and 2 gives flow conditions for possible operating points and an operating line for the assumed conditions of zero flight speed and jet nozzle area equal to 485 square inches (the tail-pipe measuring station area). The results of superimposing the component performance curves are presented in figure 3, which is a plot of compressor total-pressure ratio against compressor-outlet weight-flow parameter for constant speeds from 50 to 100 percent of compressor equivalent design speed. The compressor surge line, the equilibrium operating line for zero flight speed and jet nozzle area of 485 square inches, the turbine power limit line, and the design turbine inlet to compressor inlet total-temperature ratio line are also shown.

The area to the right of the turbine power limit line in figure 3 is shaded. Operation in this region is not possible because the turbine power output is insufficient to drive the compressor and accessories.

The operating points in the surge region were obtained by extrapolating the constant pressure-ratio lines of figure 1(b).

DISCUSSION OF RESULTS

The possible operating region for this J35-A-23 compressor-turbine combination is small above 65 percent of compressor equivalent design speed as indicated by figure 3. For a speed range between 76 and 83 percent of compressor equivalent design speed, the surge line and turbine power limit line make stable operation impossible unless auxiliary methods, such as bleed, are used in the compressor. Above 85 percent of compressor equivalent design speed, the line of design turbine inlet to compressor inlet total-temperature ratio further restricts the possible operating region. Operation at compressor equivalent design speed requires a ratio of turbine inlet to compressor inlet total temperature higher than the design value of 4.04.

The operating line presented in this analysis corresponds to equilibrium operation from 50- to 100-percent design engine speed at static flight conditions with the tail-pipe jet nozzle assumed open $5\frac{1}{2}$ percent beyond the normal wide-open position. Therefore, the problems encountered in accelerating the engine are indicated in figure 3 by the operating line from low to high speeds. At low speeds, the operating line follows the compressor surge line very closely. The distance between the two lines represents the accelerating margin. Rapid acceleration would shift the engine operating line in figure 3 to the left or closer to the surge region.

At approximately 65 percent of compressor equivalent design speed, the operating line crosses the surge line into the unstable region. Acceleration to design speed is therefore impossible unless means can be found to move the operating line into the stable region or to move the surge line farther to the left. As is indicated in reference 4, bleeding air from the compressor discharge would move both the operating line and turbine power limit line to the right. Completely alleviating the surge problems by bleed at the compressor discharge alone is considered impractical for the present engine because of the large quantities of air bleed required and the resulting excess power output required of the turbine. Bleeding air from within the compressor would be more desirable because less bleed air and excess turbine power would be required and flow conditions would be improved throughout the compressor, which would result in altered component performance characteristics. Redesign of the compressor to alter the position and shape of the surge line and to increase the efficiency and weight flow at each speed in the critical intermediate speed range would be the most desirable means of alleviating the problems involved in accelerating to high engine speed. In general, it appears that the principal improvements in operation in the intermediate speed range are to be gained by compressor modifications, but modification in the turbine, such as increased turbine exit area, may also result in some improvement. Any turbine change which increases the power available from the turbine will shift the turbine power limit line in figure 3 to higher flow parameter values and tend to alleviate the accelerating problem through intermediate speeds.

At approximately 83 percent of compressor equivalent design speed, the operating line recrosses the surge line into the stable operating region. The operating line then crosses the line of design turbine inlet to compressor inlet temperature ratio at approximately 90 percent of compressor equivalent design speed. Increasing the speed to design requires engine operation at a ratio of turbine inlet to compressor inlet total temperature higher than design.

At or somewhat below design engine speed, the jet nozzle area must be closed down from the wide-open position so as to obtain the large thrust required for take-off. At the operating point shown in figure 3 at design speed, the turbine inlet to compressor inlet total-temperature ratio is approximately 22 percent higher than design. As the nozzle is closed, the operating point moves up the speed line to a higher pressure ratio and a still higher ratio of turbine inlet to compressor inlet total temperature. Operation at design speed, therefore, is not practical unless the components are redesigned so as to move the line of design turbine inlet to compressor inlet temperature ratio to lower values of flow parameter and to move the operating point with wide-open jet nozzle and the turbine power limit line to higher values of flow parameter. Because the compressor efficiency at the design point is approximately 80 percent (reference 1), significant improvements in engine performance at design conditions are not considered obtainable by modification of the compressor. The principal gains are to be made by redesigning the turbine to give efficiencies appreciably higher than the 75 percent at the design point determined in the investigation of reference 2.

Therefore, in accelerating this engine from 50- to 100-percent design speed and take-off thrust, two problems are encountered as a result of the matching characteristics of the compressor and turbine; at intermediate speeds, the operating line passes through the surge region, and at design speed the attainment of design thrust requires a ratio of turbine inlet to compressor inlet total temperature considerably higher than design. Redesign of the components to solve each of these problems will involve compromises because any modification of either component will affect engine operation over the entire speed range. For example, changing the compressor stage loading distribution might alleviate surge at intermediate speeds but, at the same time, adversely affect compressor performance at design speed.

SUMMARY OF RESULTS

The results of the matching analysis of the J35-A-23 compressor and two-stage turbine can be summarized as follows:

1. For the assumed zero flight speed and 485-square-inch jet nozzle area, engine operation at design speed required a ratio of turbine inlet to compressor inlet total temperature approximately 22 percent higher than design, and engine operation for maximum thrust would require an even higher temperature ratio.

2. If no auxiliary means such as compressor air bleed were used, no stable operating region existed for a speed range between approximately 76 and 83 percent of compressor equivalent design speed.

3. The equilibrium operating line, determined for zero flight speed and a jet nozzle area approximately $5\frac{1}{2}$ percent greater than the normal wide-open nozzle area, entered the compressor surge region at approximately 65 percent speed and re-entered the stable region at approximately 83 percent speed.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 6, 1951

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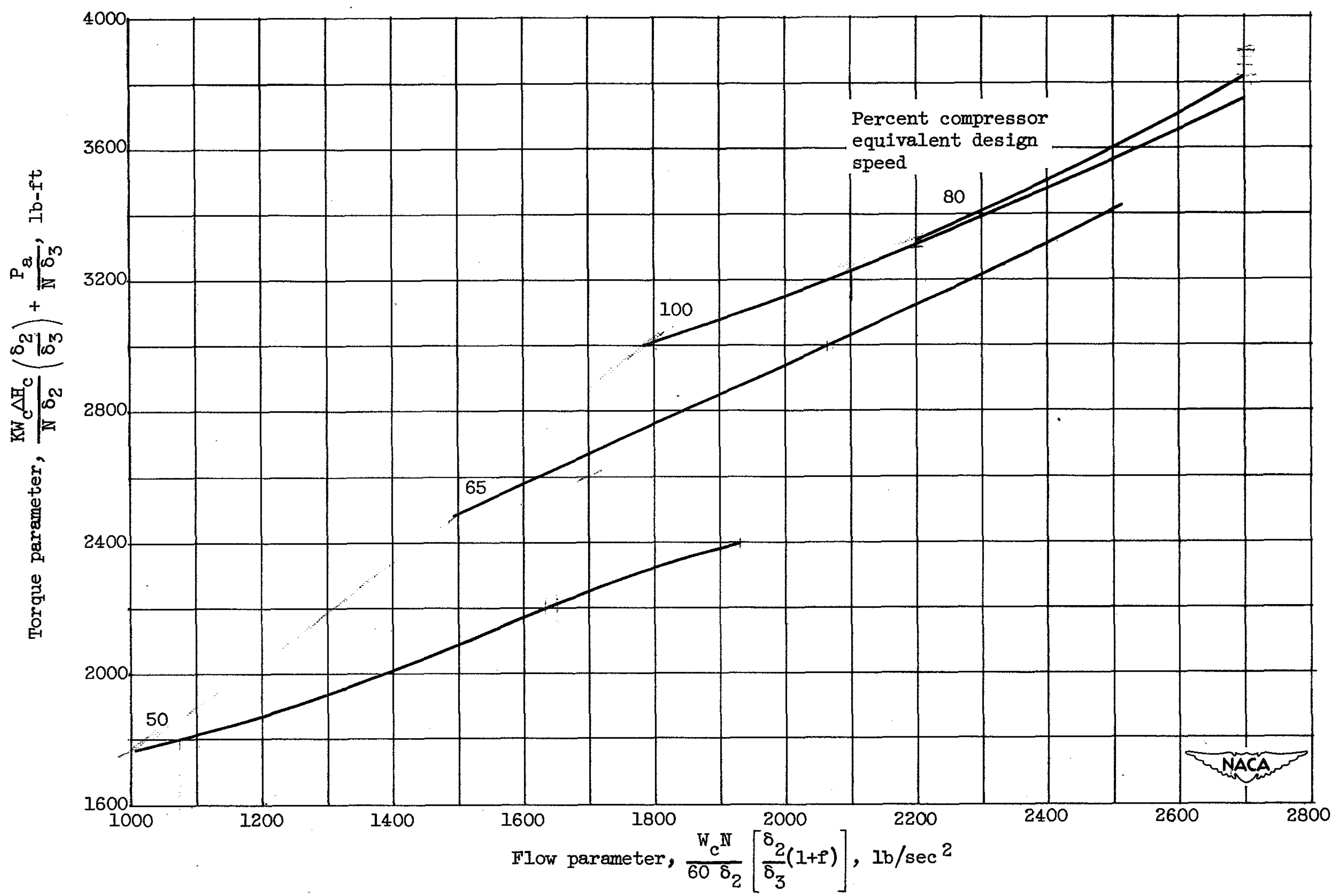

(a) Constant speed.

Figure 1. - J35-A-23 16-stage compressor performance characteristics.

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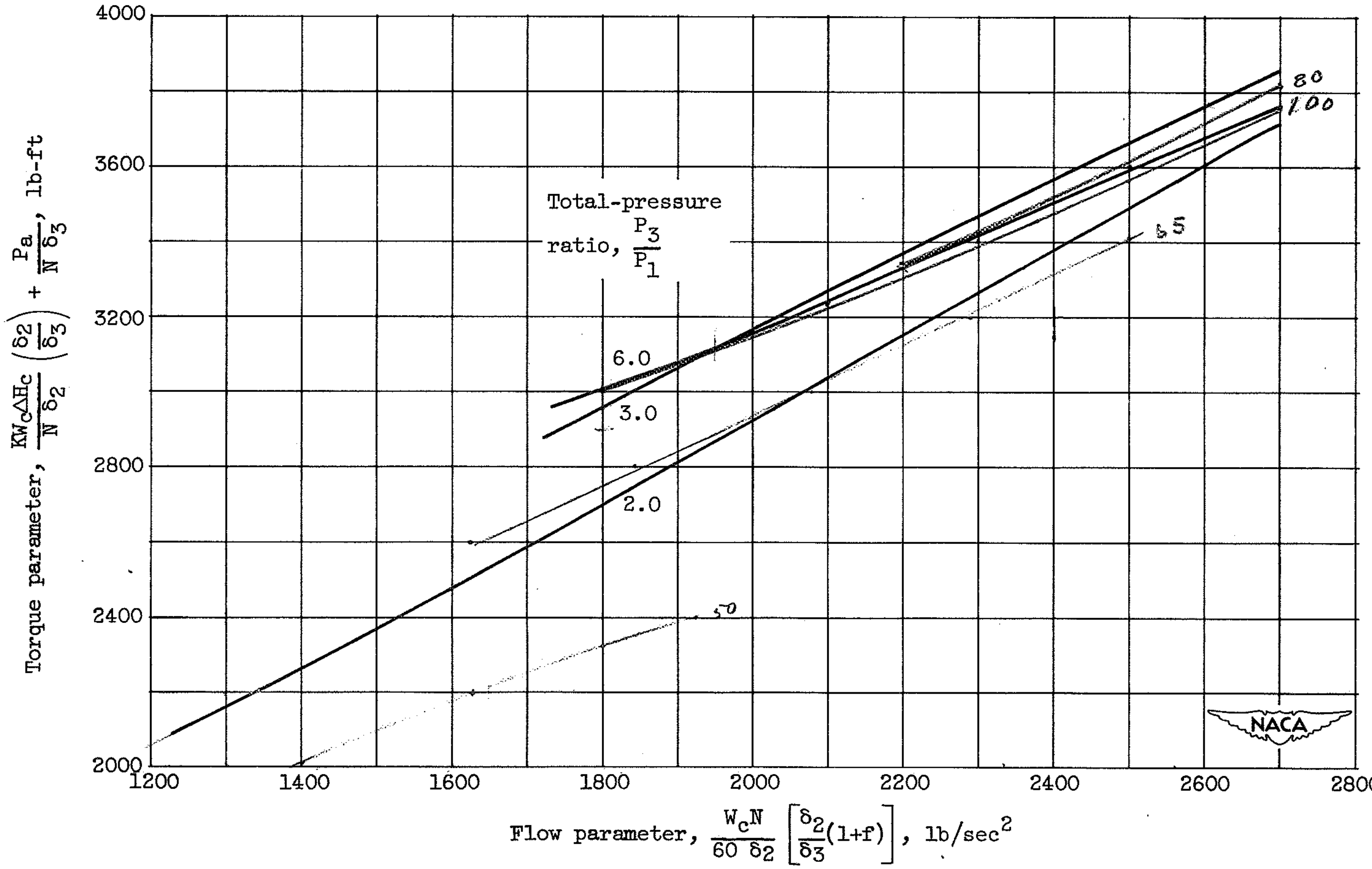

(b) Constant pressure ratio.

Figure 1. - Concluded. J35-A-23 16-stage compressor performance characteristics.

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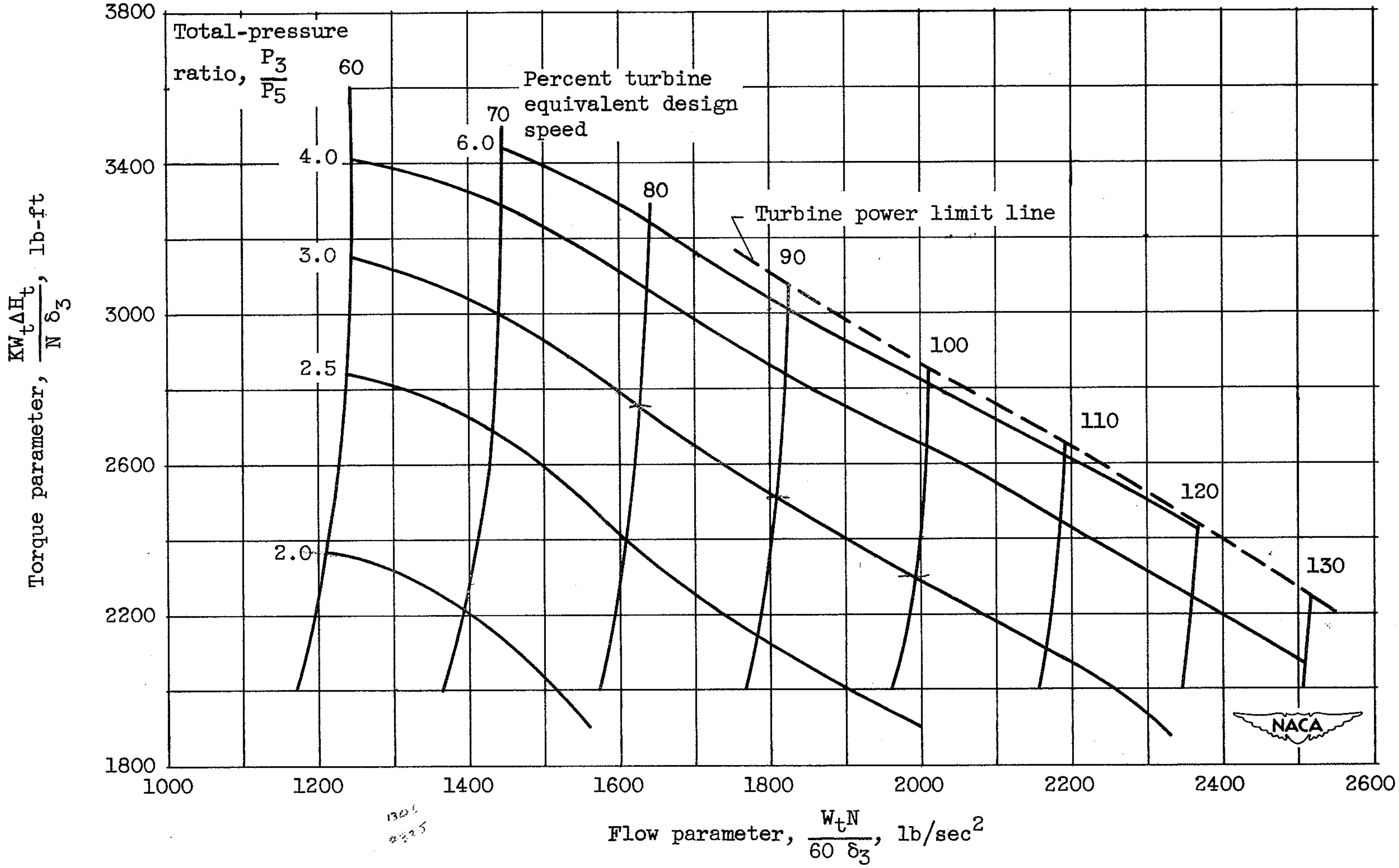

Figure 2. - J35-A-23 two-stage turbine performance characteristics.

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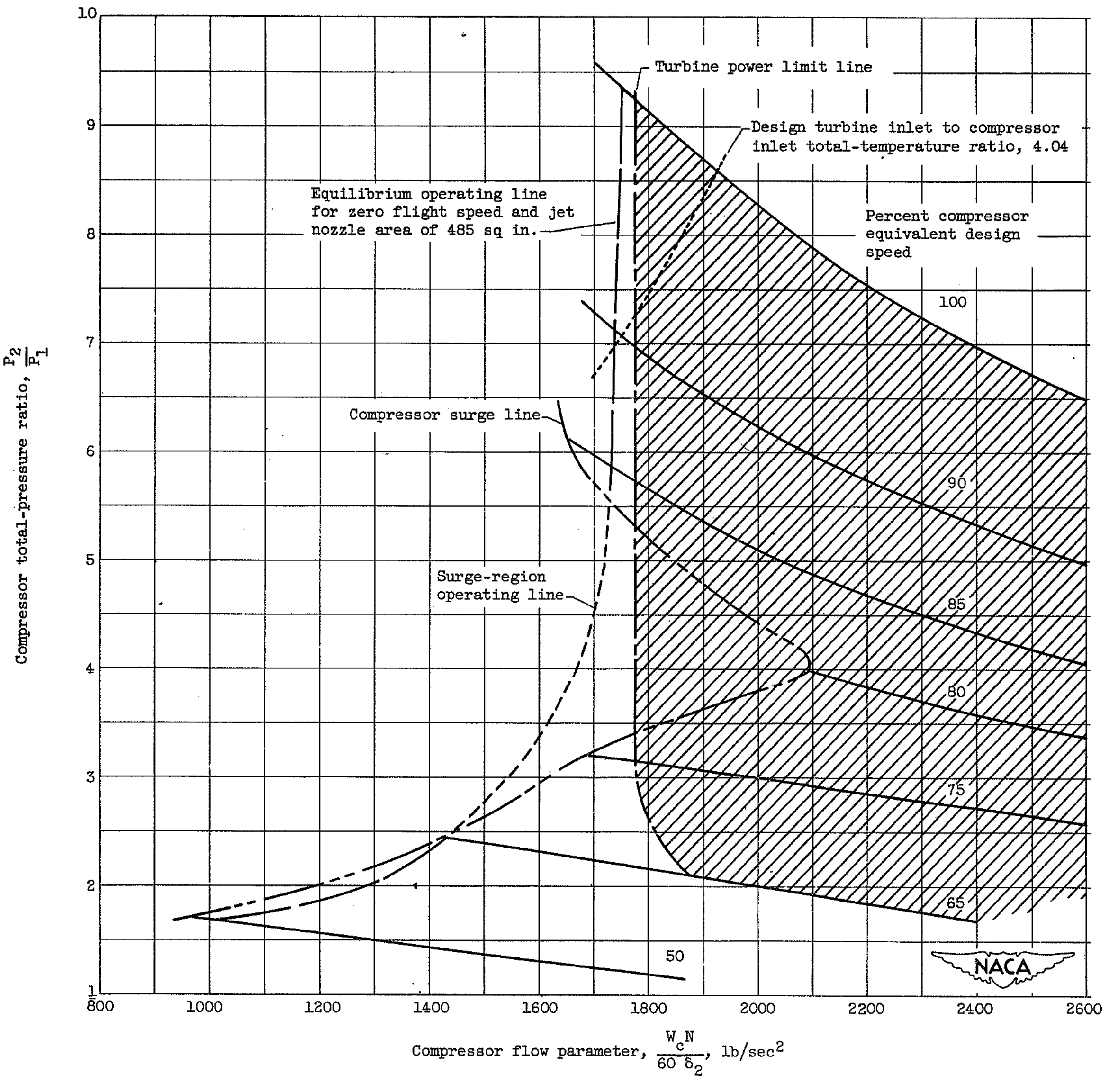

Figure 3. - Matched performance characteristics of J35-A-23 compressor and two-stage turbine.

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Engines, Turbojet	3.1.3
Compressors - Matching	3.6.3
Turbines - Matching	3.7.4

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Abstract

Component data on the J35-A-23 compressor and two-stage turbine were used to determine the problems in matching the two units for operation in a turbojet engine. Possible operating regions were determined and an equilibrium operating line was also determined for the assumed conditions of zero flight speed and a jet nozzle area approximately $5\frac{1}{2}$ percent greater than the wide-open nozzle area.