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RESEARCH MEMORANDUM

ALTITUDE-WIND-TUNNEL INVESTIGATION OF A 3000-POUND-THRUST AXIAL-FLOW TURBOJET ENGINE

I - ANALYSIS OF TURBINE PERFORMANCE

By Earl W. Conrad, Robert O. Dietz, Jr.
and Richard L. Golladay

Flight Propulsion Research Laboratory
Cleveland, Ohio

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SUMMARY

An investigation has been conducted in the NACA Cleveland altitude wind tunnel to determine the performance of a turbine operating as an integral part of a turbojet engine. Turbine performance data were obtained while the engine was run over its full operable range of speeds at various simulated altitudes and flight Mach numbers and with four nozzles of different outlet area.

An analysis of the turbine performance data showed that the turbine was effectively utilized in the standard installation. A maximum turbine efficiency of 0.875 was obtained with the standard exhaust nozzle at a simulated altitude of 15,000 feet, a flight Mach number of 0.53, and a corrected turbine speed of 5900 rpm.

INTRODUCTION

The performance of a turbine operating as an integral part of a turbojet engine is of interest because it is desirable to know the capabilities of the turbine and how effectively the turbine is utilized in the engine. A complete turbojet engine was investigated in the NACA Cleveland altitude wind tunnel and an analysis of the turbine performance data obtained is presented. Turbine data were obtained over a much wider range of operating conditions than in previous turbine investigations in the altitude wind tunnel.

The investigation was conducted at various simulated altitudes and flight Mach numbers. At each simulated flight condition, the engine was run over its full operable range of speeds. The use of four engine exhaust nozzles of different outlet area extended the range of turbine operation over which performance data could be obtained.

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Turbine performance data obtained for various altitudes, flight Mach numbers, and with different exhaust-nozzle-outlet areas are reduced to sea-level conditions and presented in a single plot. Curves of constant corrected turbine speed, constant turbine pressure ratio, and constant efficiency are shown therein.

INSTALLATION AND INSTRUMENTATION

The engine was installed in a wing section that extended across the 20-foot-diameter test section of the altitude wind tunnel (fig. 1). The modified 24C turbojet engine used in this investigation has an 11-stage axial-flow compressor, a double-annulus combustion chamber, a two-stage reaction turbine, a tail pipe, and an exhaust nozzle. The standard exhaust nozzle has an outlet area of 171 square inches. Rated thrust of the engine is 3000 pounds at sea-level static conditions and an engine speed of 12,500 rpm. The corresponding air flow is about 58.5 pounds per second. Compressor-inlet pressures corresponding to flight at high speeds were obtained by introducing dry refrigerated air from the tunnel make-up air system. The air was throttled from approximately sea-level pressure to the desired pressure at the engine inlet and was conducted to the engine through a make-up air duct. A frictionless slip joint in the make-up air duct permitted the measurement of thrust with the wind-tunnel balance-scale system.

The two-stage reaction turbine delivers approximately 5000 horsepower when the engine is operating at sea-level rated conditions. The blade-tip diameter of both turbine rotors is 20.813 inches. A detail drawing of the turbine installation presenting other pertinent dimensions is presented in figure 2. Both the first-stage stator (fig. 3(a)) and the first-stage rotor (fig. 4) of the turbine have 55 blades; the second-stage stator (fig. 3(b)) has 54 blades, and the second-stage rotor (fig. 4) has 34 blades.

Four exhaust-nozzle configurations were used during the investigation. With one configuration, exhaust gases were discharged from the straight tail pipe, which had an area of 330 square inches. With the other three configurations, nozzles 20 inches in length were used. These nozzles tapered uniformly from an area of 330 square inches to outlet areas of 232, 189, and 171 square inches. Rated conditions were obtained with the 171-square-inch nozzle.

Instrumentation for the measurement of pressures and temperatures was installed at several stations through the engine (fig. 5). The methods of calculation used to determine turbine performance from these pressures and temperatures are given in the appendix.

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RANGE OF INVESTIGATION

Engine performance data were obtained at simulated altitudes of 15,000, 25,000, 35,000, and 45,000 feet and a flight Mach number of 0.53. At a simulated altitude of 25,000 feet, the engine was operated at flight Mach numbers of 0.26, 0.53, 0.72, and 0.86. At each simulated flight condition, the engine was run over the full operable range of speeds. Data were obtained over this range of conditions with each of the four exhaust-nozzle configurations.

RESULTS AND DISCUSSION

Data obtained with the turbine operating as an integral part of the turbojet engine over a wide range of simulated flight conditions and with four exhaust-nozzle configurations were plotted to determine the variation in the basic turbine-performance parameters with corrected turbine speed. These curves containing the data for all operating conditions were used to make a composite plot showing efficiency contours and lines of constant corrected turbine speed and constant turbine pressure ratio on coordinates of corrected enthalpy drop per pound and gas-flow factor (fig. 6). Turbine performance is completely defined at any point on this composite plot.

The curves on the turbine-characteristic plot (fig. 6) were drawn through the average of the generalized data points. Certain efficiency contours were discontinued in the region of a corrected turbine speed of 6500 rpm because the data in this region were insufficient to define clearly the position of the contours. A separate region of high efficiency located in the vicinity of a corrected turbine speed of 7000 rpm was partly defined by the available data. The presence of this high-efficiency region is indicated by the data shown in figure 7.

Choking in the exhaust nozzle resulted in a rapid rise in turbine temperatures and pressures as the engine speed increased. Consequently, over the normal operating engine-speed range (10,500 to 12,500 rpm) the increase in corrected turbine speed was very small, but there was an appreciable increase in turbine efficiency (fig. 7(a)). The higher turbine efficiencies are attributed to a higher ratio of useful work to the relatively fixed turbine losses and changes in the state of the working fluid as evidenced by the change in the ratio of specific heats (figs. 7(b), 7(c), and 7(d)). This increase in efficiency has been corroborated by other data taken at various altitudes, flight Mach numbers, and with different exhaust-nozzle areas.

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For a fixed turbine speed, the work required by the compressor per pound of air increased with altitude, thereby causing the shift in turbine operating lines shown in figure 8(a) (flight Mach number of 0.53 and standard exhaust-nozzle-outlet area). The shift in the turbine operating lines caused by changes in flight Mach number (fig. 8(b)) and exhaust-nozzle-outlet area (fig. 8(c)) also resulted from changes in the power requirements of the compressor. Inasmuch as the highest over-all turbine pressure ratio obtained was about 2.6 and a two-stage reaction turbine was used, no choking occurred in the turbine.

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The effects of altitude on turbine efficiency are shown in figure 8(a), in which the turbine operating lines for simulated altitudes of 15,000 and 25,000 feet are near the region of maximum efficiency, whereas the operating lines for higher altitudes are in regions of successively lower efficiency. The turbine operating line for a flight Mach number of 0.53 is in the region of high efficiency over the normal range of engine operating speeds (corrected turbine speeds above 6000 rpm). (See fig. 8(b).) The position of the operating lines for various flight Mach numbers is such that turbine efficiency increased as flight Mach number was raised from 0.26 to 0.53 and then decreased as the flight Mach number was raised from 0.53 to 0.86. Over the normal range of engine operation, the operating lines for the standard 171-square-inch exhaust-nozzle configuration and the 189-square-inch exhaust-nozzle configuration are in the region of highest efficiency (fig. 8(c)). Operating lines for the 231- and 330-square-inch exhaust-nozzle configurations are in regions of lower turbine efficiency.

The peak efficiency was obtained at an altitude of 15,000 feet, a flight Mach number of 0.53, and with the standard 171-square-inch exhaust nozzle. This efficiency of 0.875 occurred at a corrected turbine speed of 5900 rpm.

An examination of the positions of the various turbine operating lines relative to the region of maximum efficiency (fig. 8) shows that the capabilities of the turbine are effectively utilized in the standard installation used in this investigation.

SUMMARY OF RESULTS

From an investigation of a complete turbojet engine in the Cleveland altitude wind tunnel under simulated conditions of altitude and flight Mach number, the turbine performance is summarized as follows:

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1. The capabilities of the turbine are effectively utilized in the standard installation used in this investigation.

2. A maximum turbine efficiency of 0.875 was obtained with the standard 171-square-inch exhaust-nozzle-outlet area at a simulated altitude of 15,000 feet, a flight Mach number of 0.53, and a corrected turbine speed of 5900 rpm.

3. Over the normal operating range of speeds, the turbine efficiency (a) decreased as the altitude was raised from 25,000 to 45,000 feet, (b) increased as the flight Mach number was raised from 0.26 to 0.53 and then decreased as the flight Mach number was raised from 0.53 to 0.86, and (c) decreased as the exhaust-nozzle-outlet area was increased from 189 to 330 square inches.

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APPENDIX - CALCULATIONS

Symbols

The following symbols are used in the calculations:

A	cross-sectional area, sq ft 907
c_p	specific heat at constant pressure, Btu/(lb)(°R)
g	acceleration due to gravity, 32.17 ft/sec^2
H	enthalpy, Btu/lb
J	mechanical equivalent of heat, 778 ft-lb/Btu
M_0	simulated flight Mach number
N	engine speed, rpm
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	gas constant, 53.3 Btu/(lb)(°R)
T	total temperature, °R
T_i	indicated temperature, °R
t	static temperature, °R
V	velocity, ft/sec
W_a	air flow, lb/sec
W_f	fuel flow, lb/sec
W_g	gas flow, lb/sec
α	thermocouple impact-recovery factor, 0.85
γ	ratio of specific heats
δ_5	pressure correction factor, $P_5/2116$ (turbine-inlet total pressure divided by NACA standard sea-level pressure)

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η_t turbine efficiency

θ_5 temperature correction factor, $\gamma_5 T_5/(1.40 \times 519)$(product of γ and total temperature at turbine inlet divided by product of γ and total temperature for air at NACA standard sea-level conditions)

θ_5' temperature correction factor, (total temperature at turbine inlet divided by total temperature for air at NACA standard sea-level conditions)

ρ density, slugs/cu ft

Subscripts:

c compressor

t turbine

1 cowl inlet

2 compressor inlet

5 turbine inlet

7 turbine outlet

Methods of Calculation

Gas flow. - The gas flow is given by the following equation

$$W_g = W_f + W_a \tag{1}$$

where the air flow W_a was determined from pressure and temperature measurements at the cowl inlet (station 1) by use of the equation

$$W_a = g\rho_1 A_1 V_1 = \frac{p_1 A_1}{R}\sqrt{\frac{2Jc_p}{gt_1}\left[\left(\frac{P_1}{p_1}\right)^{\frac{\gamma_1 - 1}{\gamma_1}} - 1\right]} \tag{2}$$

and the fuel flow W_f was measured by the use of a calibrated rotameter.

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Temperatures. - Static temperature was calculated from the indicated temperature by use of the equation

$$t = \frac{T_i}{1 + \alpha\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{3}$$

The thermocouple impact-recovery factor α was found to be 0.85 from calibration tests.

Total temperature was determined by the adiabatic relation

$$\frac{T}{t} = \left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} \tag{4}$$

Direct measurement of the turbine-inlet temperature is difficult because of radiation effects, but it may be evaluated with fair accuracy by the following indirect method:

When accessory power and bearing friction are neglected, the turbine power equals the power requirement of the compressor, which is given by $W_a c_p \Delta T_c$ or $W_a \Delta H_c$. The power extracted by the turbine is $W_g \Delta H_t$.

$$\Delta H_t = \Delta H_c\left(\frac{W_a}{W_g}\right) \tag{5}$$

The compressor work ΔH_c is obtained from temperature measurements at the inlet and outlet of the compressor. With the value of ΔH_t from equation (5) and the measured value of turbine-outlet temperature, the enthalpy and therefore the turbine-inlet temperature T_5 may be obtained from enthalpy charts. Values for T_5 obtained by this method are slightly low because some turbine power is used to drive the engine accessories.

Efficiency. - Adiabatic turbine efficiency was calculated using the equation

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$$\eta_t = \frac{1 - \frac{T_7}{T_5}}{\left[1 - \left(\frac{P_7}{P_5}\right)\right]^{\frac{\gamma_t - 1}{\gamma_t}}} \qquad (6)$$

Values of γ_t were based on the average temperature of the gases flowing through the turbine and the fuel-air ratio. The fuel-air ratio was determined from the air flow (equation (2)) and the measured fuel flow..

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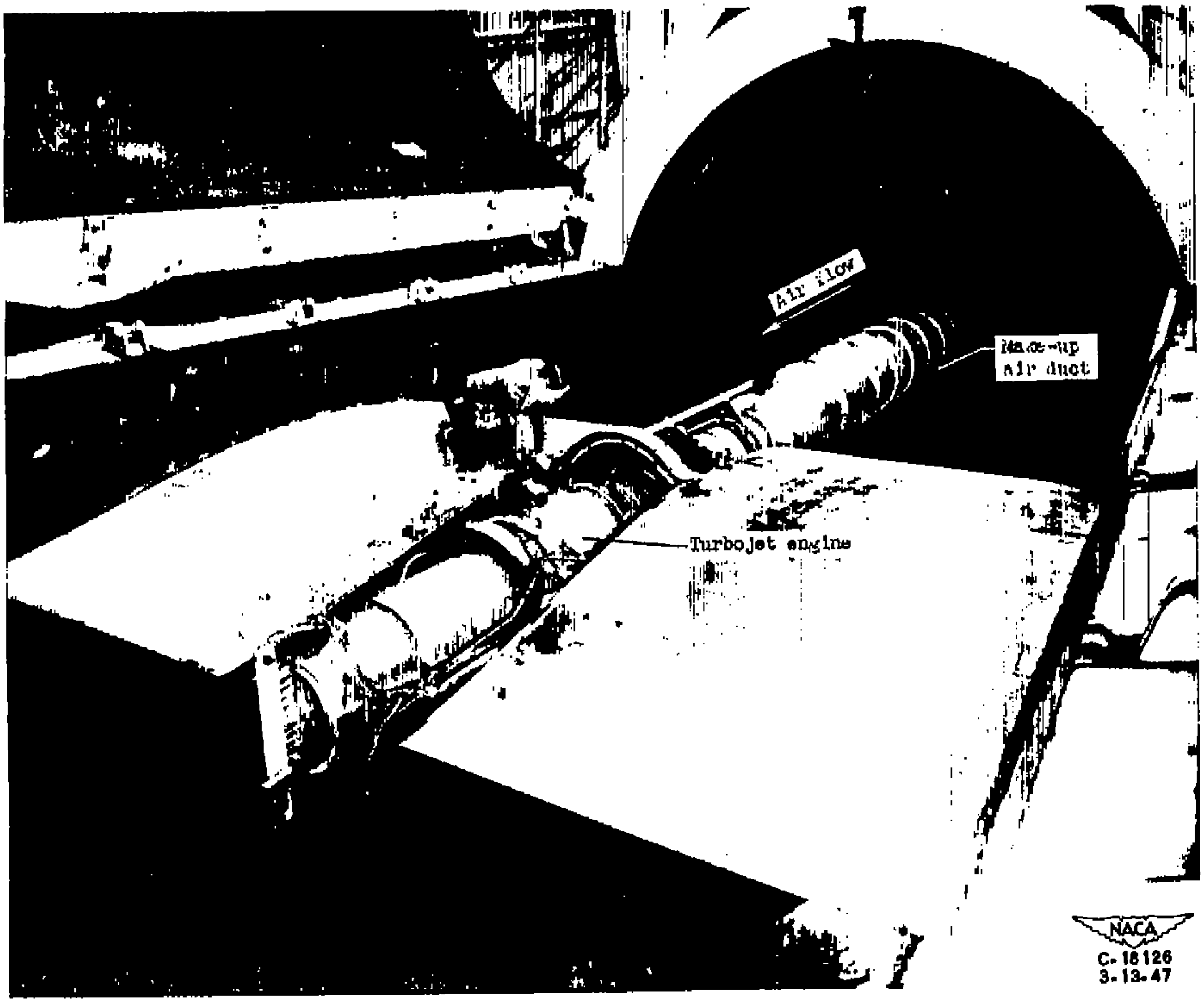

Figure 1. - Installation of turbojet engine in wing section in 20-foot-diameter test section of altitude wind tunnel.

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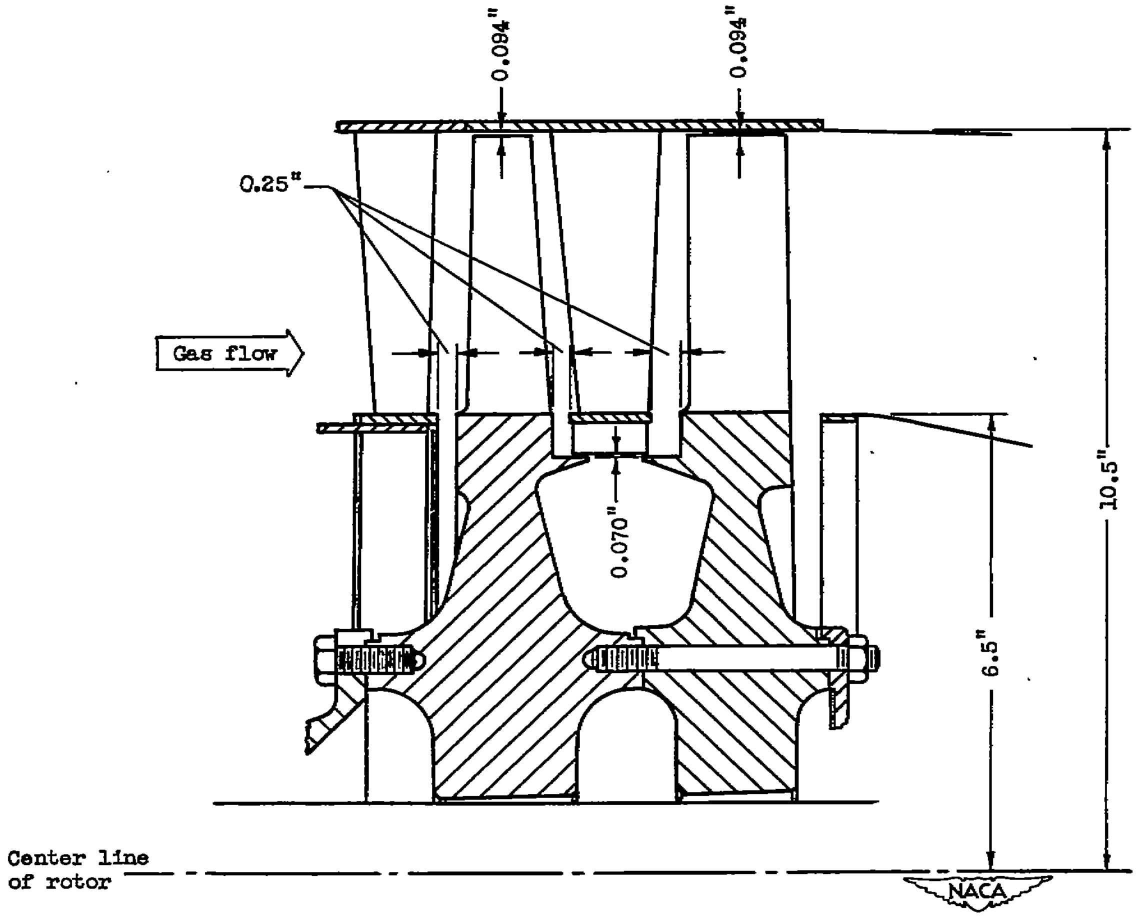

Figure 2. - Sectional view of turbine showing pertinent dimensions.

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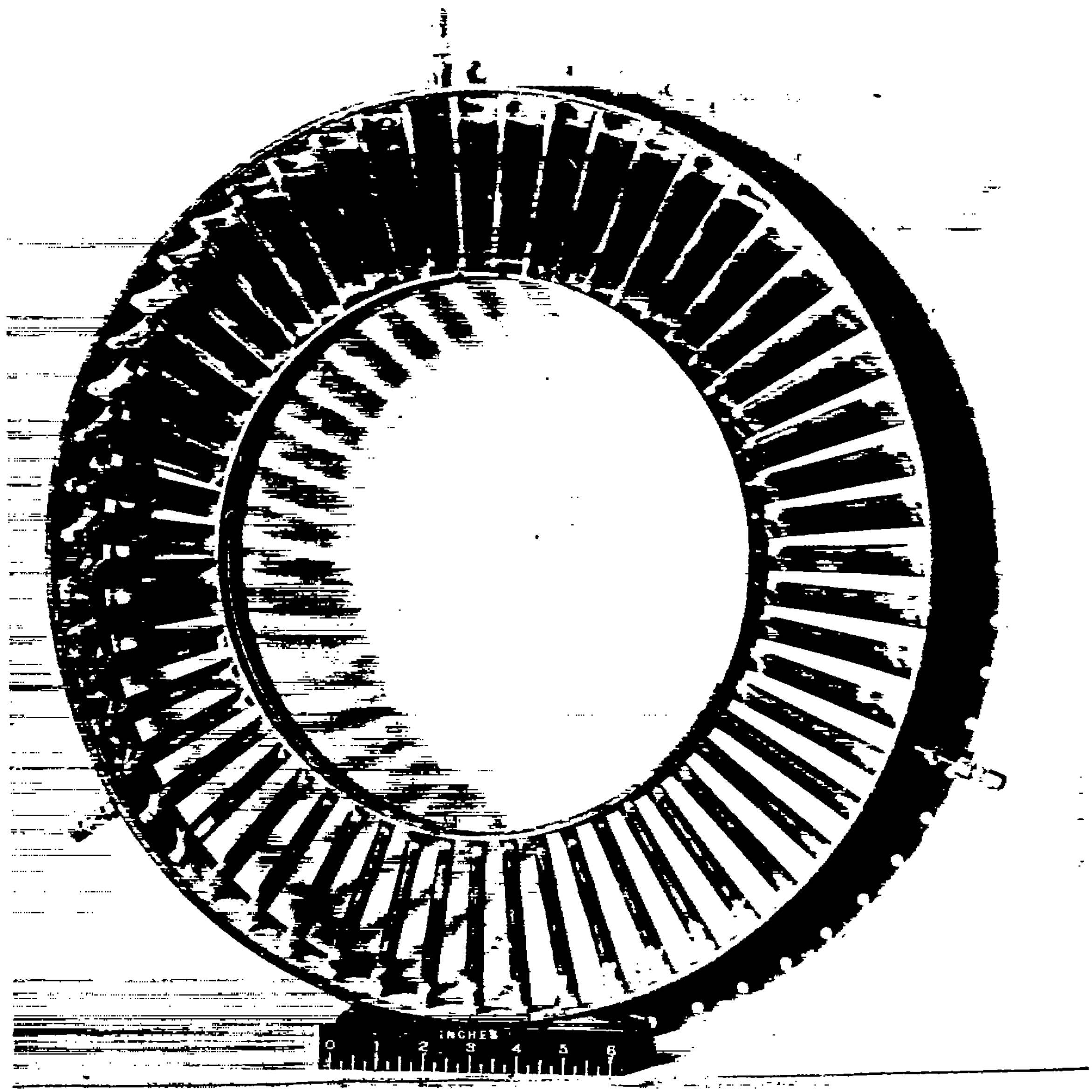

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(a) First stage.

Figure 3. - Inlet side of stator blades of turbine.

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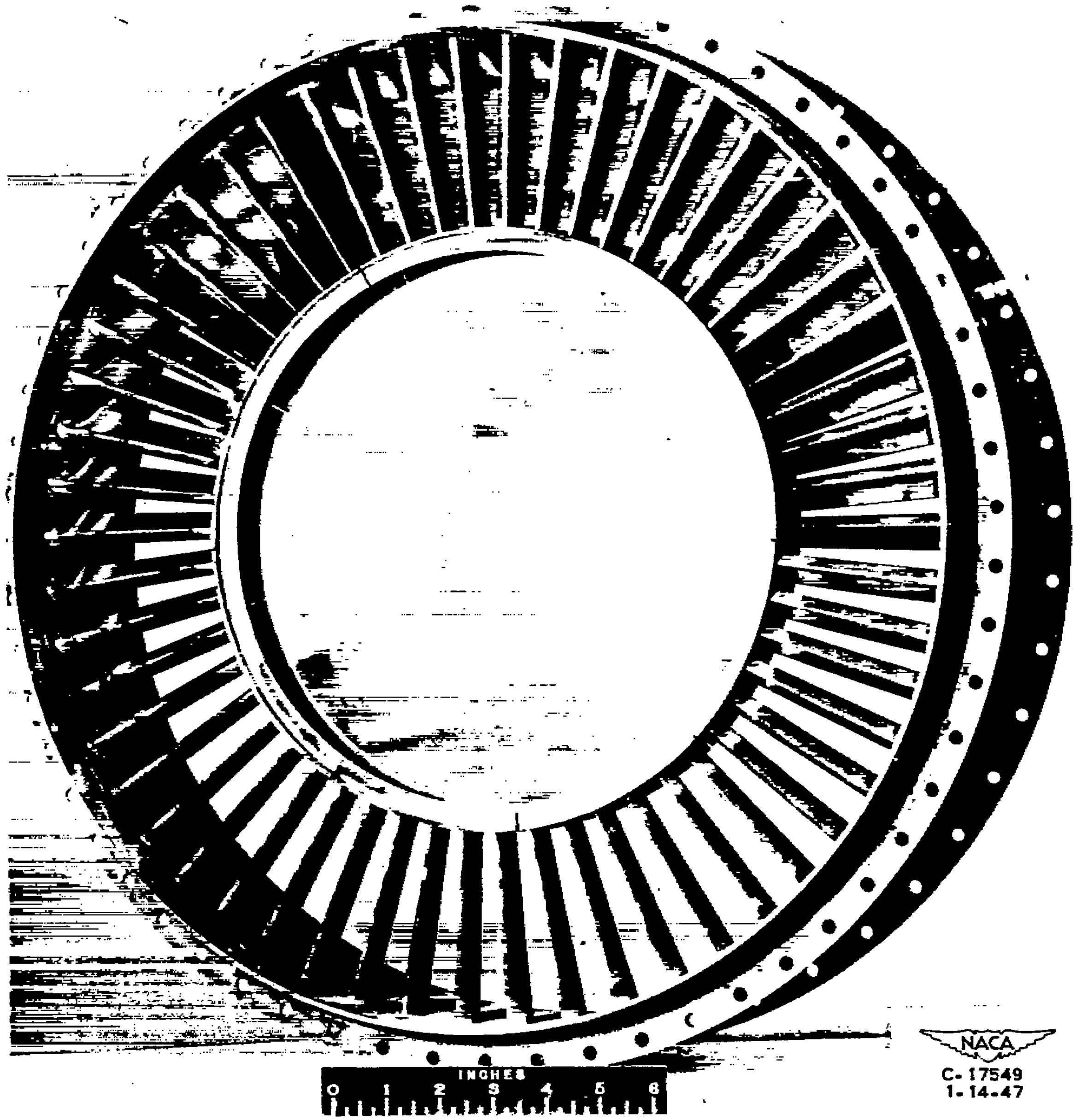

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(b) Second stage.

Figure 3. - Concluded. Inlet side of stator blades of turbine.

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Figure 4. - Turbine-rotor assembly.

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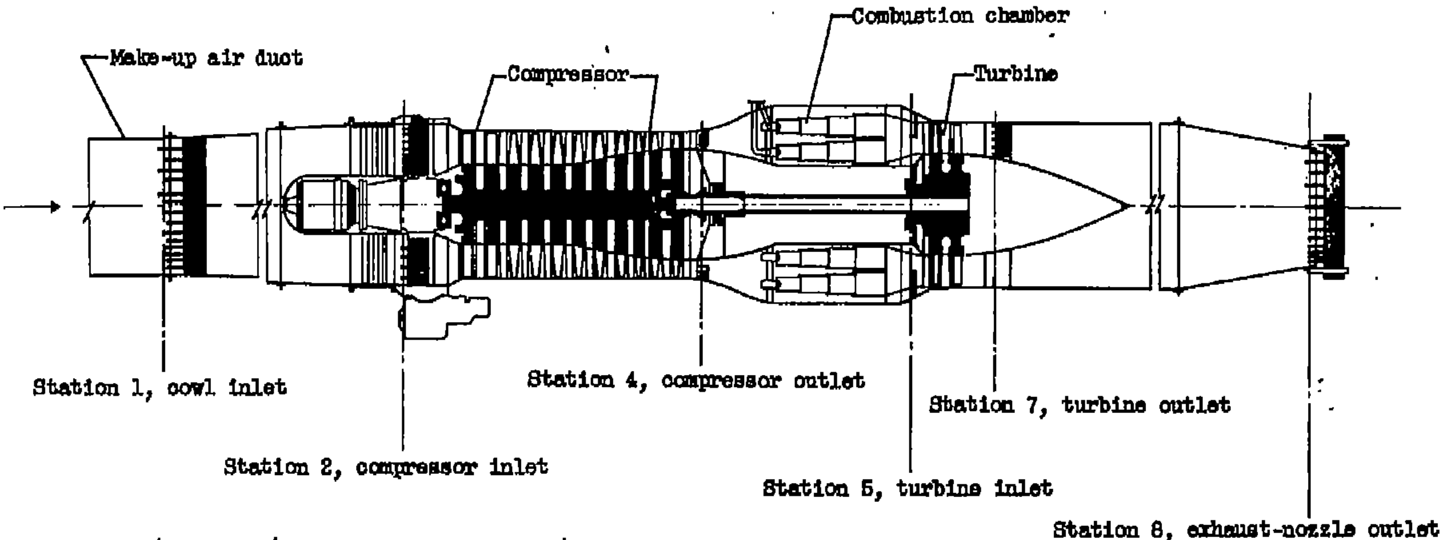

Station	Total-pressure tubes	Static-pressure tubes	Wall static-pressure orifices	Thermo-couples
1	16	3	4	6
2	16	8	4	6
4	15	6	6	6
5	4			
7	10		3	52
8	8	3	4	16

Figure 5. - Cross section of turbojet engine showing stations at which instrumentation was installed.

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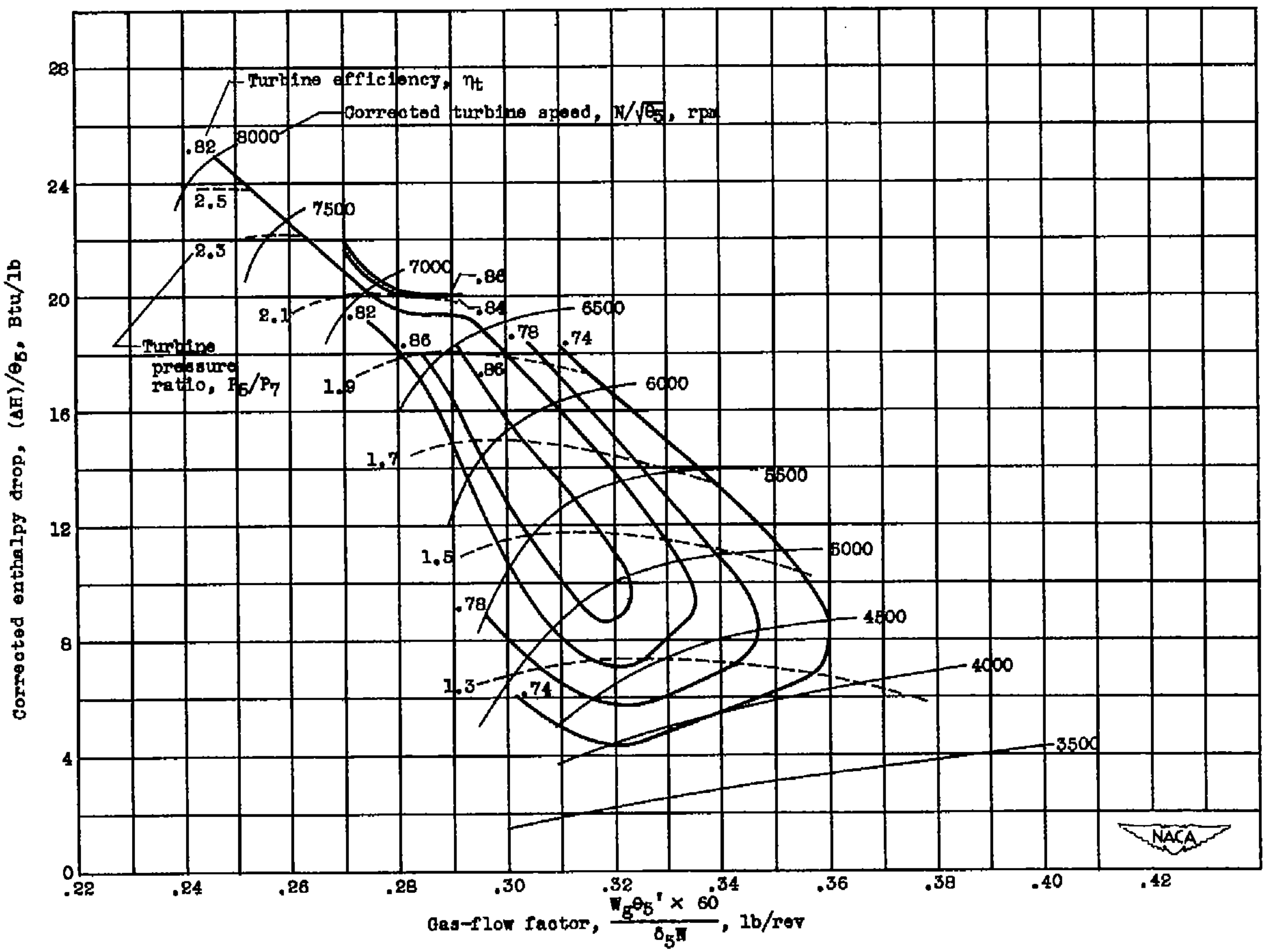

Figure 6. – Turbine-characteristic curve for turbine operation in complete turbojet engine.

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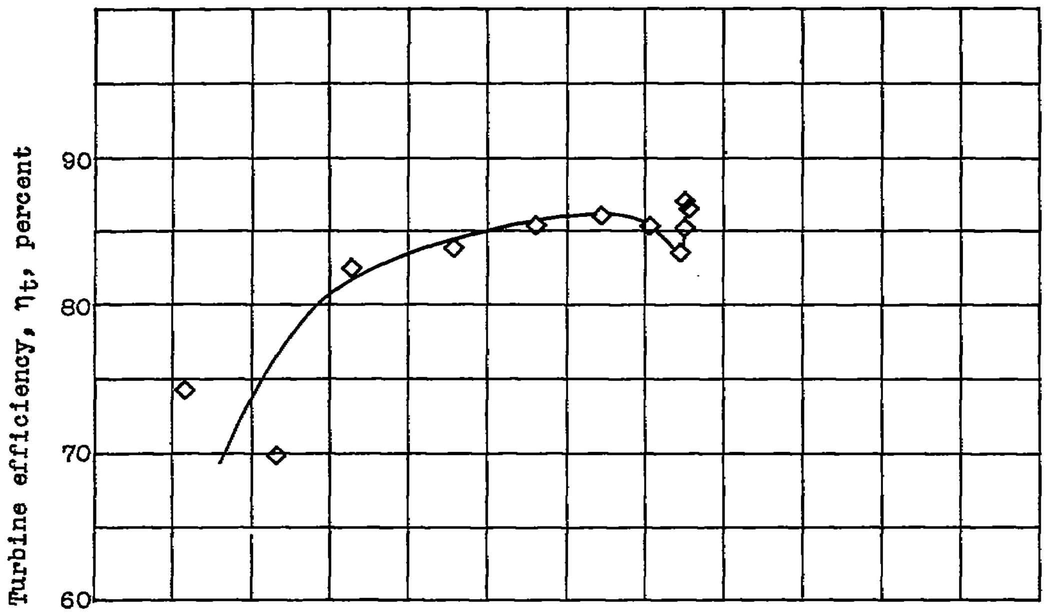
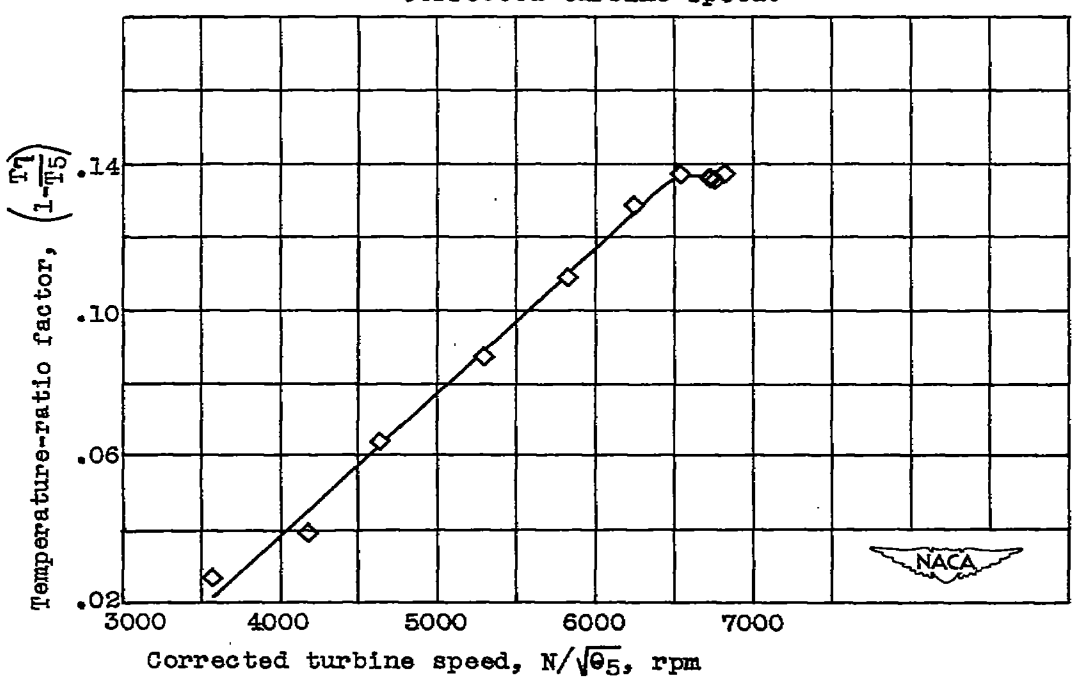


(a) Relation between turbine efficiency and corrected turbine speed.



(b) Relation between temperature-ratio factor and corrected turbine speed.

Figure 7. - Factors involved in sharp changes in turbine efficiency at high corrected turbine speeds. Simulated altitude, 25,000 feet; flight Mach number, 0.53; exhaust-nozzle-outlet area, 171 square inches.

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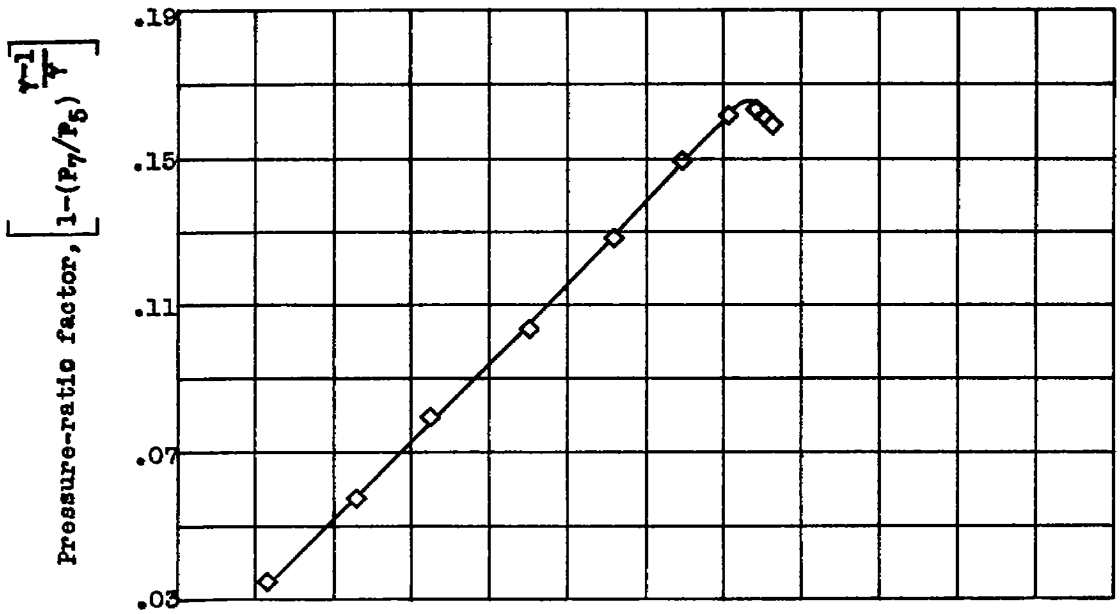
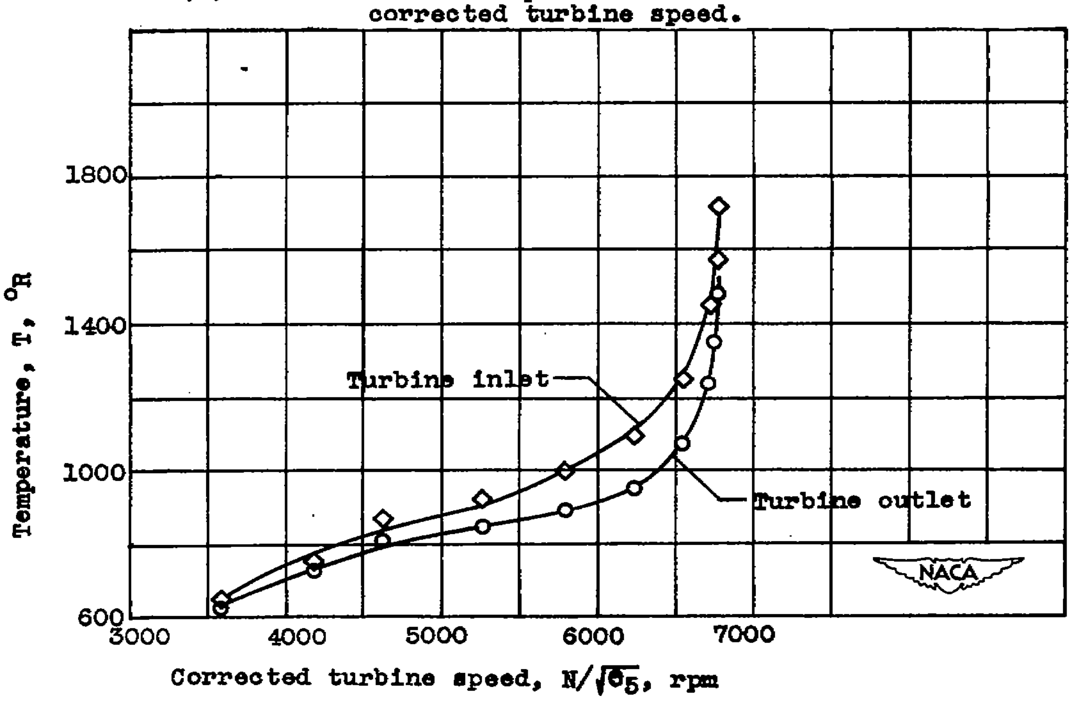


(c) Relation between pressure-ratio factor and corrected turbine speed.



(d) Relation between turbine temperatures and corrected turbine speed.

Figure 7. - Concluded. Factors involved in sharp changes in turbine efficiency at high corrected turbine speeds. Simulated altitude, 25,000 feet; flight Mach number, 0.53; exhaust-nozzle-outlet area, 171 square inches.

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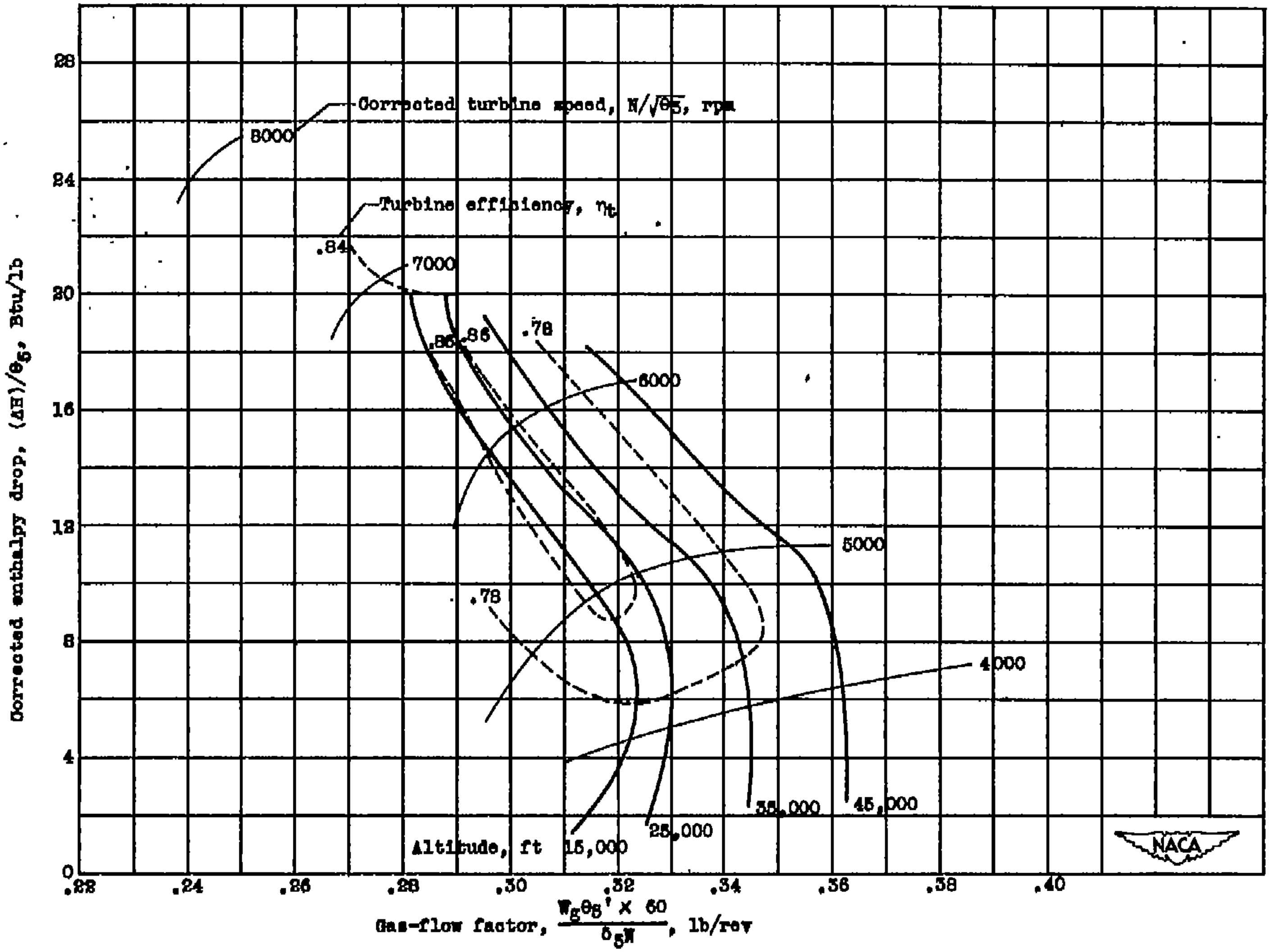

(a) Turbine operating lines for various altitudes. Flight Mach number, 0.53; exhaust-nozzle-outlet area, 171 square inches.

Figure 8. - Turbine operating lines superimposed on turbine-characteristic curve.

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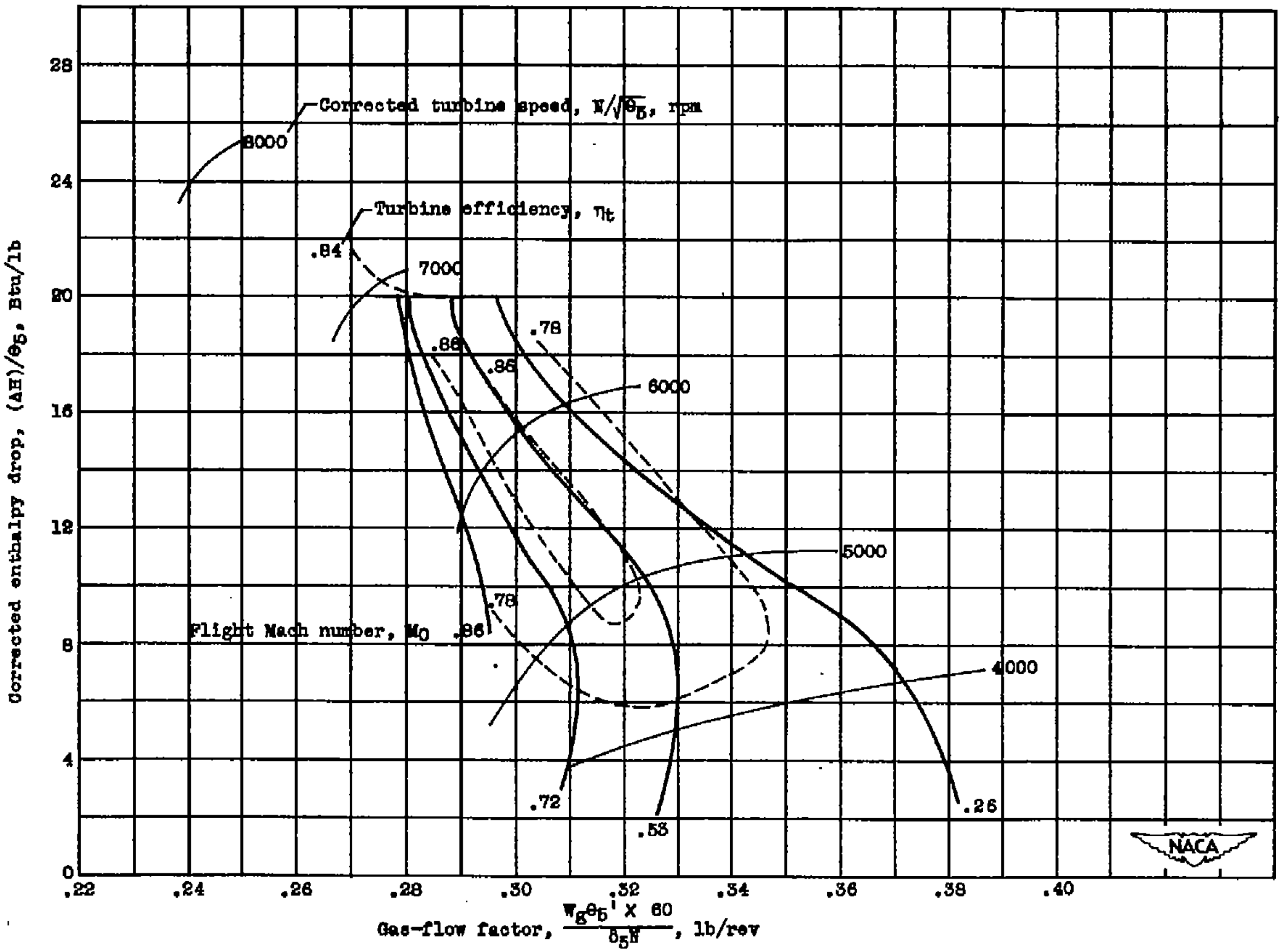

(b) Turbine operating lines for various flight Mach numbers. Altitude, 25,000 feet; exhaust-nozzle-outlet area, 171 square inches.

Figure 8. – Continued. Turbine operating lines superimposed on turbine-characteristic curve.

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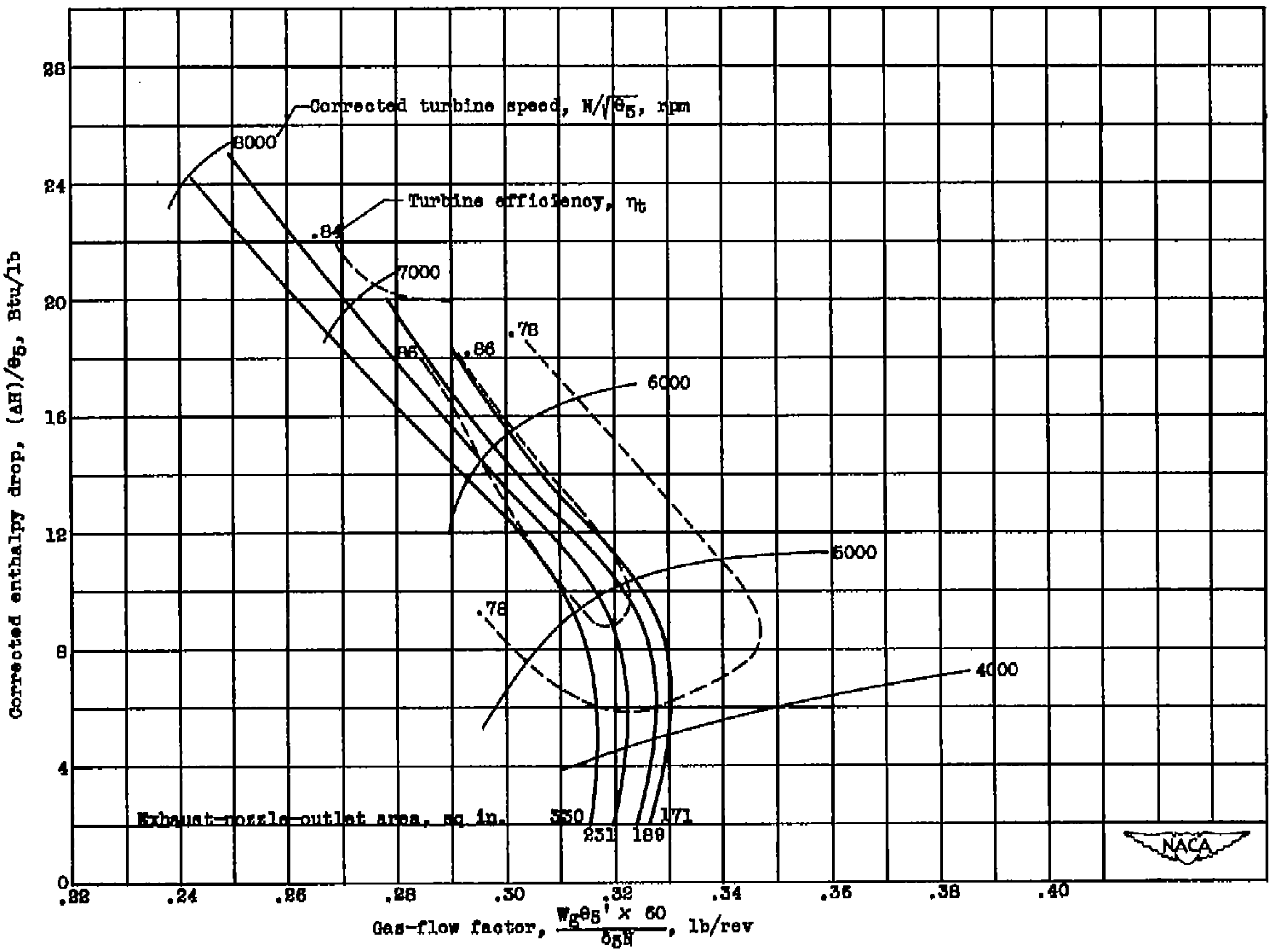

(c) Turbine operating lines for various exhaust-nozzle-outlet areas. Altitude, 25,000 feet; flight Mach number, 0.53.

Figure 8. - Concluded. Turbine operating lines superimposed on turbine-characteristic curve.