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PERFORMANCE OF J33 TURBOJET ENGINE

WITH SHAFT POWER EXTRACTION

II - COMPRESSOR

By Albert O. Ross, John R. Esterly
and J. Cary Nettles

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RESEARCH MEMORANDUM

PERFORMANCE OF J33 TURBOJET ENGINE WITH SHAFT POWER EXTRACTION

II - COMPRESSOR

By Albert O. Ross, John R. Esterly
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SUMMARY

The performance characteristics of the centrifugal compressor of a J33 jet-propulsion engine installed on a test stand were determined. The investigation was conducted over a range of compressor-impeller tip speeds between 1025 and 1435 feet per second and a range of turbine-inlet temperatures between 1425° and 2000° R. This range of performance, greater than that covered in service operation, was made possible by the attachment of a dynamometer to the engine, which permitted the speed to be held constant over the range of turbine-inlet temperatures. The performance characteristics are presented as functions of air flow and compressor tip speeds corrected to sea-level static conditions.

The maximum compressor efficiency observed was 73 percent at a compressor-impeller tip speed of 1025 feet per second and a pressure ratio of 2.04. The efficiency varied approximately 3 percent as turbine-inlet temperature was varied at each of the engine speeds investigated. At a corrected compressor-impeller tip speed of 1435 feet per second, the compressor efficiency was 71.2 percent; the corrected compressor air flow was 65.6 pounds per second; the compressor pressure ratio was 3.52; and the compressor pressure coefficient was 0.656.

The efficiency contours on the compressor performance chart confirmed that the jet engine operates at conditions such that the quantities of air consumed are greater than those for maximum compressor efficiency.

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INTRODUCTION

The performance of a Brayton cycle gas-turbine engine is very closely related to the characteristics of the particular compressor used. The thermal efficiency and power developed by such an engine is influenced to a large extent by the pressure ratio, the air capacity, and the adiabatic efficiency of the compressor. As part of a general analysis of the performance of turbine-propeller engines, a test-stand investigation of the performance of a J33 (I-40) jet-propulsion engine was conducted at the NACA Cleveland laboratory to determine (1) the over-all engine performance, presented in reference 1, and (2) the performance characteristics of the various engine components. Previous performance data of compressors as large as the J33 compressor were limited to an operating line for one tail-pipe flow area; however, for this report, the performance characteristics of the compressor were obtained over as wide a range of operating conditions as possible in order that the relations between the characteristics of the compressor and those of the other engine components might be evaluated. Performance data of a J33 compressor over a range of air flows greater than that encountered in service operation, which was made possible by the attachment to the engine of a dynamometer that permitted engine speed to be held constant over a range of turbine-inlet temperature, are presented.

DESCRIPTION OF COMPRESSOR

The compressor unit of the J33 (I-40) engine is comprised of an impeller, a compressor casing, a diffuser, bearing supports, guide blades, and truss rings.

The double-entry centrifugal impeller (fig. 1) is machined from an aluminum forging; each side has 31 blades that discharge the air into a common diffuser. The outer blade tip diameter is 30 inches and the inner blade tip diameter is $18\frac{1}{4}$ inches. The diameter of the impeller hub is 8 inches. The axial width of the impeller hub is 11 inches and the axial width of the impeller at the outer blade tips is 2.75 inches. The impeller is supported on antifriction bearings by stub shafts attached to the front and the rear and is directly connected to the turbine.

The compressor casing consists of two magnesium-alloy casings, which are separated axially by a magnesium-alloy diffuser.

The diffuser is cast with 14 channels radiating outwards on all sides, which distribute the air into the 14 air adapters leading to the 14 combustion chambers.

A truss ring is bolted to each side of the compressor casing and serves to support the compressor-bearing supports. The guide blades occupy the space under the truss rings and direct the air into each side of the impeller.

The compressor was designed to develop at sea level a pressure ratio of 4.0 with an air flow of 80.0 pounds per second and a turbine speed of 11,500 rpm.

INSTALLATION AND INSTRUMENTATION

The compressor was investigated as a component of a J33 engine that was directly coupled to an inductor-brake dynamometer and mounted on a bedplate suspended on cables. This suspension afforded measurement of jet thrust, which was determined by a strain-gage weighing device developed at the NACA. A tail pipe 21 inches in diameter and 60 inches in length was attached to the engine tail cone. The air-flow characteristics of the engine were not altered by the installation and ambient conditions for the engine during the investigation were sea-level atmospheric.

The engine was instrumented to obtain gas temperatures and pressures at the stations shown in figure 2. Measurements of total and static pressure and temperature at station 1 indicated ambient conditions. At station 2, alternate air adapters contained an iron-constantan thermocouple and a pitot tube so located in the air stream as to give representative values of total and static pressure. The thermocouples were of the unshielded type, and the static and total pitot pressure tubes were designed and fabricated according to A.S.M.E. standards.

Conditions at station 4 were determined from total-pressure, static-pressure, and temperature instrumentation installed in a tail-pipe section 4 inches long, which was attached to the engine tail cone. This instrument ring contained 2 static-pressure tubes, 2 total-pressure tubes, and 14 unshielded thermocouples and is similar to that used by the General Electric Company for static calibration of engines.

The fuel flow to the engine was measured by a calibrated rotameter.

SYMBOLS

The following symbols and values are used in this report:

A	area, (sq ft)
a	speed of sound in air, (ft/sec)
c_p	specific heat of gas at constant pressure, (Btu/lb/°R)
c_v	specific heat of gas at constant volume, (Btu/lb/°R)
D	diameter of rotor, (ft)
g	acceleration of gravity, (ft/sec^2)
J	mechanical equivalent of heat, 778, (ft-lb/Btu)
K	correction factor for gas flow, 0.81
M	Mach number
N	engine speed
P	total pressure, (lb/sq in. absolute)
p	static pressure, (lb/sq in. absolute)
R	gas constant, 53.3
shp	shaft horsepower (measured on dynamometer)
T	total temperature, (°R)
t	static temperature, (°R)
U	compressor-impeller tip speed, (ft/sec)
V	velocity, (ft/sec)
W	weight flow, (lb/sec)
γ	ratio of specific heats, (c_p/c_v)
δ	ratio of compressor-inlet total pressure to NACA standard sea-level pressure, $P_1/14.7$

860

η efficiency, percent

θ ratio of compressor-inlet total temperature to NACA standard sea-level temperature, $T_1/518.6$

ρ density, (lb/cu ft)

ψ compressor pressure coefficient

860

Subscripts:

1 compressor inlet

2 compressor outlet

3 turbine inlet

4 tail-pipe instrument ring

a air

c compressor

g gas

i indicated

t turbine

METHODS OF CALCULATION

Mach number. - The compressor Mach number is defined as the ratio of the speed of the compressor-blade tips to the velocity of sound in air at the total temperature of the inlet air. This Mach number is represented by the dimensionless ratio

$$M_c = \frac{U_c}{a} = \frac{\pi DN}{60\sqrt{\gamma g R T_1}} \tag{1}$$

Temperature. - The tail-pipe static temperature was not directly indicated because an unshielded thermocouple in a gas stream of appreciable velocity indicates the static temperature of the gas plus some part of the difference between static temperature and total temperature. The proportion of this difference, or

dynamic temperature ΔT, that is indicated depends on the Mach number of the fluid; however, a value of 0.6 for the proportion can be used throughout the operating range with reasonable accuracy (reference 2). Thus

$$T_{i,4} = t_4 + 0.6\ \Delta T \tag{2}$$

$$\Delta T = t_4 \left[\left(\frac{P_4}{p_4}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{3}$$

$$t_4 = \frac{T_{i,4}}{1 + 0.6\left[\left(\frac{P_4}{p_4}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{4}$$

A direct measurement of turbine-inlet temperature is both difficult and unsatisfactory. A value that indicates the trends of this temperature with reasonable accuracy can be obtained by measuring the total temperature of the gas after the turbine and adding the value of the equivalent temperature drops of the compressor work and of the shaft power.

$$T_3 = T_4 + \frac{c_{p,c}}{c_{p,t}}\left(T_2 - T_1\right) + \frac{550\ \text{shp}}{J\ c_{p,t}\ W_g} \tag{5}$$

Air flow. - A direct measurement of the air inducted into the engine was impossible with the type of engine installation used. The engine air flow was computed from values of gas temperature and pressure observed at the tail-pipe instrument ring (station 4).

The simple expression for the weight of gas flow through the tail pipe is

$$W_g = A_4 V_4 \rho_4 \tag{6}$$

The expression for the velocity of the gas in terms of the difference between static and total temperature is

$$V_4 = \sqrt{2gJc_p\left(T_4 - t_4\right)} \tag{7}$$

The relation between the static temperature of the gas and the total and static pressures of the gas is

$$(T_4 - t_4) = t_4 \left[\left(\frac{P_4}{p_4} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \tag{8}$$

The equation of state for a perfect gas gives the following expression for density:

$$\rho_4 = \frac{p_4}{Rt_4} \tag{9}$$

When the values obtained from equations (4), (7), (8), and (9) are substituted in equation (6), the final expression for weight of gas flow is

$$W_g = \frac{Kp_4A_4 \sqrt{2gJc_p}}{R} \sqrt{\frac{\left[\left(\frac{P_4}{p_4} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \left\{ (1 + 0.6) \left[\left(\frac{P_4}{p_4} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \right\}}{T_{1,4}}} \tag{10}$$

A correction must be applied to the tail-pipe area to allow for the effect of the boundary layer on the total and static pressures associated with the true average velocity across the tail-pipe section. Account is taken of these two factors by assuming that 81 percent of the calculated value represents the true value. The constant K, which appears in equation (10), compensates for these factors. This constant applies only to the configuration of pressure taps used in the tail-pipe instrument ring and is the same as that used by the General Electric Company. In order to obtain the weight of air flow, the weight of fuel flow was substracted from the corrected gas flow.

The following parameter was used to correct air flow to standard sea-level conditions:

$$\frac{W_g \sqrt{\theta}}{\delta}$$

Efficiency. - The expression for the adiabatic efficiency of the compressor is

$$\eta_c = \frac{\text{isentropic temperature rise}}{\text{actual temperature rise}}$$

$$= \frac{T_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{(T_2 - T_1)} \tag{11}$$

Pressure coefficient. - The compressor pressure coefficient is defined as the square of the ratio of the compressor-tip Mach number theoretically required to produce the observed pressure ratio to the tip Mach number actually present.

$$\psi = \frac{gJc_p}{U_c^2} T_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{12}$$

PROCEDURE

The engine was operated over a range of turbine-inlet temperatures from 1425° to 2000° R at constant compressor-impeller tip speeds of 1025, 1152, 1293, and 1435 feet per second. The speed limitation on the dynamometer prevented operation of the engine at the designed speed range. At each tip speed, turbine-inlet temperature was varied by changing the dynamometer load and fuel flow. For each change of turbine-inlet temperature up to a maximum of 2000° R, data were recorded on fuel flow, temperatures, and static and total pressures throughout the engine.

RESULTS AND DISCUSSION

Sea-level static compressor performance characteristics presented herein are based on turbine-inlet temperatures and compressor-impeller tip speeds as engine operating variables. All parameters were generalized to NACA standard atmospheric conditions at sea level (reference 3). An operating line that represents the relation between the compressor pressure ratio and compressor-tip Mach number for a turbine-inlet temperature of 2000° R is shown in figure 3. The position of the operating line with respect to the coordinates is a function of the turbine-nozzle area, the ratio of the turbine-nozzle-inlet temperature to the compressor-inlet temperature, and ram pressure.

Values of compressor efficiency calculated by use of equation (11) plotted against corrected air flow for various compressor-impeller tip speeds are shown in figure 4. The air flow through the compressor decreased with an increase in turbine-inlet temperature at constant compressor-impeller tip speeds (fig. 5). At a compressor-impeller tip speed of 1435 feet per second, the efficiency was 71.2 percent for a corrected air flow of 65.6 pounds per second and 69.0 percent for a corrected air flow of 68.1 pounds per second (fig. 4). Efficiency decreased with increase in air flow; the range of efficiencies, of the order of 3 percent, was approximately the same for each compressor-impeller tip speed. The highest observed value for compressor efficiency was 73 percent at a compressor-impeller tip speed of 1025 feet per second and the lowest value was approximately 69 percent at a compressor-impeller tip speed of 1293 feet per second.

Variation of compressor pressure coefficient with change in corrected air flow at several compressor-impeller tip speeds is shown in figure 6. At each tip speed, the pressure coefficient decreased with an increase in air flow. The maximum pressure coefficient, 0.707 (fig. 6), was obtained at a pressure ratio of 2.04 and an air flow of 38.6 pounds per second at a corrected compressor-impeller tip speed of 1025 feet per second (fig. 7). At a corrected compressor-impeller tip speed of 1435 feet per second, the maximum compressor efficiency was 71.2 percent at corrected air flow of 65.6 pounds per second, the pressure coefficient was 0.656, and pressure ratio was 3.52 (figs. 4, 6, and 7).

The performance chart of the compressor at several efficiencies covering the range of conditions investigated is shown in figure 7. The operating line for the engine with a 19-inch nozzle is superimposed on the figure to indicate the relation between the range covered in this investigation and the jet-engine operating range. The curve shows that the jet engine operates at conditions such that the quantities of air consumed are greater than those for maximum compressor efficiency. The minimum air flow for each compressor-impeller tip speed was limited in each case by turbine-inlet temperature and not by compressor surge over the range investigated. The compressor showed no evidence of surging.

SUMMARY OF RESULTS

The following results were obtained in an investigation of the performance of the centrifugal compressor of a J33 jet-propulsion

engine over a range of turbine-inlet temperatures between 1425° and 2000° R for corrected compressor-impeller tip speeds of 1025, 1152, 1293, and 1435 feet per second:

1. Compressor efficiency varied approximately 3 percent over the range of air flow at each compressor-impeller tip speed; the highest observed value was 73 percent at a compressor-impeller tip speed of 1025 feet per second and a pressure ratio of 2.04; the lowest value was approximately 69 percent at a compressor-impeller tip speed of 1293 feet per second.

2. The maximum pressure ratio observed was 3.52 at a corrected compressor-impeller tip speed of 1435 feet per second, a corrected air flow of 65.6 pounds per second, and a compressor efficiency of 71.2 percent. The maximum pressure coefficient observed was 0.707 at a compressor-impeller tip speed of 1025 feet per second; this value decreased to 0.656 for the highest compressor-impeller tip speed.

3. The efficiency contours on the compressor performance chart confirmed that the jet engine operates at conditions such that the quantities of air consumed are greater than those for maximum efficiency.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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2. King, W. J.: Measurement of High Temperatures in High-Velocity Gas Streams. A.S.M.E. Trans., vol. 65, no. 5, July 1943, pp. 421-431.

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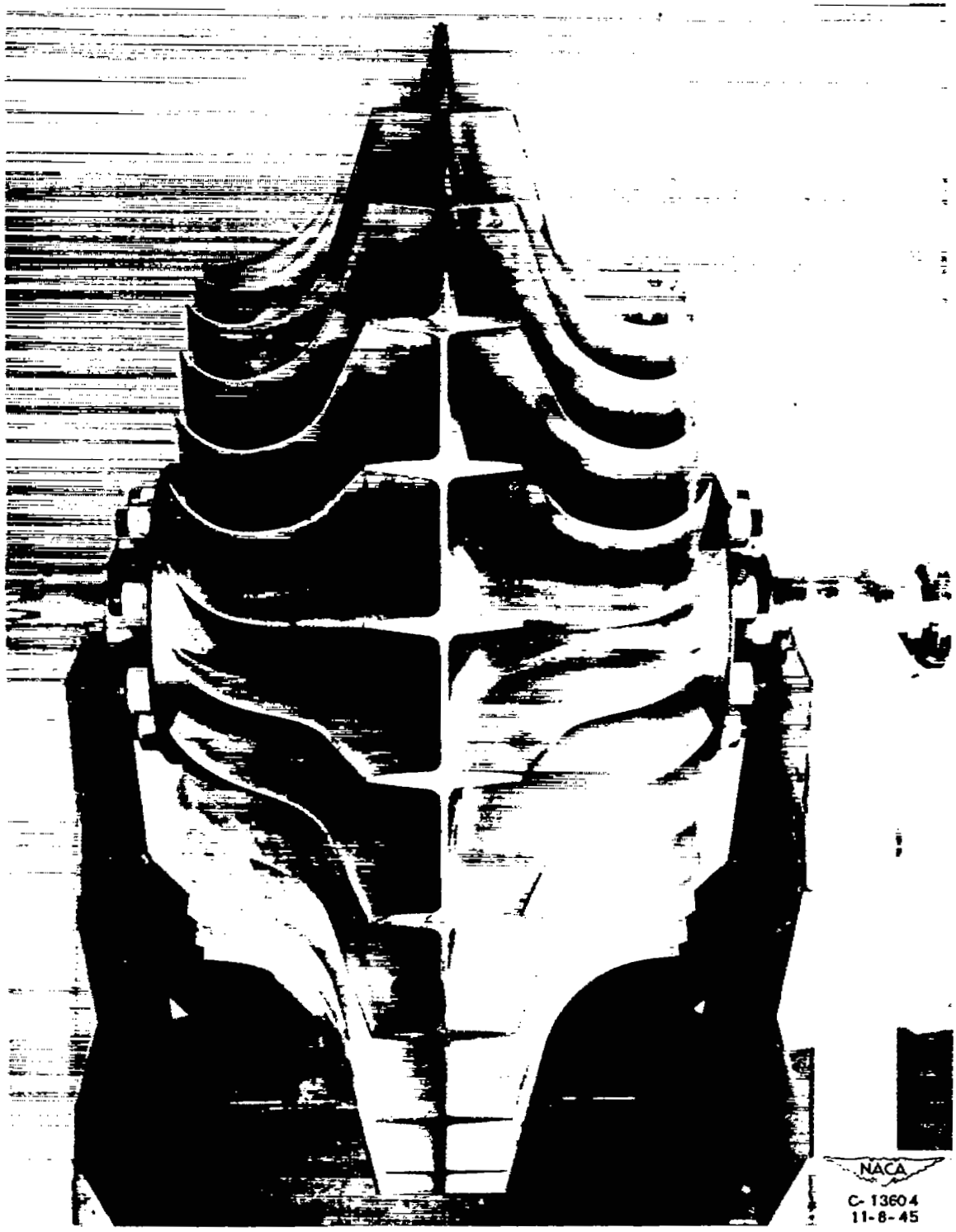

Figure 1. - J33 double-entry centrifugal impeller.

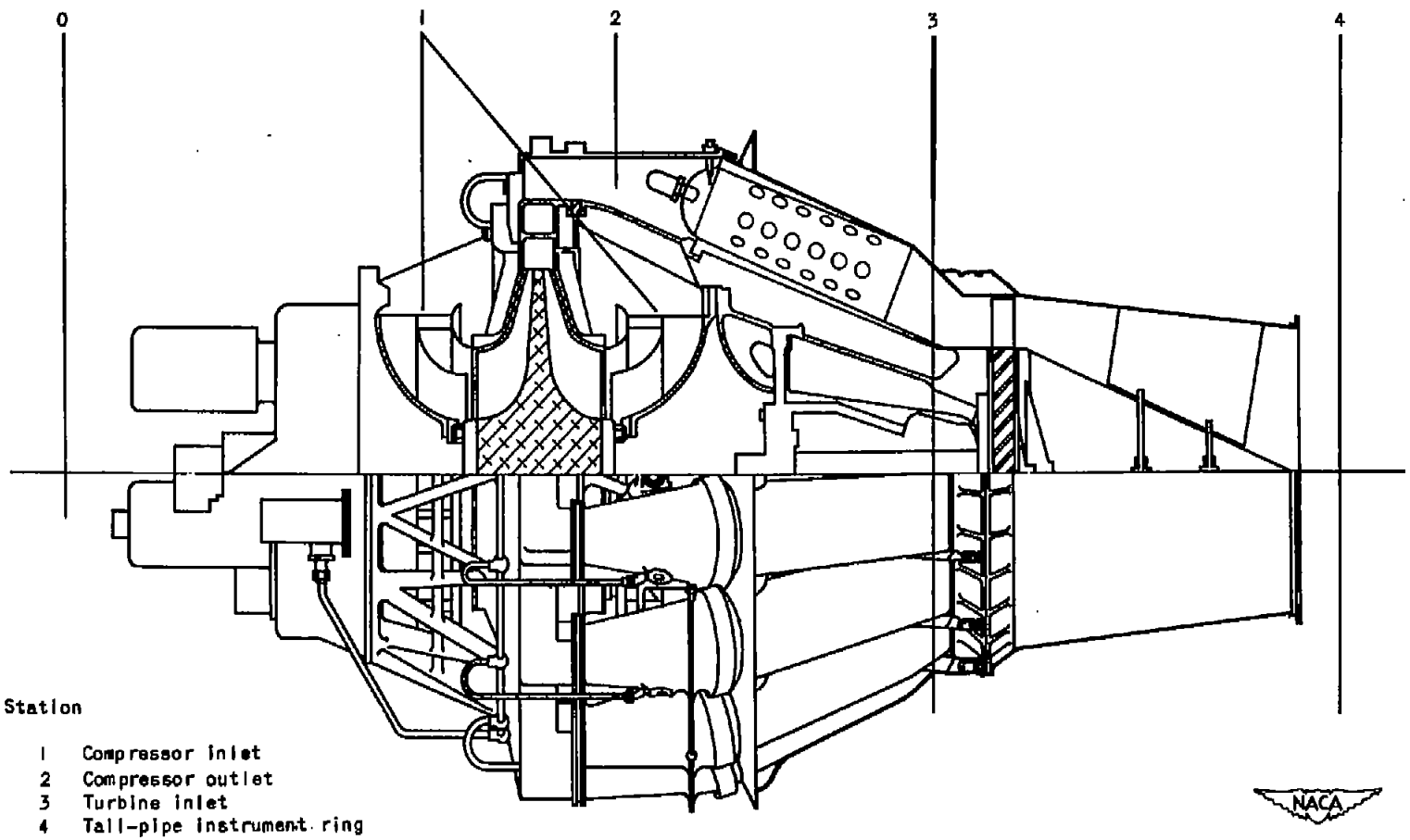

Figure 2. - Cross section of J33 engine showing cycle stations.

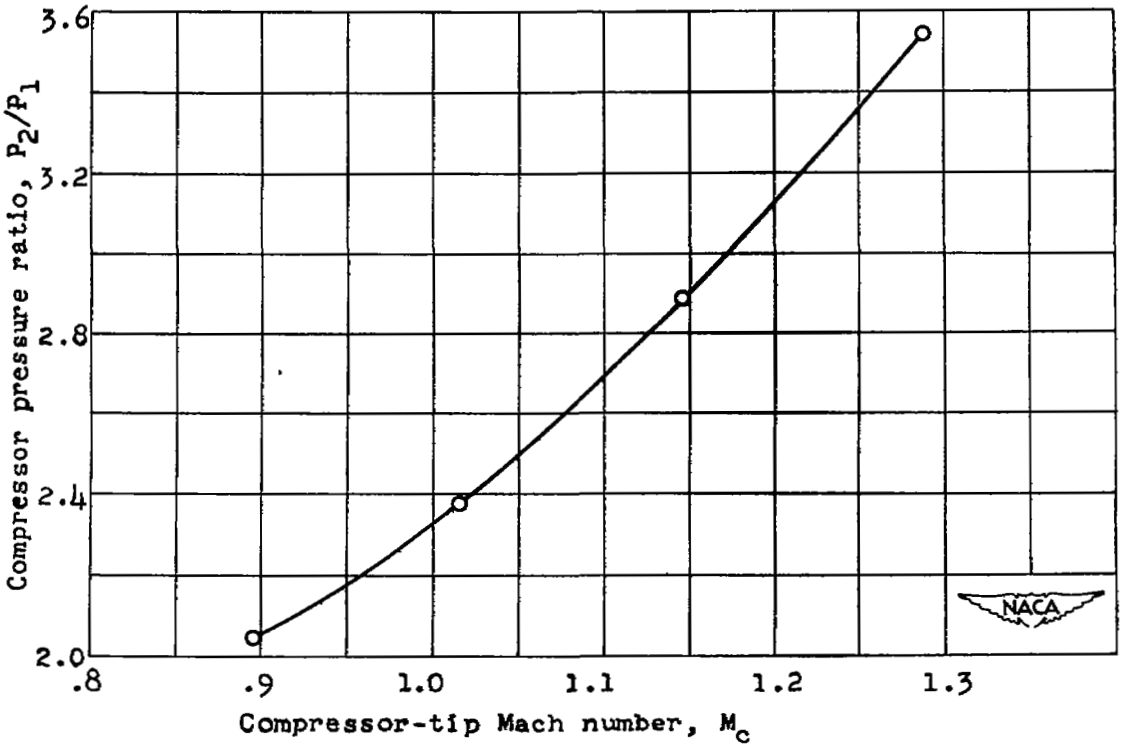

Figure 3. - Variation of compressor pressure ratio with compressor-tip Mach number. Turbine-inlet temperature, 2000° R.

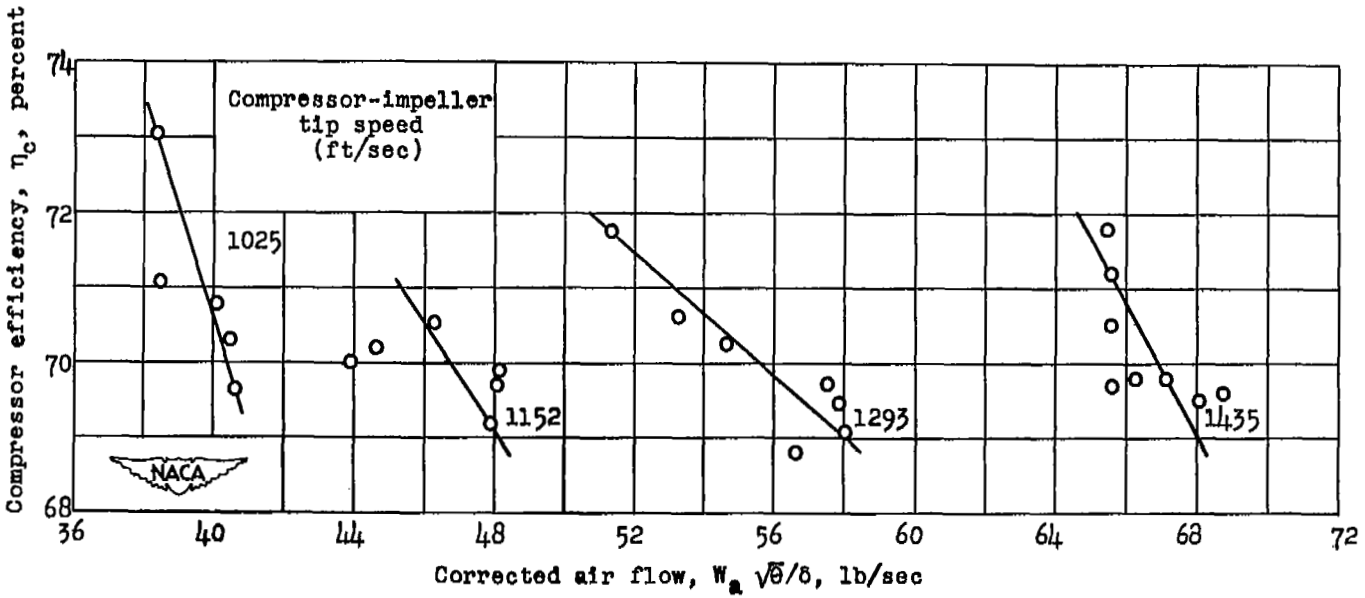

Figure 4. - Variation of compressor efficiency with corrected air flow at four compressor-impeller tip speeds.

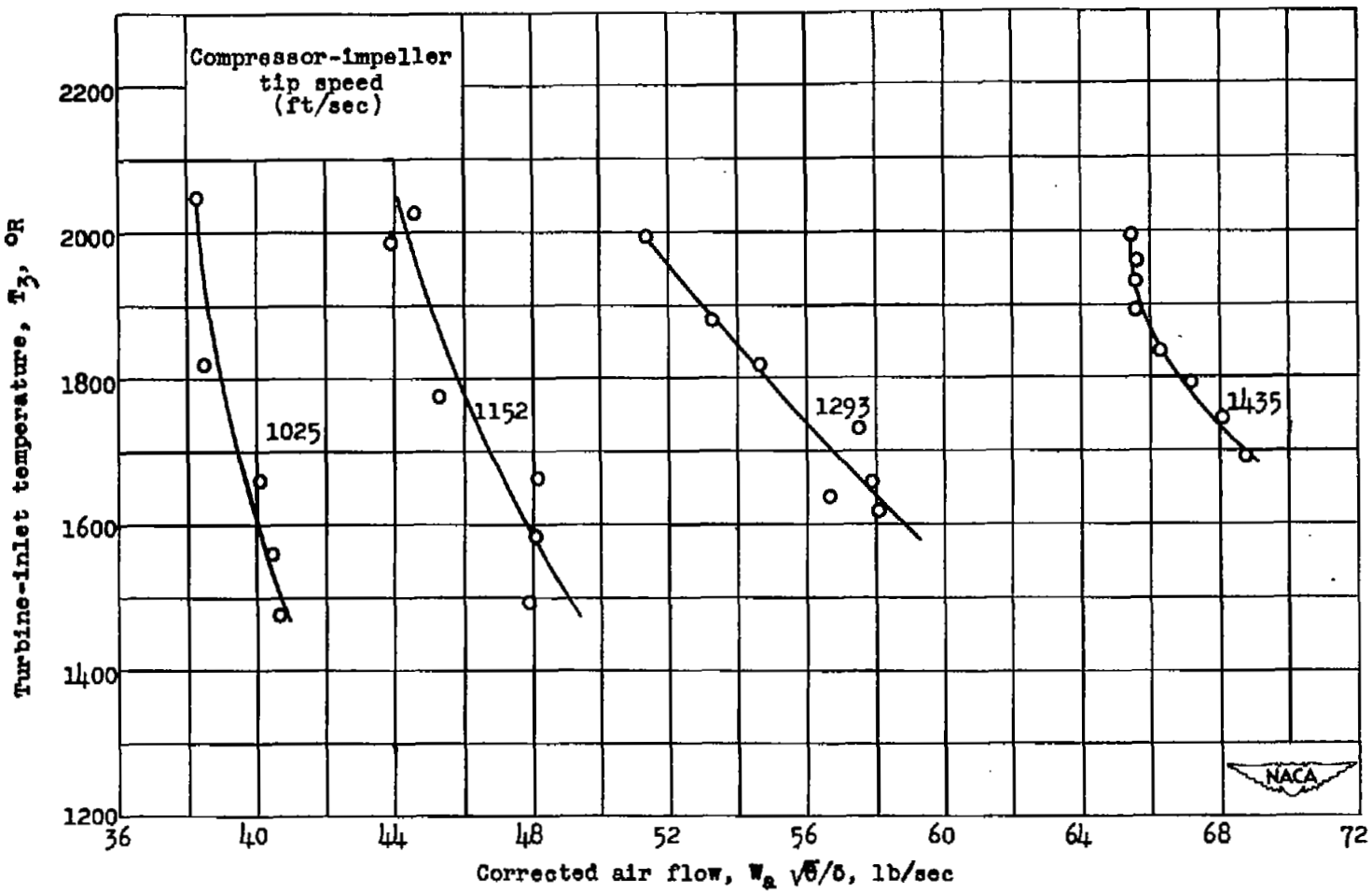

Figure 5. - Variation of turbine-inlet temperature with corrected air flow at four compressor-impeller tip speeds.

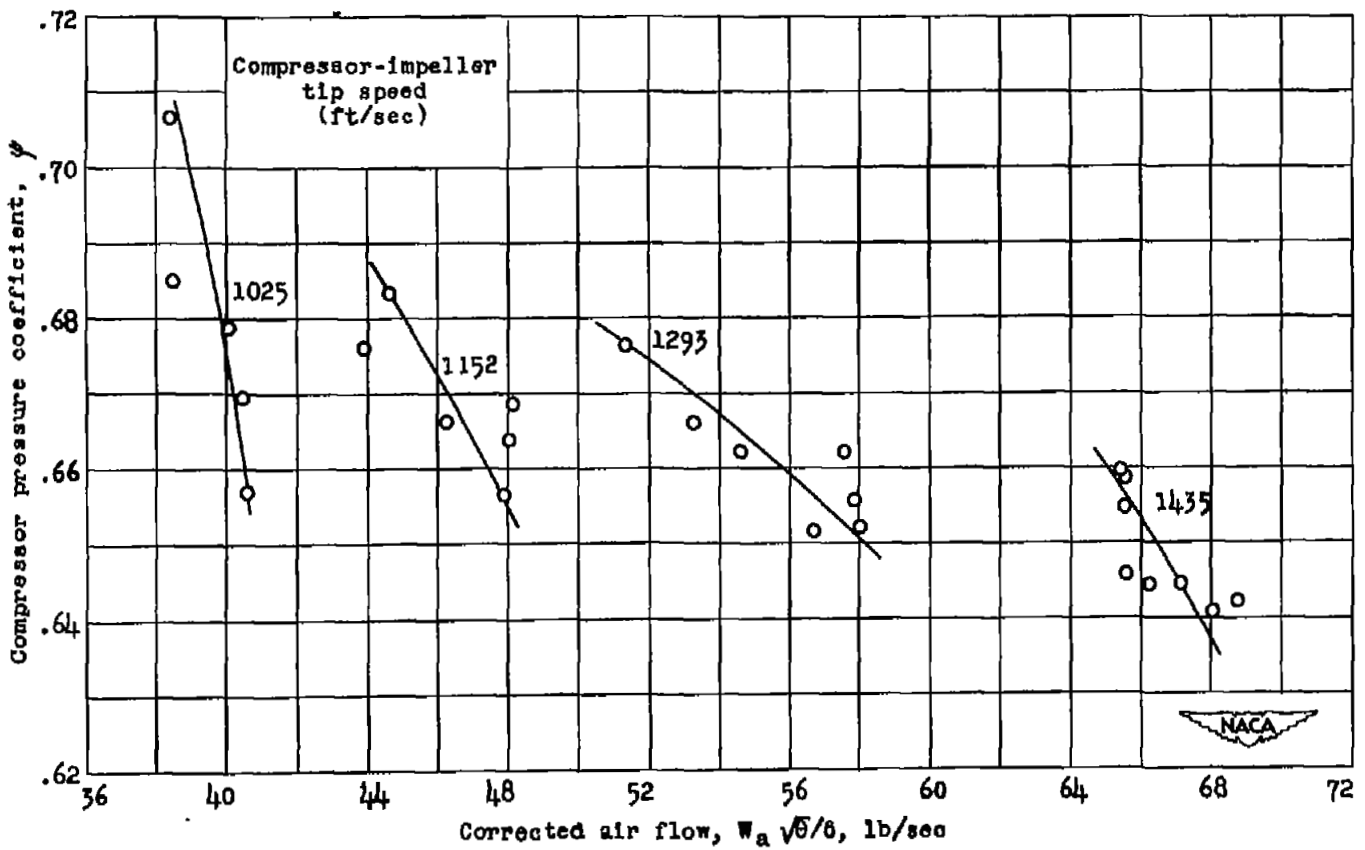

Figure 6. - Variation of compressor pressure coefficient with corrected air flow at four compressor impeller tip speeds.

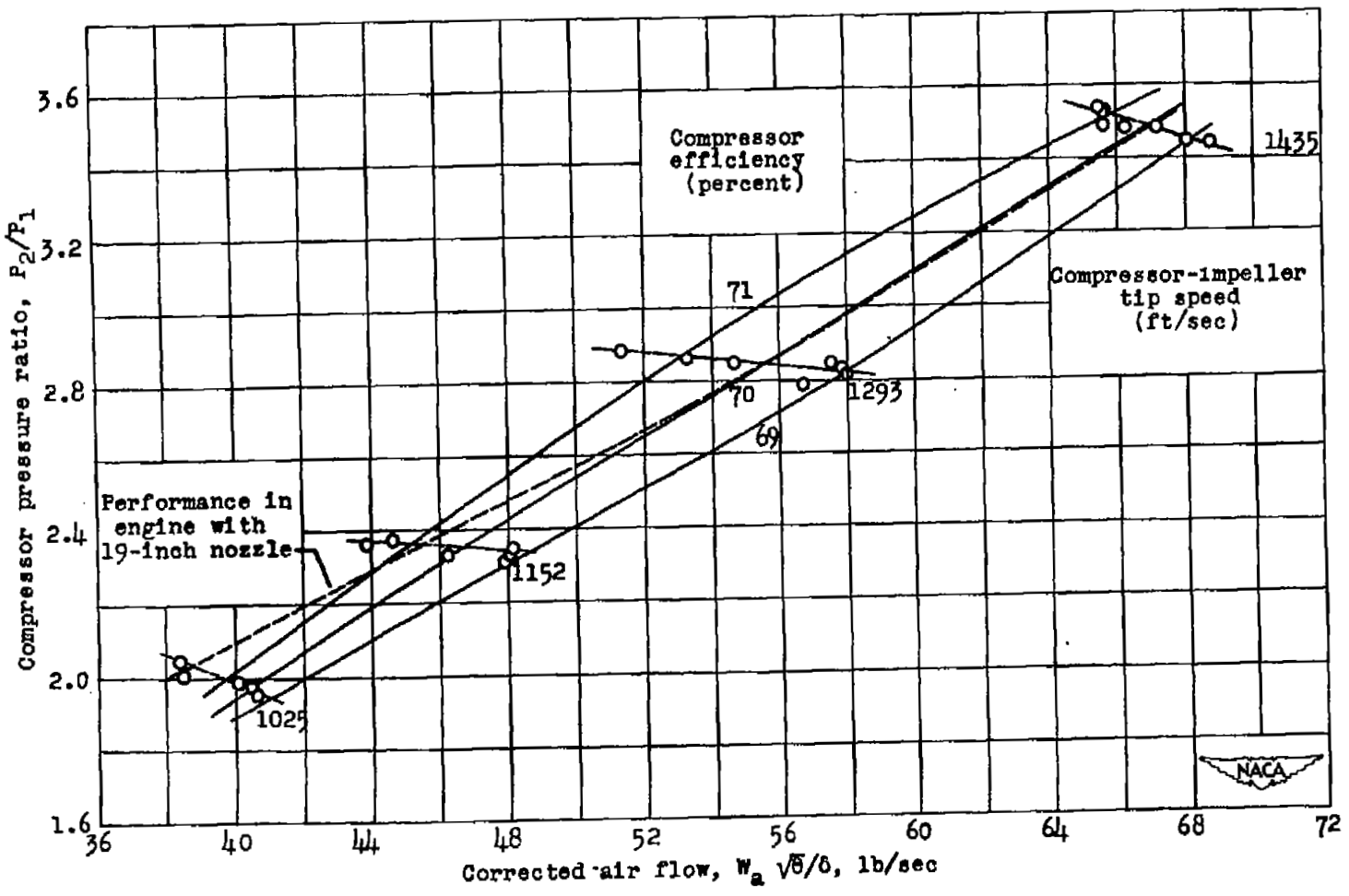

Figure 7. - Performance chart of J33 compressor.

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