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RESEARCH MEMORANDUM

OVER-ALL PERFORMANCE OF THE J71 THREE-STAGE TURBINE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

An investigation was conducted to determine the over-all performance of the three-stage turbine from the J71 turbojet engine.

The turbine operated with a maximum brake internal efficiency of approximately 0.84 at an equivalent over-all pressure ratio of approximately 3.6 and an equivalent rotor speed of about 110 percent of the equivalent design value. At the equivalent design pressure ratio of 3.5 and 100 percent of equivalent design rotor speed, the brake internal efficiency was 0.83. Equivalent design work was obtained at a pressure ratio higher than the equivalent design value. At equivalent design speed and work, the brake internal efficiency was 0.83. The turbine choked downstream from the first stator above a stagnation pressure ratio $p_1'/p_{x,2}'$ of about 3.8 for all speeds investigated. The equivalent weight flow passed by the turbine at equivalent design pressure ratio and rotor speed was 105 percent of the equivalent design value. Limiting blade loading did not occur in the last stage of the turbine over the range of operating conditions investigated.

INTRODUCTION

The over-all performance of the three-stage turbine from the J71 turbojet engine was evaluated as a part of an investigation of the operational characteristics of high-work-output, low-speed, multistage turbines at the NACA Lewis laboratory.

The turbine was operated at a constant inlet stagnation pressure of 40.5 inches of mercury absolute and an inlet stagnation temperature of 700° R over a range of pressure ratios for equivalent rotational speeds of 20, 40, 60, 70, 80, 90, 100, 110, 120, and 130 percent of the equivalent design value.

The over-all performance is presented in terms of brake internal efficiency and equivalent work (each based on torque measurements), equivalent pressure ratio, equivalent rotor speed, and equivalent weight flow. The equivalent design parameters are discussed in reference 1.

SYMBOLS

The following symbols are used in this report:

E enthalpy drop based on torque measurement (Btu/lb)

g acceleration due to gravity (32.174 ft/sec^2)

N rotational speed (rpm)

p' stagnation pressure (lb/sq ft) 2543

p'_x static pressure plus the velocity pressure corresponding to axial component of velocity (lb/sq ft)

R universal gas constant (53.379 ft-lb/(lb)(^{o}R))

T' stagnation temperature (^{o}R)

V_{cr} critical velocity, $\sqrt{\frac{2\gamma}{\gamma+1} gRT'}$

w weight flow (lb/sec)

$\frac{wN\beta}{60\delta}$ weight-flow parameter based on equivalent weight flow and equivalent rotational speed

β function of γ, $\frac{\gamma_0}{\gamma_e}\left[\frac{\left(\frac{\gamma_e+1}{2}\right)^{\frac{\gamma_e}{\gamma_e-1}}}{\left(\frac{\gamma_0+1}{2}\right)^{\frac{\gamma_0}{\gamma_0-1}}}\right]$

γ ratio of specific heats

δ ratio of inlet-air pressure to NACA standard sea-level pressure (p'_1/2116 (lb)(sq ft))

η_i brake internal efficiency defined as ratio of actual turbine work based on torque measurements to ideal turbine work based on inlet stagnation pressure p'_1 and outlet stagnation pressure corrected for whirl $p'_{x,2}$

θ_{cr} squared ratio of critical velocity to critical velocity at NACA standard sea-level temperature (518.4° R), $(V_{cr,e}/V_{cr,0})^2$

τ torque (ft-lb)

Subscripts:

0 NACA standard sea-level conditions

1 turbine-inlet measuring station

2 turbine-outlet measuring station

cr critical

e engine operating conditions

x axial

APPARATUS

Turbine. - The three-stage turbine for the J71 turbojet engine was designed for the following conditions:

	Engine design conditions	Equivalent design conditions
Work (Btu/lb)	131.2	32.4
Weight flow (lb/sec)	150.0	37.58
Rotative speed (rpm)	6100	3028
Inlet temperature (°R)	2160	518.4
Inlet pressure (in. Hg abs.)	249	29.92

The turbine was designed for a work split of 38.5 percent in the first stage, 33.0 percent in the second stage, and 28.5 percent in the third stage. This design resulted in 12.4, 15.7, and 16.3 percent reaction in the respective stages at the mean radius. The turbine tip diameter is constant at 33.5 inches; the annular area increases through the turbine with the inner shroud having a cone half-angle of 11°. The mean hub-tip radius ratios for the first-, second-, and third-stage rotors are 0.795, 0.746, and 0.697, respectively.

Power absorbers. - Two cradled eddy-current-type dynamometers were used to absorb the power output of the turbine.

Test installation. - The experimental installation of the turbine is shown in figure 1. Air was supplied to the unit from the laboratory combustion-air system at approximately 110 inches of mercury absolute. The air was throttled to a pressure of about 40.5 inches of mercury absolute and then heated to 700° R by two standard jet-engine combustors. The air flow was divided and entered the plenum chamber through two openings spaced 180° apart. This may be seen in figure 1 and internally in figure 2. This plenum replaced the standard combustor assembly used on an engine build-up and, with the aid of the screen, helped to equalize the velocity distribution of the entering air. From the plenum, the air passed into 10 standard engine transition sections, each of which supplied air to a segment of the first stator row, thence through the successive blade rows and the tail cone, and finally into the laboratory exhaust system.

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INSTRUMENTATION

Turbine weight flow. - The air weight flow was determined with the use of a calibrated A.S.M.E. flat-plate flange-tap submerged orifice. Fuel flow to the heaters was measured with calibrated rotameters in the fuel supply line.

Power output. - Turbine shaft output was measured with an NACA balanced-diaphragm torquemeter attached to the cradled dynamometer casing. The turbine rotational speed was measured with an electric chronometric tachometer that was driven by a generator coupled directly to the dynamometer shaft.

Gas state. - The gas state in the turbine was measured at the two axial stations shown in figure 2. The stagnation conditions at the inlet to the turbine were measured by 10 combination probes, one probe being located in each of the transition sections. Each combination probe had a shielded total-pressure tube and a calibrated spike-type thermocouple on the same stem. Wall static pressures were measured by 20 static-pressure taps, two taps being located in each of the 10 standard transition sections ahead of the first stator blade row. The gas conditions at the exit from the third rotor were measured by five total-pressure probes and four calibrated spike-type total-temperature rakes, each temperature rake having five thermocouples. The pressure probes and the thermocouples were arranged circumferentially around the annulus and located radially so as to be at the centroids of five equal annulus areas. A total of eight static-pressure taps, four on the inner shroud and four on the outer shroud, arranged circumferentially and opposite each other in pairs, were used to measure static pressure at this measuring station.

Precision of instruments. - The instruments used for this investigation resulted in obtaining data having the following precision:

Temperature, °R	±1.0
Pressure, in. Hg abs.	±0.05
Air weight flow, percent	±1.0
Rotor speed, percent	±0.5
Torque, percent	±0.5

Measurements made with this precision would have a cumulative effect on turbine brake internal efficiency of ±2.0 percent.

METHODS AND PROCEDURE

Variations in the ratio of specific heats from the design turbine-inlet temperature to standard sea-level temperature are of sufficient magnitude to warrant consideration along with the variations in temperature when determining the equivalent conditions of the turbine. Mach numbers through the turbine are close to the value of 1.0; hence, an approximation of equivalent conditions can be obtained by a method based on critical velocity determined from the stagnation temperature at the turbine inlet and an average equilibrium value of γ. Derivation of this method is presented in reference 1. It should be noted that exact correlations can never be obtained. For over-all engine performance analysis, however, the errors thus introduced are usually small and are probably less than those resulting from combinations of miscellaneous factors such as random air leaks, changes in tip clearance, and changes in turbine area. The curves necessary for the application of this method to the performance map given in this report are reproduced here for convenience. The variation of β as a function of γ for a range of γ from 1.30 to 1.40 is shown in figure 3. Figure 4 gives the variation of the ratio of pressure ratio at equivalent conditions to pressure ratio at engine conditions with ratio of specific heats.

The pressure $p'_{x,2}$ is defined as the static pressure after the third rotor plus the velocity pressure corresponding to the axial component of the absolute velocity at the exit from the turbine. This calculated value of turbine-exit stagnation pressure charges the turbine for the energy of the whirl component existent in the leaving velocity of the gas. Uniform flow is also assumed, which further charges the turbine for the energy represented by the velocity variations at the turbine exit. This pressure is calculated from the general energy equation and continuity with the use of the known annulus area at the measuring station and measured values of weight flow, static pressure, stagnation pressure, and stagnation temperature. The design pressure ratio at engine operating conditions was determined from the velocity diagrams at the mean radius. Since the design exit velocity had less than 1° of whirl, it was assumed that $(p'_{x,2})_e$ equaled $(p'_2)_e$. The equivalent design pressure ratio $(p'_1/p'_{x,2})_0$ was determined from figure 4, which considers the variation of γ.

The turbine was operated at a constant inlet stagnation pressure and temperature of approximately 40.5 inches of mercury absolute and 700° R, respectively, for equivalent rotative speeds of 20, 40, 60, 70, 80, 90, 100, 110, 120, and 130 percent of the design values over a range of pressure ratios $p_1'/p_{x,2}'$ from 1.4 to 4.4.

RESULTS AND DISCUSSION

The over-all performance of the J71 three-stage turbine is pre- 2543
sented in terms of equivalent work, equivalent weight flow, brake internal efficiency, equivalent total-pressure ratio, and equivalent rotor speed.

A composite map is presented in figure 5 showing the over-all performance of the turbine in terms of equivalent work E/θ_{cr} and a weight-flow parameter $wN\beta/60\delta$ for lines of constant equivalent pressure ratio $p_1'/p_{x,2}'$ and constant equivalent rotor speed $N/\sqrt{\theta_{cr}}$ with contour lines showing the brake internal efficiency levels η_i over the operating range of the turbine.

The turbine operated with a maximum brake internal efficiency of approximately 0.84 at an equivalent over-all pressure ratio of approximately 3.6 and an equivalent rotor speed of about 110 percent of the equivalent design value. At the equivalent design pressure ratio of 3.5 and 100 percent of equivalent design rotor speed, the brake internal efficiency was 0.83. Equivalent design work was obtained at a pressure ratio higher than the equivalent design value. At equivalent design work and rotor speed, the brake internal efficiency was 0.83.

A curve showing the relation between the equivalent weight flow and over-all pressure ratio $(p_1'/p_{x,2}')$ for lines of constant equivalent rotor speed is presented as figure 6. It can be seen that the turbine choked above an over-all pressure ratio of about 3.8 for all rotor speeds investigated. However, the choking weight flow was different for each rotor speed, indicating a choking condition somewhere downstream of the first stator. The equivalent weight flow obtained at equivalent design speed and pressure ratio is 105 percent of the design equivalent weight flow.

The equivalent torque output τ/δ plotted against the over-all pressure ratio $p_1'/p_{x,2}'$ is shown in figure 7. It may be seen that the equivalent torque is still rising with an increase in over-all pressure ratio for all speeds investigated, even though figure 6 shows a choking flow condition for equivalent rotor speeds of 100 through 130 percent of design for all equivalent pressure ratios above about 3.8. It is indicative from this that limiting blade loading has not occurred in the last stage of the machine as was the case for the turbine investigated in reference 1.

SUMMARY OF RESULTS

The over-all performance investigation of the J71 three-stage tur-
2543 bine produced the following results:

1. The turbine operated with a maximum brake internal efficiency of approximately 0.84 at an equivalent over-all pressure ratio of approximately 3.6 and an equivalent rotor speed of about 110 percent of the equivalent design value.

2. At the equivalent design pressure ratio of 3.5 and 100 percent of equivalent design rotor speed, the brake internal efficiency was 0.83. Equivalent design work was obtained at a pressure ratio higher than the equivalent design value. At equivalent design speed and work, the brake internal efficiency was 0.83.

3. The turbine choked downstream of the first stator above an over-all pressure ratio $p_1'/p_{x,2}'$ of about 3.8 for all speeds investigated. The equivalent weight flow passed by the turbine at equivalent design pressure ratio and rotor speed was 105 percent of the equivalent design value.

4. Limiting blade loading did not occur in the last stage of the turbine over the range of operating conditions investigated.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 19, 1952

REFERENCE

1. Rebeske, John J., Jr., Berkey, William E., and Forrette, Robert E.: Over-All Performance of J35-A-23 Two-Stage Turbine. NACA RM E51E22, 1951.

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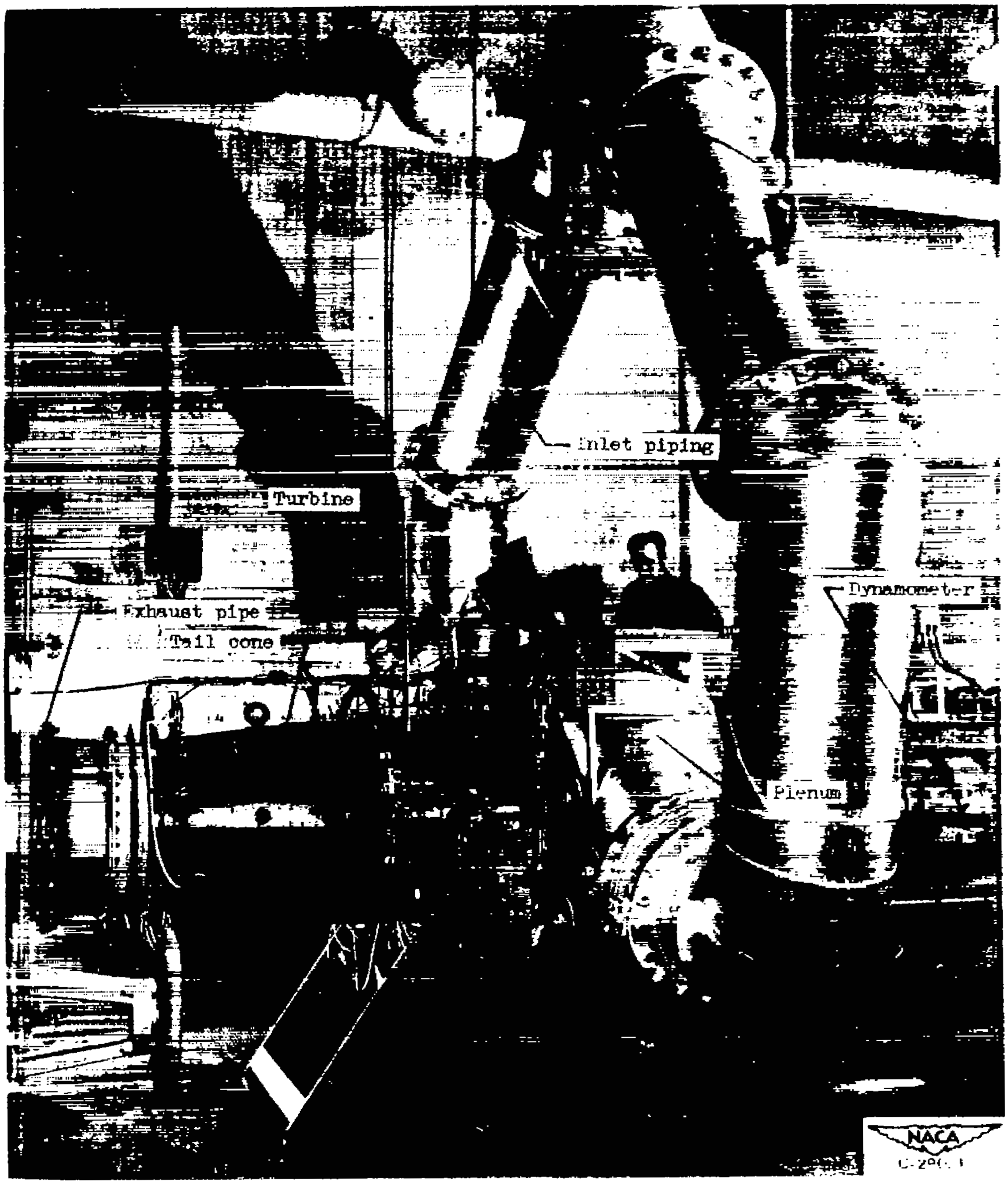

gure 1. - Installation for experimental investigation of J71 three-stage turbine showing inlet plenum and instrumentation.

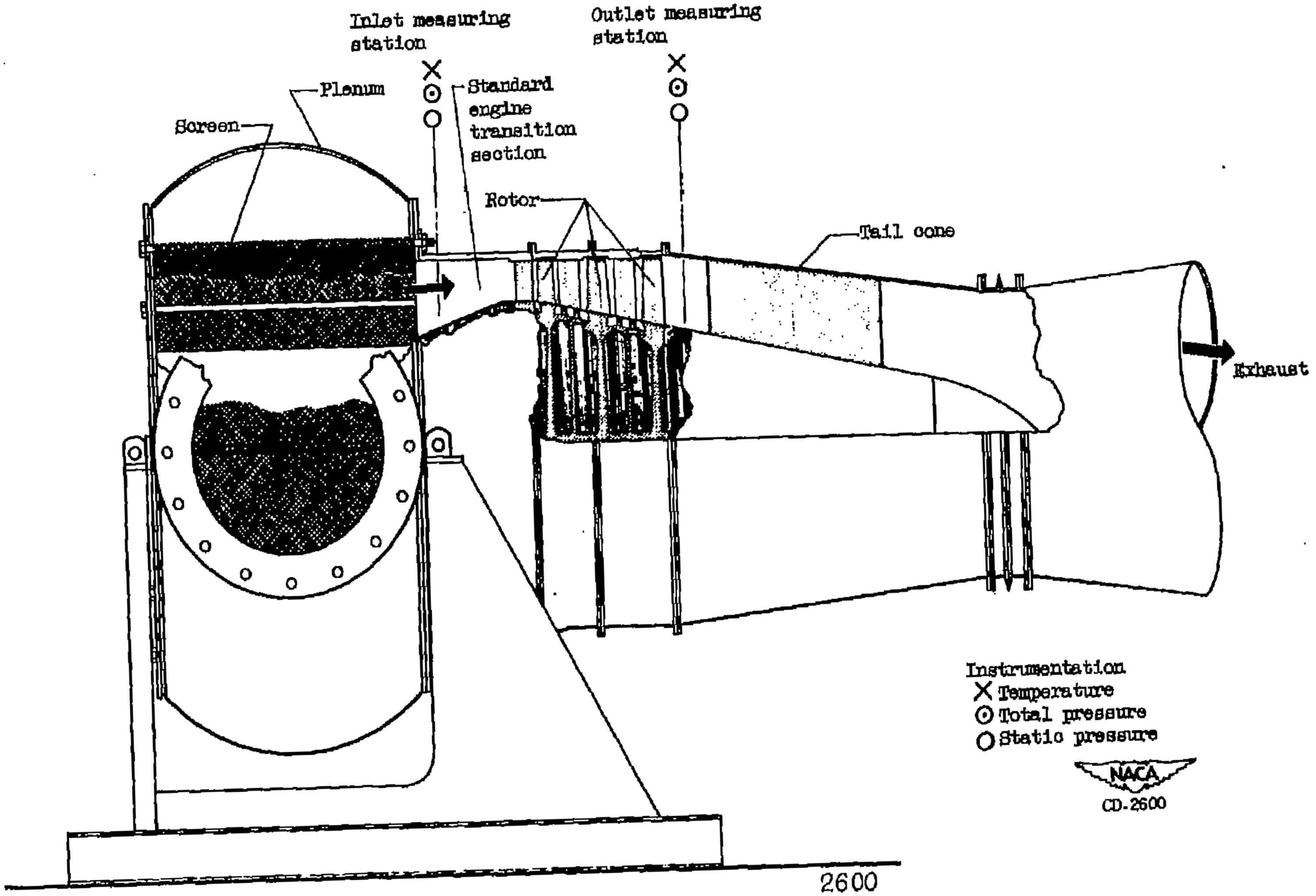

Figure 2. - Schematic diagram of turbine assembly and instrumentation.

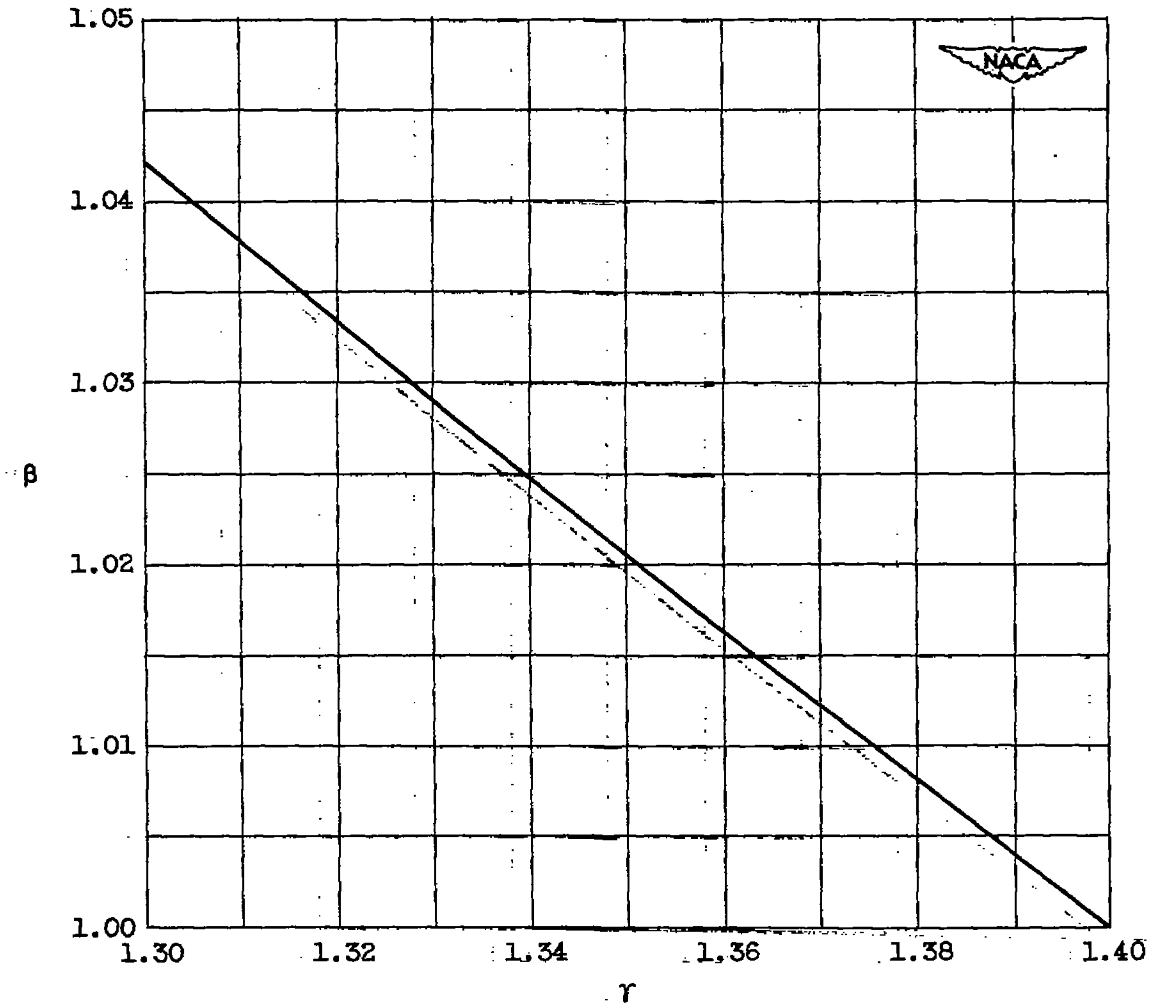

Figure 3. - Variation of β as a function of γ (fig. 6 of reference 1).

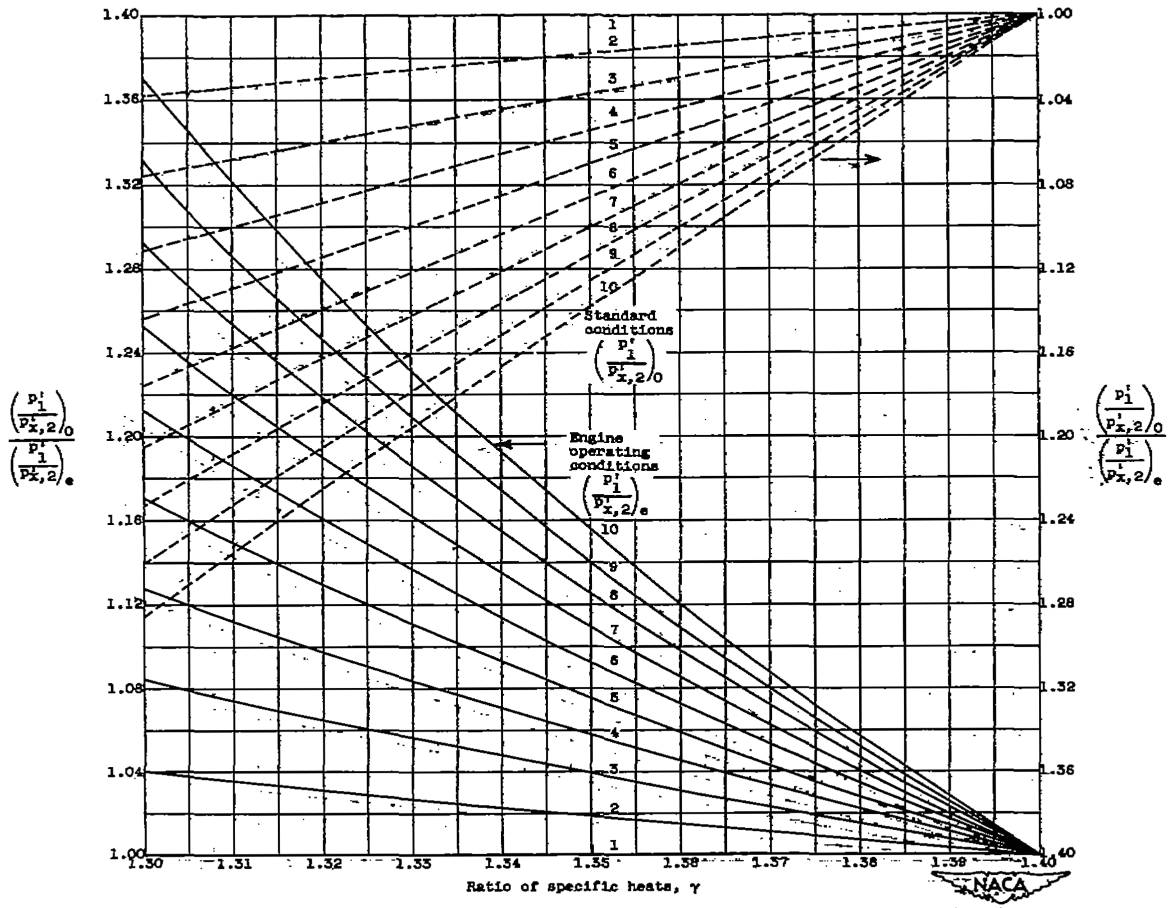

Figure 4. - Variation of the ratio of pressure ratio at standard conditions to pressure ratio at engine conditions with ratio of specific heats (fig. 7 of reference 1).

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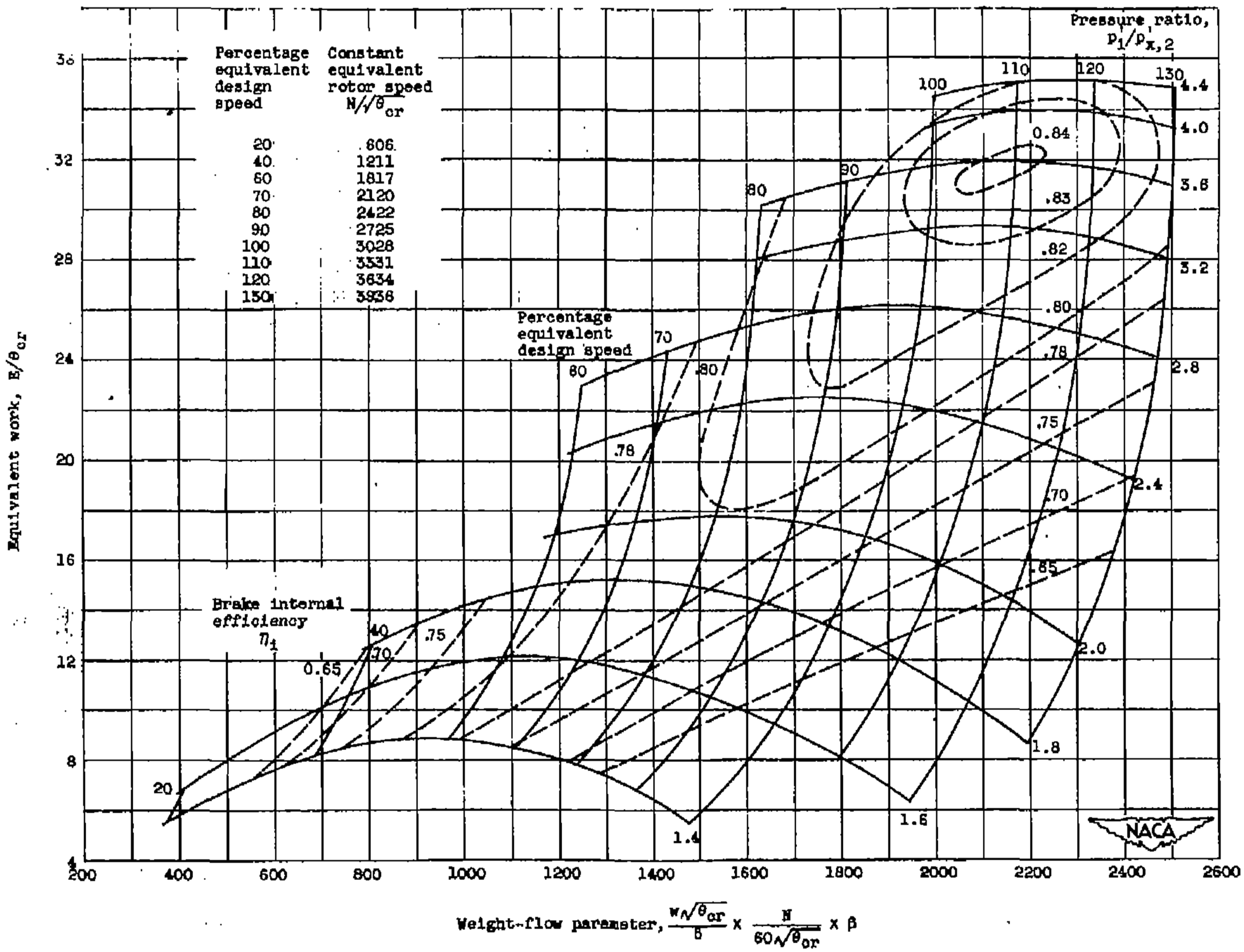

Figure 5. - Over-all performance of J71 three-stage turbine presented in terms of equivalent work and a weight-flow parameter for lines of constant equivalent speed, pressure ratio, and brake internal efficiency.

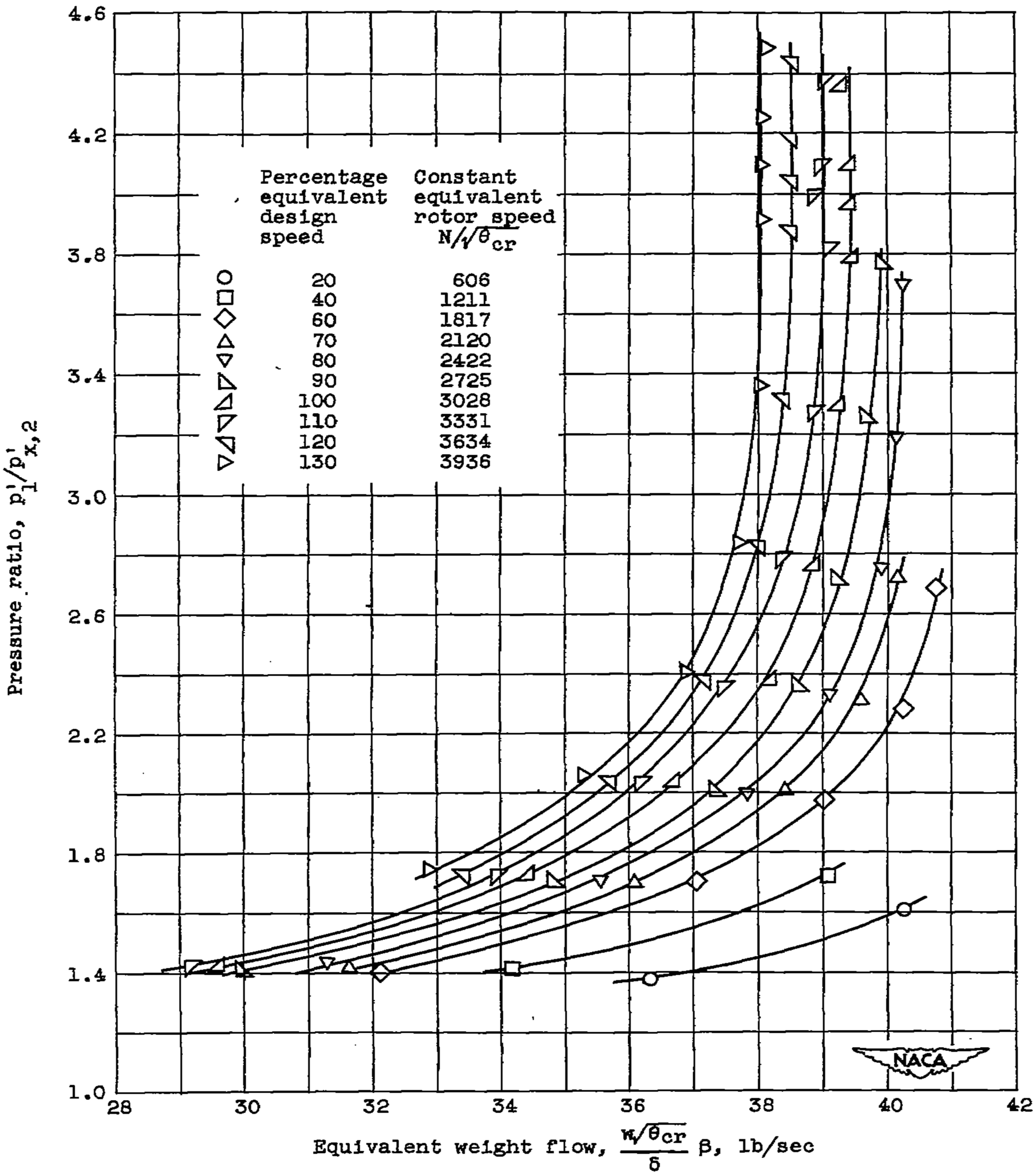

Figure 6. - Variation of equivalent weight flow with pressure ratio for various turbine speeds.

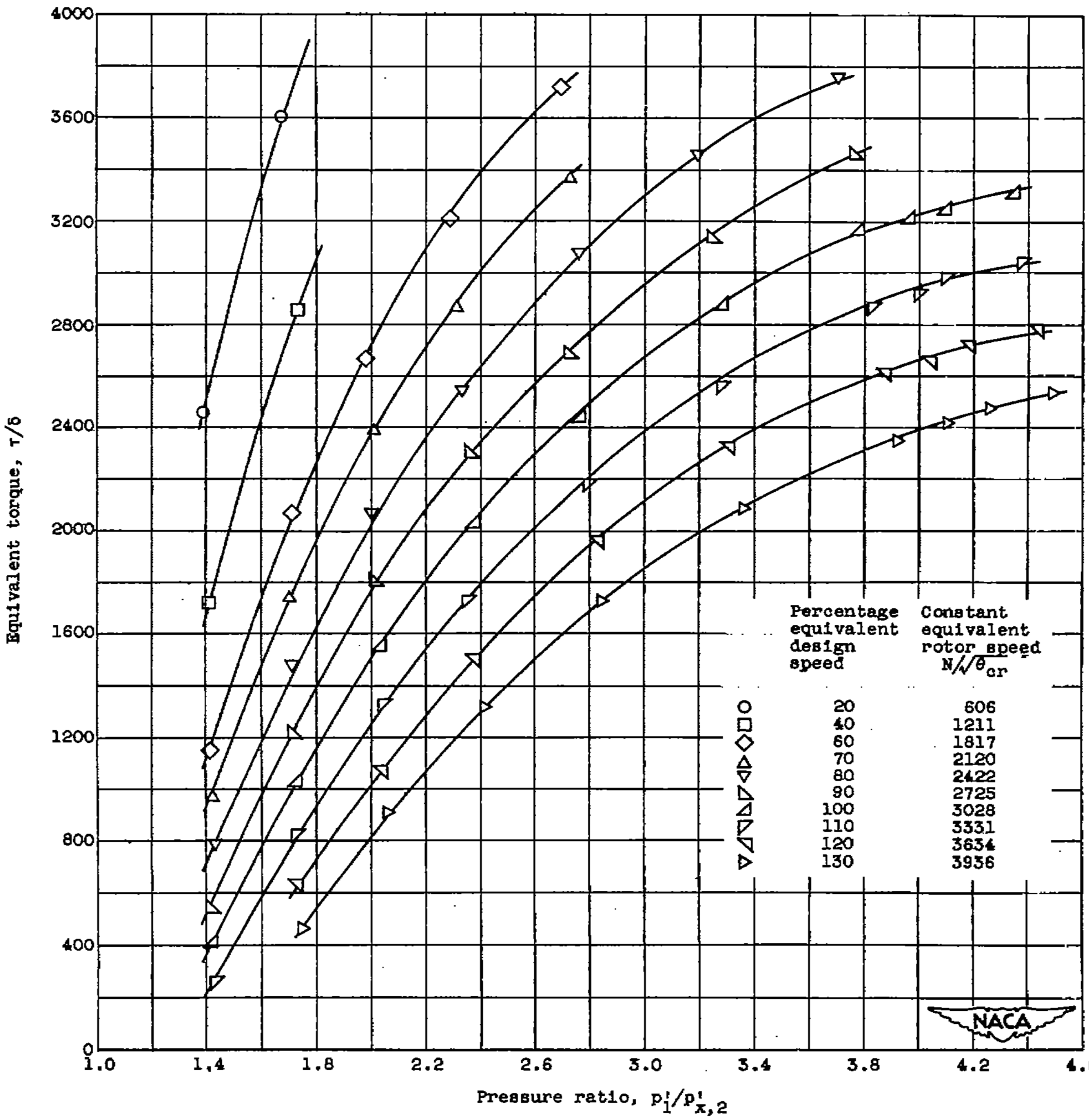

Figure 7. - Variation of equivalent torque with pressure ratio for various turbine speeds.

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SECURITY INFORMATION

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