RESEARCH MEMORANDUM

for the

Air Materiel Command, Army Air Forces

PRELIMINARY RESULTS OF AN ALTITUDE-WIND-TUNNEL

INVESTIGATION OF A TG-100A GAS

TURBINE-PROPELLER ENGINE

II - WINDMILLING CHARACTERISTICS

By E. W. Conrad and J. D. Durham

Flight Propulsion Research Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
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CONFIDENTIAL
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY RESULTS OF AN ALTITUDE-WIND-TUNNEL INVESTIGATION OF

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SUMMARY

An investigation has been conducted in the Cleveland altitude wind tunnel to determine the operational and performance characteristics of the TG-10CA gas turbine-propeller engine. As a part of the investigation, windmilling characteristics were determined for a range of altitudes from 5000 to 35,000 feet, true airspeeds from 100 to 273 miles per hour, and propeller-blade angles from 45° to 46°.

The desirability of feathering the propeller of an inoperative engine was indicated by the high windmilling speeds and high drag values otherwise obtained. Extrapolation of the data showed that excessive windmilling speeds would be reached for propeller-blade angles from 5° to 41° at a true airspeed of 500 miles per hour. At an altitude of 35,000 feet, a true airspeed of 273 miles per hour, and a propeller-blade angle of 36°, the drag horsepower of the test installation was 585. When the propeller-blade angle was decreased to 6°, with a true airspeed in the tunnel of 255 miles per hour, the drag horsepower of the installation increased to 2647. For all conditions, maximum engine windmilling speed was obtained at propeller-blade angles between 10° and 16°. The application of generalizing factors to engine windmilling speed, air flow, and combustion-chamber pressure drop gave good results.

INTRODUCTION

At the request of the Air Materiel Command, Army Air Forces, an investigation has been conducted in the Cleveland altitude wind tunnel to determine the operational and performance characteristics
of the TG-100A gas turbine-propeller engine. The performance characteristics are presented in reference 1.

As a part of the investigation, the windmilling characteristics were obtained for a range of altitudes from 5000 to 35,000 feet, true airspeeds from 190 to 273 miles per hour, and propeller-blade angles from 4° to 46°. The windmilling speed, the air flow, and the drag are presented for the range of simulated flight conditions investigated. Over-all pressure distributions through the engine and pressure surveys at each of the measuring stations are shown for the maximum windmilling speed at each simulated flight condition. A complete tabulation of the data is presented. No correction has been made for the tunnel blocking effects of the propeller.

INSTALLATION AND TEST PROCEDURE

Components of the TG-100A gas turbine-propeller engine include a 14-stage axial-flow compressor, nine cylindrical counterflow combustion chambers, and a single-stage turbine. Power is transmitted to the propeller by two stages of planetary gears having an over-all reduction ratio of 11.3513 to 1. A four-blade superhydromatic propeller (hub design 4260) 12 feet, 7 inches in diameter was used. Automatic and manual propeller controls and a blade-angle indicator were provided for this investigation. The blade-form curves for this propeller are shown in figure 1.

The engine was mounted in a specially designed wing nacelle installed in the 20-foot-diameter test section of the altitude wind tunnel (fig. 2). Air was supplied to the engine by two ducts having openings in the leading edge of the wing, as shown in figure 3. Temperature and pressure measurements were obtained at eight stations along the path of air flow through the installation. A more complete description of the engine and test installation is given in reference 1.

Each series of conditions was obtained by varying the propeller-blade angle and maintaining constant altitude and true airspeed. The investigation was conducted at approximately NACA standard altitude conditions.

SYMBOLS

The following symbols are used in the calculations:

A  cross-sectional area, square feet
D/q0  windmilling drag coefficient,
      total drag of installation - streamline drag, square feet
      free-stream dynamic pressure

Dt  total drag of installation, pounds

g  acceleration due to gravity, feet per second per second

H  enthalpy, Btu per pound

J  mechanical equivalent of heat, foot-pounds per Btu

N  engine speed, rpm

P  total pressure, pounds per square foot absolute

p  static pressure, pounds per square foot absolute

q0  free-stream dynamic pressure, pounds per square foot

R  gas constant

shp  shaft horsepower (excluding friction horsepower and gear losses)

T1  indicated temperature, °R

t  static temperature, °R

V0  tunnel airspeed, feet per second

Wa  air flow, pounds per second

β  propeller-blade angle at 72-inch radius, degrees

γ  ratio of specific heats for air

S  ratio of tunnel-test-section static pressure to pressure of NACA standard atmosphere at sea level

θ  ratio of tunnel-test-section absolute static temperature to absolute temperature of NACA standard atmosphere at sea level

Subscripts:

0  tunnel test section free air stream

1  wing-duct inlet
compressor inlet
compressor outlet
compressor-outlet elbow
turbine inlet
turbine outlet
exhaust-cone outlet
tail-pipe-nozzle outlet

The following parameters are generalized to NACA standard sea-level conditions:

\( \frac{N}{\sqrt{\theta}} \)  corrected engine speed, rpm
\( \frac{(W_a \sqrt{\theta})}{\delta} \)  corrected air flow, pounds per second
\( \frac{(\Delta P)}{\delta} \)  corrected total-pressure drop across combustion chambers, pounds per square foot

**CALCULATIONS.**

The shaft horsepower delivered to the engine under windmilling conditions, excluding friction horsepower and gear losses, is approximated by the change in energy of the air flowing through the engine

\[
\text{shp} = \frac{J}{550} W_{a,2} (H_3 - H_2) \tag{1}
\]

where \( W_{a,2} \) was obtained from the equation

\[
W_{a,2} = A_2 P_2 \sqrt{\frac{2 \gamma E}{(\gamma-1) R} \left[ \frac{P_2}{P_2} \right]^{-1} - 1} \tag{2}
\]
The static temperature is given by the equation

\[ t_2 = \frac{T_{1,2}}{0.85 \left( \frac{P_2}{P_2} \right)^{\frac{\gamma - 1}{\gamma}} + 1} \]

The constant of 0.85 in equation (3) is the thermocouple impact recovery factor, which was experimentally determined. Air flows measured at the compressor inlet were used in the calculations because they were more consistent than measurements at the wing-duct inlets or the tail-pipe survey rake. Values of enthalpy used in equation (1) were obtained from reference 2.

RESULTS AND DISCUSSION

A complete tabulation of the windmilling data is presented in table I. Windmilling performance characteristics are presented in figures 4 to 12 and pressure surveys throughout the installation are shown in figures 13 to 19. No correction has been made for tunnel blocking effects. These effects are believed to be negligible at high propeller-blade angles, but data obtained at low blade angles may be affected.

**Windmilling performance characteristics:** Engine windmilling speeds obtained at several airspeeds and altitudes are shown in figure 4 as a function of propeller-blade angle. A maximum windmilling speed of 15,100 rpm was obtained at an altitude of 35,000 feet, a true airspeed of 269 miles per hour, and a propeller-blade angle of 16° (fig. 4 (d)). For all simulated flight conditions, the maximum windmilling speeds were obtained at propeller-blade angles from 10° to 16°. The data in figure 4 were cross-plotted and extrapolated to determine the true airspeed at which the rated engine speed of 13,000 rpm would be obtained for any propeller-blade angle in the operating range of 40° to 48° (fig. 5). At a true airspeed of 500 miles per hour, the rated engine speed would be exceeded for all blade angles from about 5° to 41°. The desirability of feathering is evident.

Windmilling shaft horsepower, as determined from the enthalpy rise of the air between the compressor inlet and the tail-pipe-nozzle outlet, are shown in figures 6 and 7 as functions of engine windmilling speed and propeller-blade angle, respectively. Gear losses, which vary from 20 horsepower at 4000 rpm to 100 horsepower at
13,000 rpm, are not included in the shaft horsepowers given. The different values of windmilling shaft horsepower at a given engine speed in figure 6 are the result of reduced engine air flow caused by high pressure losses across the propeller disk at low blade angles.

Maximum windmilling shaft horsepowers occurred in a range of propeller-blade angles from 100° to 160°. A value of 612 shaft horsepower was obtained at an altitude of 15,000 feet, a true airspeed of 209 miles per hour, and a propeller-blade angle of 120° (fig. 7(b)).

Air flow through the engine is given as a function of engine windmilling speed in figure 8. A plot of the same data in generalized form in figure 9 shows that the use of generalizing factors gives good results. Air flows obtained at windmilling conditions and at operating conditions are very nearly the same.

The corrected total-pressure drop across the combustion chambers as a function of corrected engine speed is shown in figure 10. These data also generalized very well.

The variation of windmilling-drag coefficient with propeller-blade angle is shown in figures 11 and 12 for various altitudes and airspeeds, respectively. Maximum values occurred at a blade angle of about 80°. For blade angles less than 120°, the windmilling-drag coefficients decreased with increasing altitude (fig. 11). The effect of change in airspeed was relatively small (fig. 12). At an altitude of 35,000 feet, a true airspeed of 273 miles per hour, and a propeller-blade angle of 360°, the windmilling-drag horsepower of the installation \( D_{t}V_{0} \) was 585. When the blade angle was decreased to 60° with a true 550 airspeed in the tunnel of only 255 miles per hour, the drag horsepower increased to 2647.

Pressure distribution. - Average total and static pressures throughout the engine are shown in figure 13 for a range of altitudes from 5000 to 35,000 feet. The data are shown for a propeller-blade angle of 120°, at which engine speeds near the maximum occurred for all flight conditions. The pressure distribution may be somewhat affected by variations in blade angle owing to differences in the blocking effect of the propeller. Engine windmilling speeds varied from 4100 to 13,000 rpm. Under all conditions, pressure drop occurred across the last few stages of the compressor. The number of compressor stages through which the pressure dropped decreased with increasing engine speed. Increases in total pressure indicated between stations 6 and 7 are attributed to misalignment of the air flow with respect to the instrumentation at the turbine outlet.
Detailed surveys at the measuring stations are shown in figures 14 to 19 for altitudes from 5000 to 35,000 feet and true airspeeds from 102 to 269 miles per hour. Data obtained at 5000 feet are presented for a propeller-blade angle of 10° and the data at other altitudes for a propeller-blade angle of 12°. These data represent engine windmilling speeds varying from 4100 to 13,000 rpm.

Separation of the airflow on the inner side of the duct upper lip in figure 14 is indicated by the low total pressures at the top of rakes 1 to 4. Under power-on conditions this separation occurred at the right duct inlet. Separation in both cases was the result of misalignment of the duct upper lip with respect to the approaching streamlines. This misalignment was apparently caused by the rotational component of velocity imparted to the airstream in passing through the propeller disk. Separation occurred under windmilling conditions for propeller-blade angles between 4° and 20°. Large circumferential velocity gradients existed at the compressor outlet, with variations in impact pressure around the compressor outlet amounting to approximately 150 pounds per square foot.

Inasmuch as the pressures measured at the turbine outlet in the windmilling investigation were unreliable, pressure surveys are not shown for that station. The average values, however, are included in table I.

A total-pressure distribution in the vertical plane at the tail-pipe-nozzle outlet was very uniform at low windmilling speeds, but at high speeds variations of 3 percent in the absolute values were found (fig. 19). At high engine speeds, somewhat higher total pressures were measured across the lower portion of the tail pipe.

**SUMMARY OF RESULTS**

An investigation of the windmilling characteristics of the TG-100A gas turbine-propeller engine was conducted in the Cleveland altitude wind tunnel for a range of altitudes from 5000 to 35,000 feet, true airspeeds from 100 to 273 miles per hour, and propeller-blade angles from 4° to 46°. The following results were obtained:

1. A windmilling speed of 13,000 rpm was obtained at an altitude of 35,000 feet, a true airspeed of 267 miles per hour, and a propeller-blade angle of 16°. Excessive engine speeds would be obtained under windmilling conditions for propeller-blade angles from about 5° to 41° at a true airspeed of 500 miles per hour.

2. The very high drag values obtained under windmilling conditions made the feathering of the propeller of an inoperative engine desirable. At an altitude of 35,000 feet, a true airspeed of 273 miles per hour,
and a propeller-blade angle of 38°, the drag horsepower of the test installation was 585. When the propeller-blade angle was decreased to 6°, with a true airspeed in the tunnel of 255 miles per hour, the drag horsepower of the installation increased to 2645.

3. For all conditions, maximum engine windmilling speed was obtained at propeller-blade angles between 10° and 16°.

4. Application of generalizing factors to engine windmilling speed, air flow, and combustion-chamber total-pressure drop gave good results.

5. The maximum windmilling shaft horsepower obtained (not including gear losses) was 612. This power was absorbed at an altitude of 15,000 feet, a true airspeed of 209 miles per hour, and a propeller-blade angle of 12°.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

E. William Conrad
E. W. Conrad,
Mechanical Engineer.

J. D. Durham
J. D. Durham,
Mechanical Engineer.

Approved: Alfred W. Young
Alfred W. Young,
Mechanical Engineer.

Abe Silverstein
Abe Silverstein,
Aeronautical Engineer.
REFERENCES


INDEX OF FIGURES

Figure 1. - Blade-form curves for Hamilton-Standard 4260 four-blade propeller.  \( b \), section chord; \( D \), propeller diameter; \( h \), section thickness; \( R \), radius to tip; \( r \), section radius.

Figure 2. - Installation of TG-100A gas turbine-propeller engine in altitude wind tunnel.

Figure 3. - Installation of TG-100A gas turbine-propeller engine showing wing duct inlets.

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(c) Altitude, 25,000 feet.
(d) Altitude, 35,000 feet.

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(c) Altitude, 25,000 feet.
(d) Altitude, 35,000 feet.

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(d) Altitude, 35,000 feet.
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(a) Altitude, 5000 feet.
(b) Altitude, 15,000 feet.
(c) Altitude, 25,000 feet.
(d) Altitude, 35,000 feet.
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**TABLE I.- WINDMILLING DATA FOR NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS**
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Figure 1. - Blade-form curves for Hamilton-Standard 4260 four-blade propeller. b, section chord; D, propeller diameter; h, section thickness; R, radius to tip; r, section radius.
Figure 2. Installation of TG-100 gas turbine-propeller engine in altitude wind tunnel.
Figure 3. - Installation of TG-100 gas turbine-propeller engine showing wing duct inlets.
Figure 4. - Variation of engine windmilling speed with propeller-blade angle and approximate true airspeed.
Figure 4. - Concluded. Variation of engine windmilling speed with propeller-blade angle and approximate true airspeed.
Figure 5. - Relation between true airspeed and propeller-blade angle at engine speed of 13,000 rpm. (Data cross-plotted and extrapolated from fig. 4.)
Figure 6. - Variation of windmilling shaft horsepower with engine speed for various propeller-blade angles.
Figure 7. - Variation of windmilling shaft horsepower with propeller-blade angle.
Figure 7. - Concluded. Variation of windmilling shaft horsepower with propeller-blade angle.
Figure 8. Variation of engine air flow with engine windmilling speed.
Corrected engine air flow, \( \frac{W_a \sqrt{\Theta}}{\Delta} \), lb/sec

Figure 9. Variation of corrected engine air flow with corrected engine windmilling speed.
Figure 10. - Variation of corrected pressure drop across combustion chambers with corrected engine windmilling speed.
Figure 11. - Variation of windmilling-drag coefficient with propeller-blade angle for several altitudes. True airspeed, 153 miles per hour.
Figure 12. - Variation of windmilling-drag coefficient with propeller-blade angle for various true airsprosds. Altitude, 15,000 feet.
Figure 13. - Variation of average total and static pressures through engine. Propeller-blade angle, 12°.
Figure 13. – Concluded. Variation of average total and static pressures through engine. Propeller-blade angle, 12°.
Figure 14. - Distribution of total and static pressures at wing-duct inlet.
Figure 14. - Continued. Distribution of total and static pressure at wing-duct inlet.
Figure 14. - Continued. Distribution of total and static pressure at wing-duct inlet.
Figure 14. - Concluded.

Distribution of total and static pressure at wing-duct inlet.

(1) Altitude: 35,000 feet.
(2) Distance from bottom of duct: 1 in.

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NATIONAL ADVISORY PANEL

FIG. 114

NACA RM NO. E7625
(a) Altitude, 5000 feet; propeller-blade angle, 10°.

Figure 15. – Distribution of total and static pressures at compressor inlet.
Figure 15. - Continued. Distribution of total and static pressures at compressor inlet.

(b) Altitude, 15,000 feet; propeller-blade angle, 12°.
Figure 15c. - Continued. Distribution of total and static pressures at compressor inlet.

(c) Altitude, 25,000 feet; propeller-blade angle, 12°.
(d) Altitude, 35,000 feet; propeller-blade angle, 12°.

Figure 15. Concluded. Distribution of total and static pressures at compressor inlet.
Figure 16. — Distribution of total and static pressures at compressor outlet.

(a) Altitude, 5000 feet.
Figure 16, Continued. Distribution of total and static pressures at compressor outlet.
Figure 16. - Continued. Distribution of total and static pressures at compressor outlet.

Total Static Windmilling
pres- pres- speed
sure sure (rpm)

- 6,400
- 8,400
- 10,500

Compressor outlet looking aft

Altitude, 25,000 feet.
Figure 16. Concluded. Distribution of total and static pressures at compressor outlet.
Figure 17. - Distribution of total and static pressures at turbine-nozzle inlet.
Figure 17. - Continued. Distribution of total and static pressures at turbine-nozzle inlet.

(b) Altitude, 15,000 feet.
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<th>Static Pressure</th>
<th>Windmilling Speed, rpm</th>
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Figure 17. - Continued. Distribution of total and static pressures at turbine-nozzle inlet.
Figure 17. - Concluded. Distribution of total and static pressures at turbine-nozzle inlet.
Figure 18. – Distribution of total and static pressures behind exhaust-cone outlet.
Total Static Windmilling pressure pressure speed, rpm

- 4,100
- 6,400
- 7,500
- 8,400
- 10,500
- 11,200
- 13,000

(c) Altitude, 25,000 feet.

(d) Altitude, 35,000 feet.

Figure 18, Concluded. Distribution of total and static pressures behind exhaust-cone outlet.
Figure 19. - Distribution of total and static pressures at tail-pipe-nozzle outlet.
Figure 19. – Concluded. Distribution of total and static pressures at tail-pipe-nozzle outlet.