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RESEARCH MEMORANDUM

GENERALIZATION OF TURBOJET AND TURBINE-PROPELLER ENGINE PERFORMANCE IN WINDMILLING CONDITION

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

GENERALIZATION OF TURBOJET AND TURBINE-PROPELLER ENGINE PERFORMANCE IN WINDMILLING CONDITION

By Lewis E. Wallner and Henry J. Welna

SUMMARY

The windmilling characteristics of several turbojet and turbine-propeller engines were investigated individually over a wide range of flight conditions in the NACA Lewis altitude wind tunnel. A study was made of all these data and windmilling performance of gas-turbine engines was generalized.

Although the internal-drag, air-flow, and total-pressure-drop parameters were generalized to a single curve for both the axial-flow turbojet engines and the centrifugal-flow turbojet engine investigated, the engine-speed parameter separated into two curves - one for all the axial-flow-type engines and another for the centrifugal-flow engine. The engine speed, component pressure changes, and windmilling-propeller drag were generalized to single curves for the two turbine-propeller-type engines investigated. By the use of these curves the windmilling performance can be estimated for axial-flow-type gas-turbine engines similar to the types investigated over a wide range of flight conditions.

INTRODUCTION

A part of each gas-turbine engine performance investigation in the NACA Lewis altitude wind tunnel has been the determination of engine windmilling performance. Windmilling drag and speed data for turbojet or turbine-propeller engines are important for several reasons. For example, a knowledge of the windmilling characteristics is needed in order to determine before flight whether the engine will windmill at sufficient speed to permit restarting in case of engine failure or whether the windmilling speed is sufficient to power engine accessories. For a multiengine plane, the drag of a windmilling engine must be known to compute the yawing moments or the drag penalty imposed by an inoperative engine, each of which affects the glide angle when a landing is attempted.

The purpose of this report is to provide a simple method by which the windmilling speed and drag of the engine, as well as the pressure

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change across the engine and the windmilling air flow through the engine, may be estimated. Windmilling characteristics of several engines are generalized, and from the curves presented, the windmilling performance of similar engines may be computed. The engines investigated included turbojet engines, both axial- and centrifugal-flow types, and turbine-propeller engines.

APPARATUS AND PROCEDURE

Windmilling performance of the gas-turbine engines described in table I has been investigated in the Lewis altitude wind tunnel at altitudes from 5000 to 50,000 feet and true airspeeds as high as 800 miles per hour.

All engines were extensively instrumented with pressure and temperature probes at the inlet and the outlet of the engine and between each of the engine components. For the turbojet engines, test points were obtained at several airspeeds at each altitude. For the turbine-propeller engines, data were obtained for several propeller blade angles at each airspeed and altitude.

The drag values were calculated from the changes in momentum of the air entering and leaving the engine; the air flows, from measurements at the inlet.

SYMBOLS

The following symbols are used in this report:

A	flow area at compressor inlet for axial-flow engines (sq ft)
D	internal drag, equal to difference between momentum of air entering and leaving engine (lb)
D_p	windmilling propeller drag, equal to total drag minus nacelle drag (lb)
N	engine speed (rpm)
$(shp)_r$	rated shaft horsepower of turbine-propeller engine
V	true airspeed (ft/sec)
W	air flow (lb/sec)

Subscript:

r	rated

Generalization factors:

δ	pressure generalization factor: ratio of total pressure at engine inlet to sea-level static pressure
θ	temperature generalization factor: ratio of total temperature at engine inlet to sea-level static temperature

Windmilling parameters:

$D/\delta A$	corrected drag (lb/sq ft)
$D_p/\delta(\mathrm{shp})_r$	corrected windmilling-propeller-drag parameter $(\mathrm{lb}/(\mathrm{shp})_r)$
$V/\sqrt{\theta}$	corrected true airspeed (ft/sec)
$W\sqrt{\theta}/\delta A$	corrected air flow (lb/(sec)(sq ft))
$N/N_r\sqrt{\theta}$	corrected engine speed

RESULTS AND DISCUSSION

Turbojet engines. - In the windmilling state, a turbojet engine operates considerably off the design condition and as a result the aerodynamic efficiencies of an engine or its components are undoubtedly low. It is logical, then, that any differences in either the design theory or the efficiencies at the design condition will be of little importance in the windmilling state. To verify this reasoning, the corrected total-pressure drop across each of several turbojet engines in the windmilling state was plotted as a function of true airspeed for altitudes from 5000 to 50,000 feet (fig. 1). The pressure changes across all the engines investigated were generalized to a single curve.

If the change in pressure of the air flowing through all the engines is the same, each of the windmilling drags should then be a function of the engine air flow, which is in turn a function of the engine size. In an effort to generalize for differences in engine size, the corrected windmilling drags were divided by the compressor-inlet areas. An inlet area for the centrifugal-flow engine was obtained by averaging the ratios of engine-inlet to exhaust-nozzle area for the axial-flow gas-turbine engines and applying the average value (1.78) to the centrifugal-flow-type engine whose nozzle area was known, thus obtaining a similar inlet area. The generalization of the windmilling-drag parameter for the engines is shown in figure 2. The considerable scatter of the drag data (without any particular trends) results from the difficulty of measuring engine air flows and velocities when the difference between total and static pressures is small. In addition, the windmilling air flows, which were also adjusted for the compressor-inlet areas, are generalized to a single curve when presented as a function of airspeed (fig. 3).

The usual practice in the design of a turbojet engine is to set the design compressor tip speed at approximately the speed of sound. With the assumption that engines windmill at about the same tip Mach number for a given airspeed, the corrected engine speed divided by rated speed for each engine was used as a speed parameter. This engine-speed parameter is plotted in figure 4 as a function of airspeed. Separate curves are defined for the axial-flow and centrifugal-flow engines; however, the data for all the axial-flow engines fall on a single curve.

The engine component characteristics in the windmilling condition, that is, the pressure change across the compressor, the combustor, and the turbine, are shown for several engines in figure 5. Although there are variations in the pressure changes in a given component for different engines, there are compensating effects when all the components for an engine are considered. If a given pressure drop is required to cause an engine to windmill, the pressure change in the turbine will depend on the magnitude of the pressure drop in the compressor. The differences in the pressure loss in the combustor are of secondary importance when compared with the over-all pressure loss across the engine.

For axial-flow turbojet engines of the type considered in this study (compressor pressure ratios from 3.45 to 5.2 - see table I) it is possible to predict the over-all windmilling performance for a range of altitudes and flight speeds. It is not known conclusively whether the windmilling curves are valid for centrifugal-flow engines, because only one engine of this type was investigated.

Turbine-propeller engines. - Reasoning similar to that used for the turbojet engines was employed in an effort to generalize the windmilling data from two turbine-propeller engines. The corrected engine-speed parameter was generalized when plotted as a function of airspeed (fig. 6). The propellers were set at the blade angles that resulted in the maximum rotating speed (about 12° and 20° for engines H and I, respectively). It should be noted that overspeeding the engine can result at airspeeds in excess of about 375 feet per second.

Corrected engine total-pressure change is shown as a function of the engine-speed parameter in figure 7. At 50 percent of rated engine speed, there is no change in pressure between the engine inlet and the tail pipe. At rated speed the corrected pressure actually increases about 80 pounds per square foot as a result of the driving of the engine rotor by the propeller. The propeller is obviously the main source of drag on a windmilling turbine-propeller installation. The corrected pressure changes across each of the components is presented in figure 8. At a given percentage of rated engine speed, about the same pressure changes were obtained for both turbine-propeller engines.

The drag resulting from windmilling turbine-propeller engines (propeller blade angle set for maximum windmilling speed) is shown in figure 9, which is a plot of propeller-drag parameter as a function of the engine-speed parameter. Drag of the propeller was divided by the rated shaft horsepower of the engine to correct for its power-absorption ability. Data from the two turbine-propeller engines determine a single curve from which the drag of a windmilling propeller engine may be estimated. For example, if a 2000-shaft-horsepower turbine-propeller engine is windmilling at 75 percent of rated speed at sea level, the propeller drag is about 4000 pounds. Although this represents the maximum drag that could be imposed by a windmilling propeller at this rotating speed, it is possible in the event of failure to full-feather the propeller.

The corrected air-flow parameter for the two axial-flow turbine-propeller engines is generalized in figure 10 as a function of the corrected engine-speed parameter. A faired curve from the axial-flow turbojet-engine air-flow data (superimposed on fig. 10) agrees with the turbine-propeller data.

SUMMARY OF RESULTS

A study of windmilling-performance data was made for several axial-flow turbojet engines, one centrifugal-flow turbojet engine and two turbine-propeller engines, investigated in the NACA Lewis altitude wind tunnel. The internal-drag, air-flow, and total-pressure-drop parameters were generalized to a single curve for both the axial-flow turbojet engines and the centrifugal-flow turbojet engine investigated; the engine-speed parameter separated into two curves, one for all the axial-flow-type engines and another for the centrifugal-flow engine. The engine speed, component pressure changes, and windmilling-propeller drag were generalized to single curves for the two turbine-propeller-type engines investigated. By the use of these curves the windmilling performance can be estimated for axial-flow-type gas-turbine engines similar to the types investigated over a wide range of flight conditions.

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TABLE I

Engine	Compressor	Desig-nation	Sym-bol	Compressor pressure ratio	Engine pres-sure ratio	Rated air flow (lb/sec)	Rated thrust (lb)	Rated thrust (shp)	Number of stages in compressor
Turbojet	Axial-flow	A	○	4.0	2.05	60	3370		11
Turbojet	Axial-flow	B	□	3.8	1.82	58	3200		11
Turbojet	Axial-flow	C	◇	5.2	1.83	97	5200		11
Turbojet	Axial-flow	D	△	4.0	1.84	67	4000		11
Turbojet	Axial-flow	E	◿	3.45	----	28	1400		6
Turbojet	Axial-flow	F	⌂	5.1	1.97	137	7500		11
Turbojet	Centrifugal-flow	G	◢	4.0	----	75	3750		1
Turbine-propeller	Axial-flow	H	∩	6.5	1.1	22		1800	14
Turbine-propeller	Axial-flow	I	⬦	5.1	1.1	54.2		3200	14

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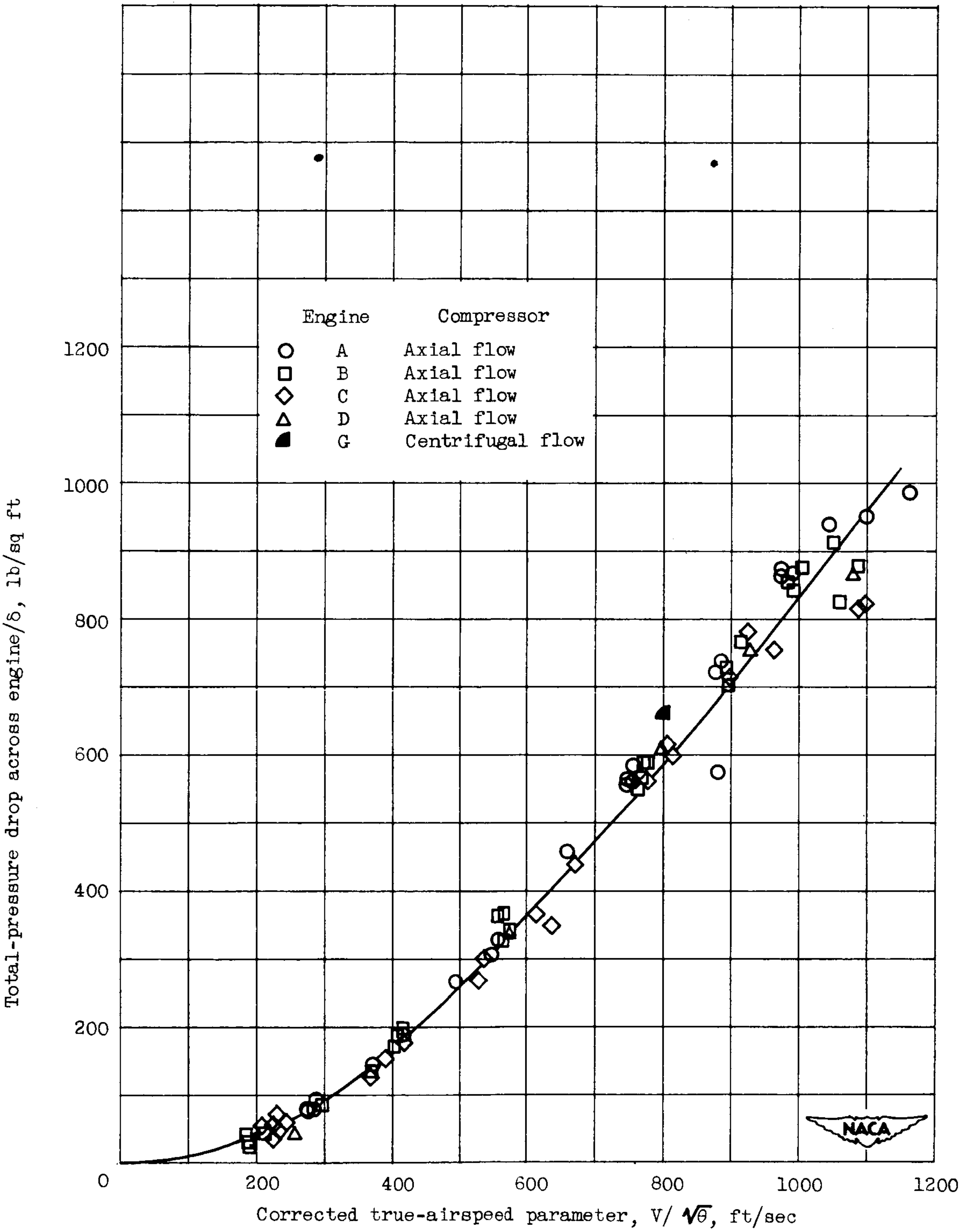

Figure 1. - Variation of engine total-pressure drop with true airspeed for axial- and centrifugal-flow-type turbojet engines in windmilling condition. Data obtained at altitudes between 5000 and 50,000 feet.

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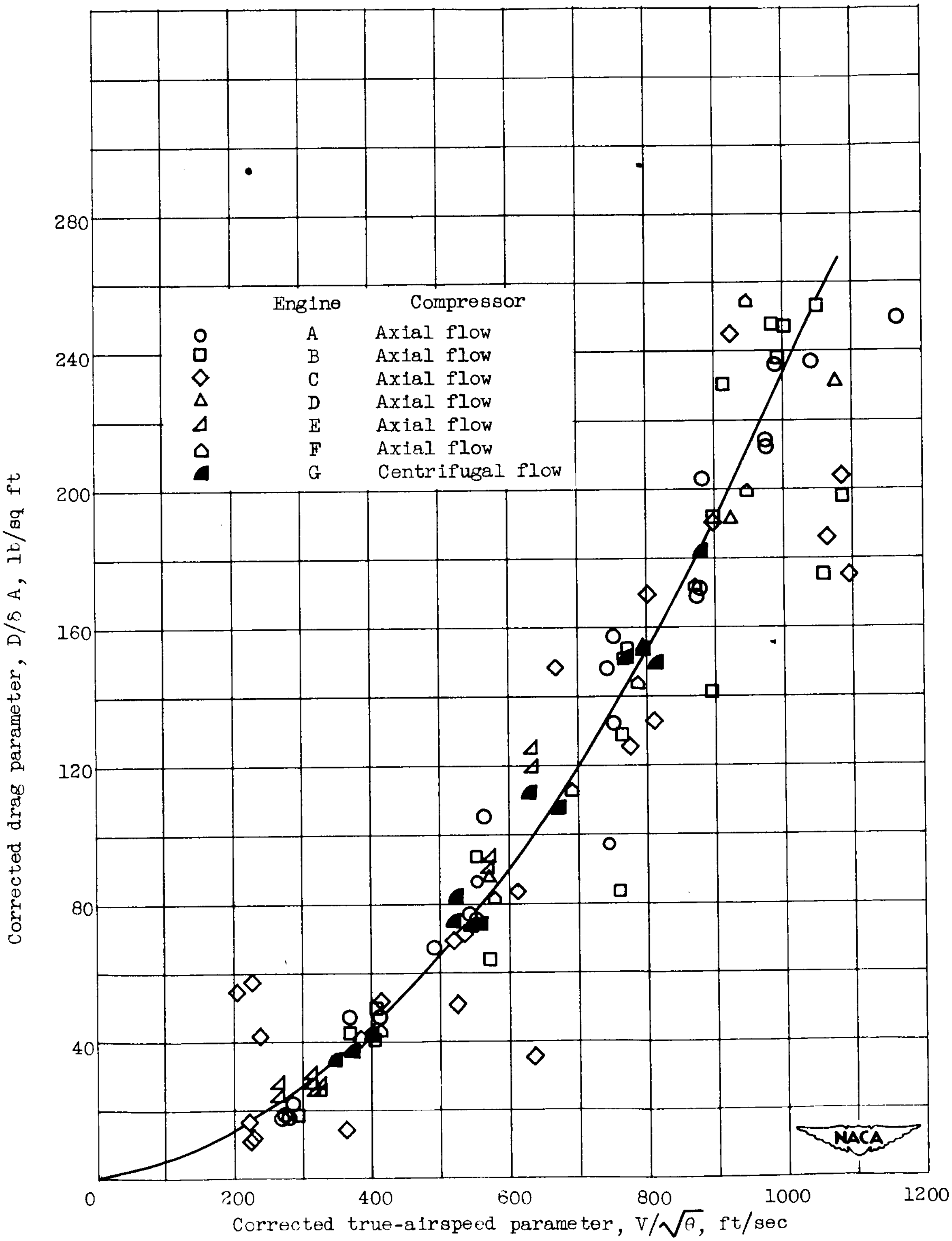

Figure 2. - Variation of internal-drag parameter with true airspeed for axial- and centrifugal-flow-type turbojet engines in windmilling condition. Data obtained at altitudes between 5000 and 50,000 feet.

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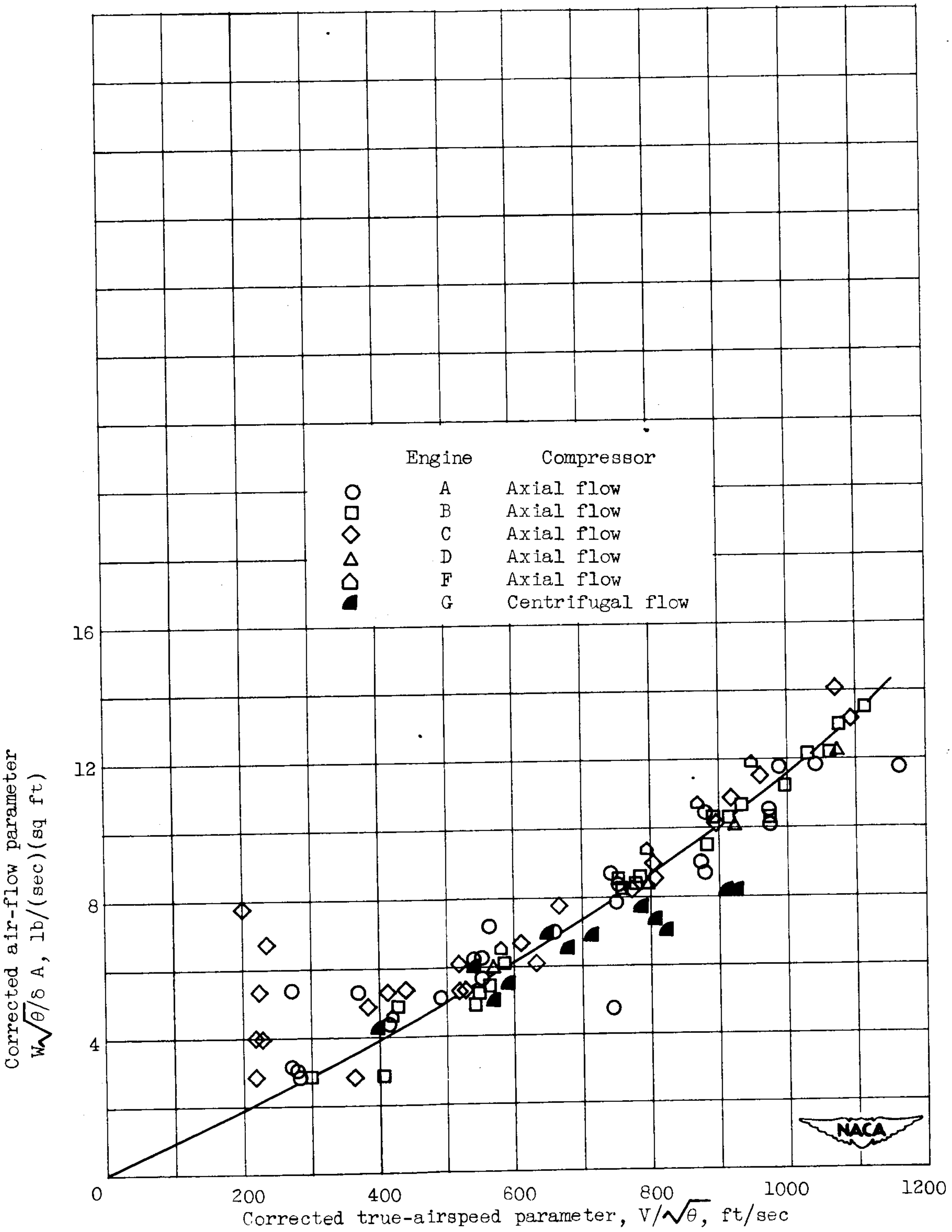

Figure 3. - Variation of air-flow parameter with true airspeed for axial- and centrifugal-flow-type turbojet engines in windmilling condition. Data obtained at altitudes between 5000 and 50,000 feet.

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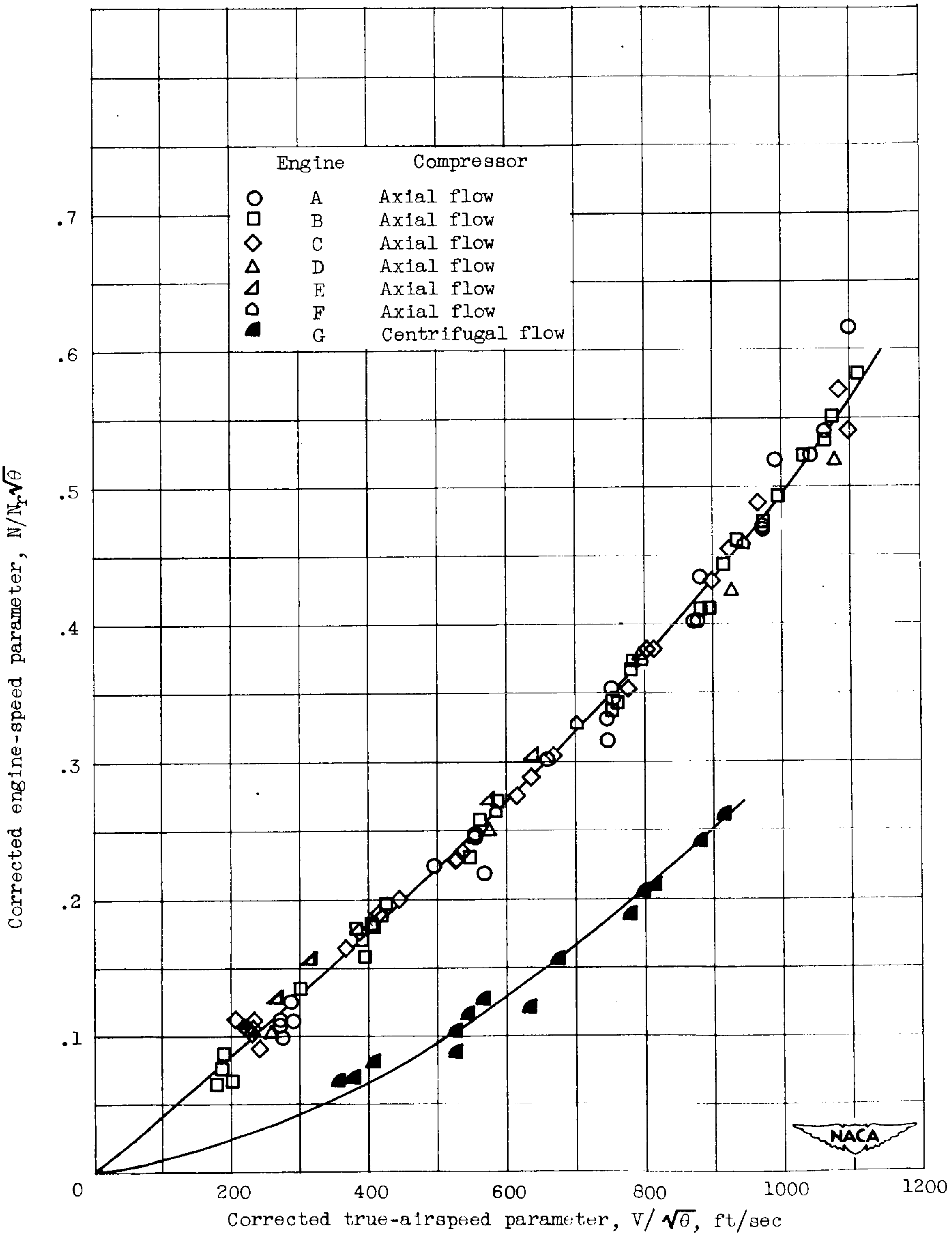
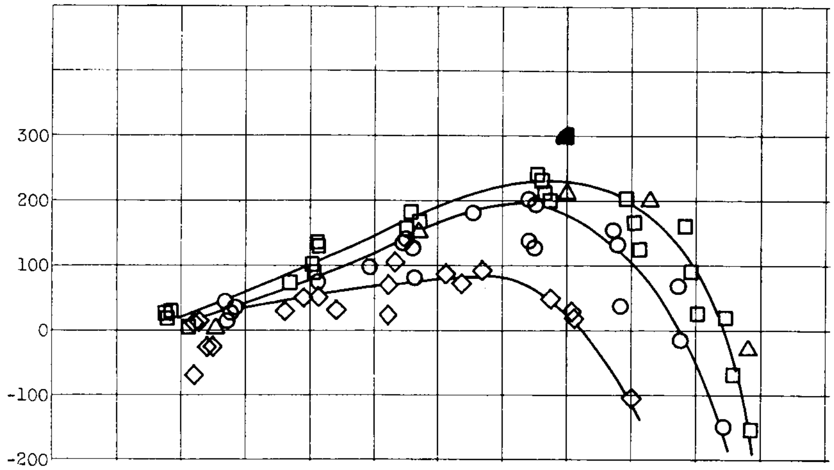
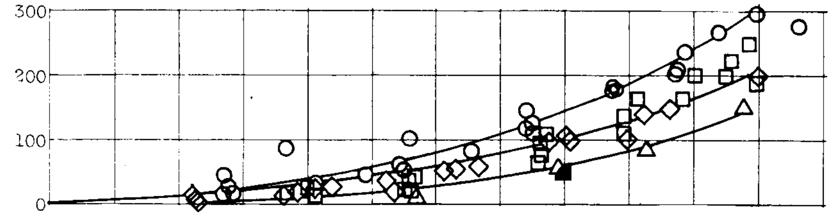


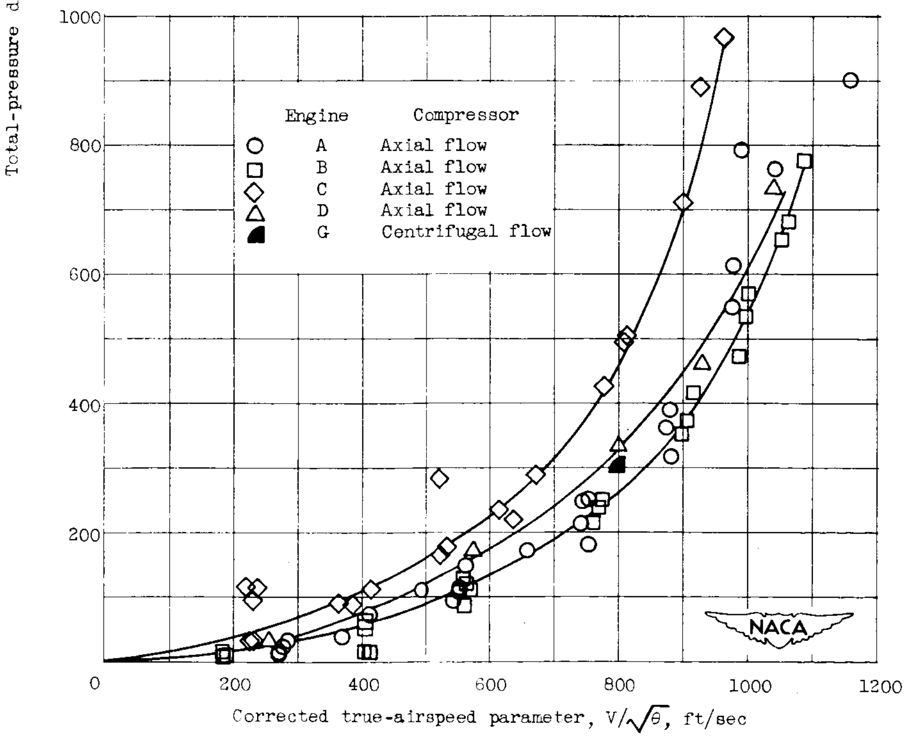
Figure 4. - Variation of engine-speed parameter with true airspeed for axial- and centrifugal-flow-type turbojet engines in windmilling condition. Data obtained at altitudes between 5000 and 50,000 feet.



(a) Compressor.



(b) Combustor.



(c) Turbine.

Figure 5. - Variation of component pressure changes with true airspeed for axial- and centrifugal-flow-type turbojet engines in windmilling condition. Data obtained at altitudes between 5000 and 50,000 feet.

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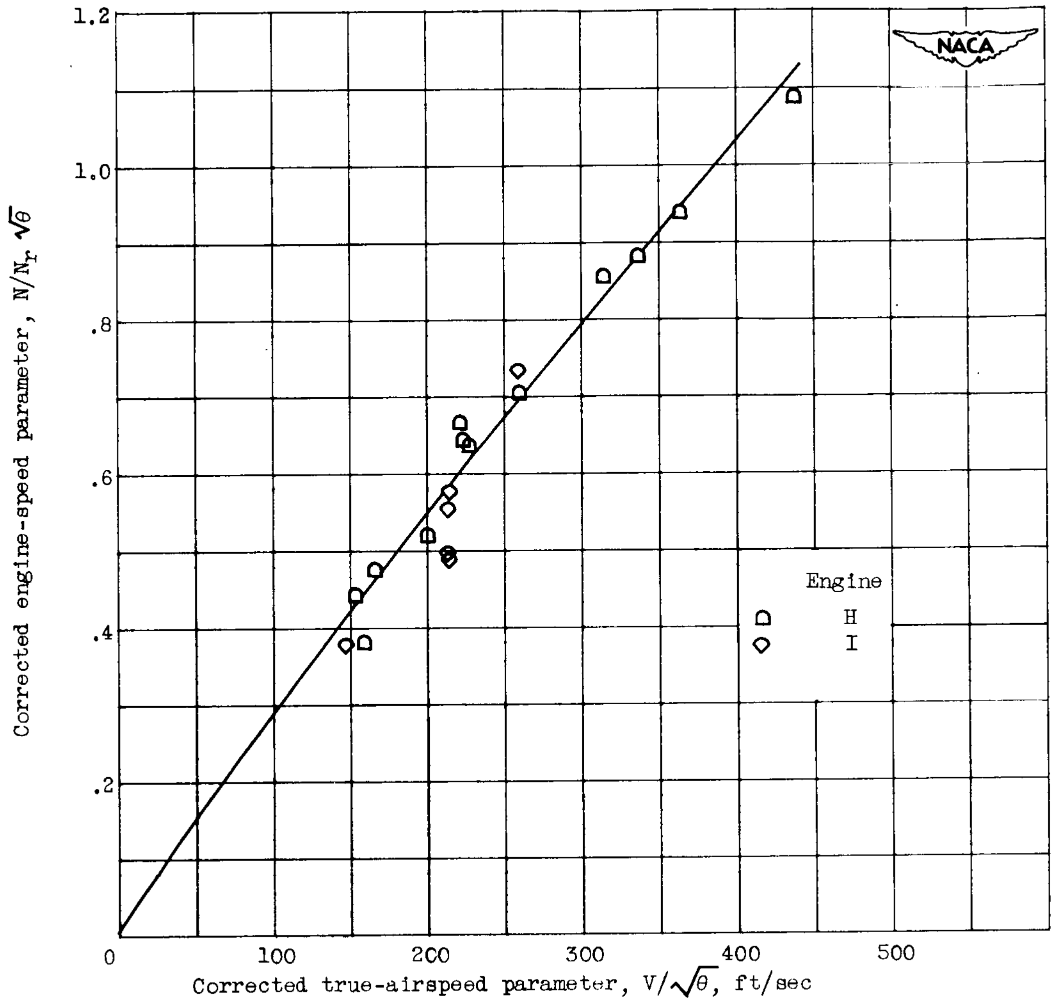

Figure 6. - Variation of engine-speed parameter with true airspeed for two axial-flow turbine-propeller engines in windmilling condition. Data obtained at altitudes between 5000 and 40,000 feet; propeller blade angles set for maximum rotating speed.

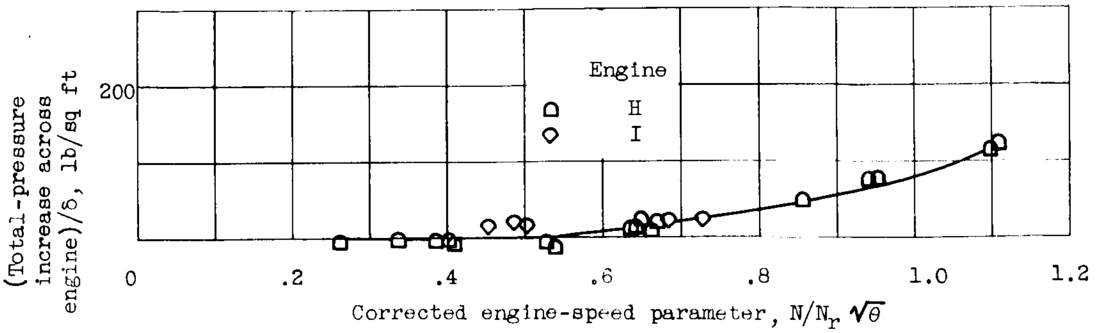

Figure 7. - Variation of engine total-pressure change with engine-speed parameter for turbine-propeller engine in windmilling condition. Data obtained at altitudes between 5000 and 40,000 feet.

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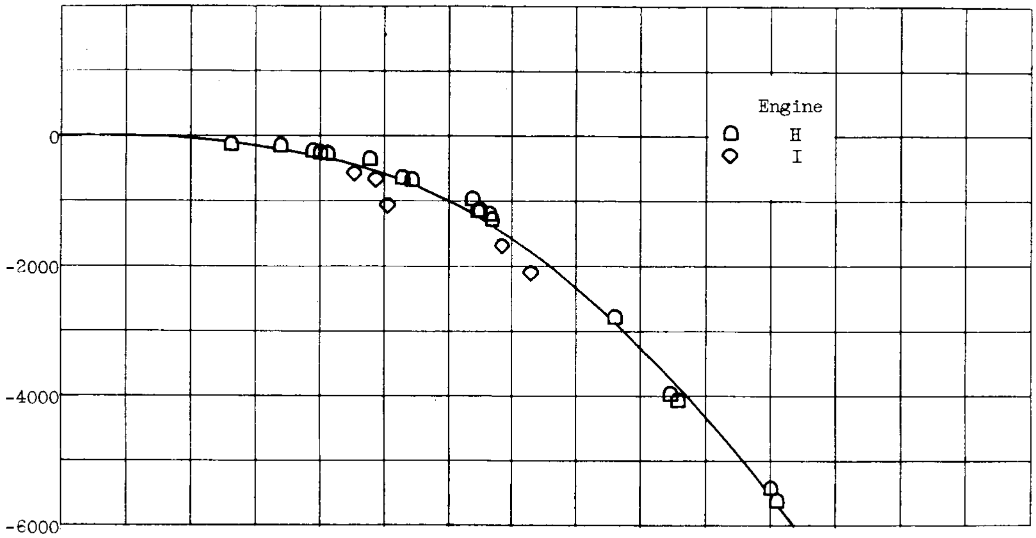
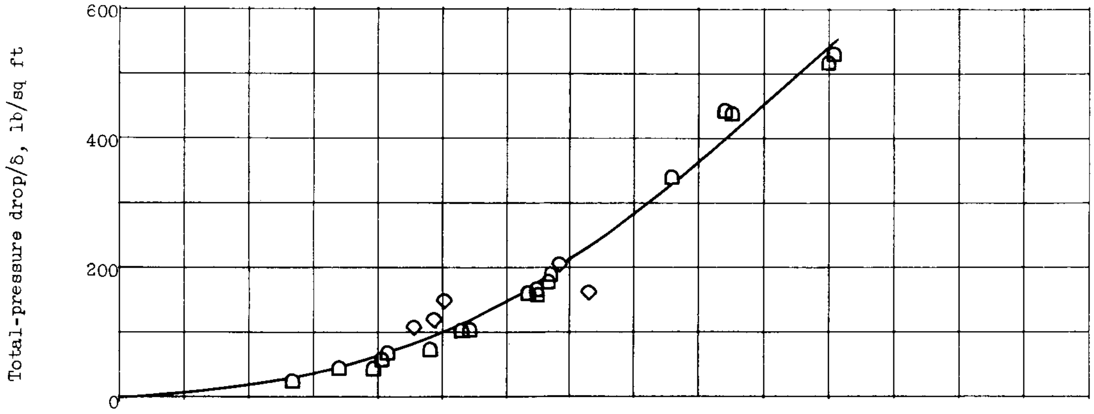
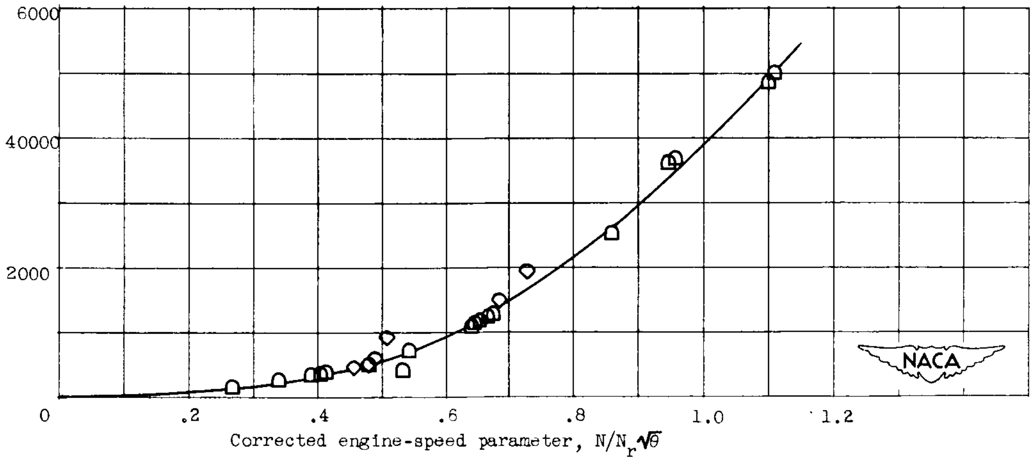


(a) Compressor.



(b) Combustor.



(c) Turbine.

Figure 8. - Variation of component pressure changes with engine-speed parameter for two turbine-propeller engines in windmilling condition. Data obtained at altitudes between 5000 and 40,000 feet.

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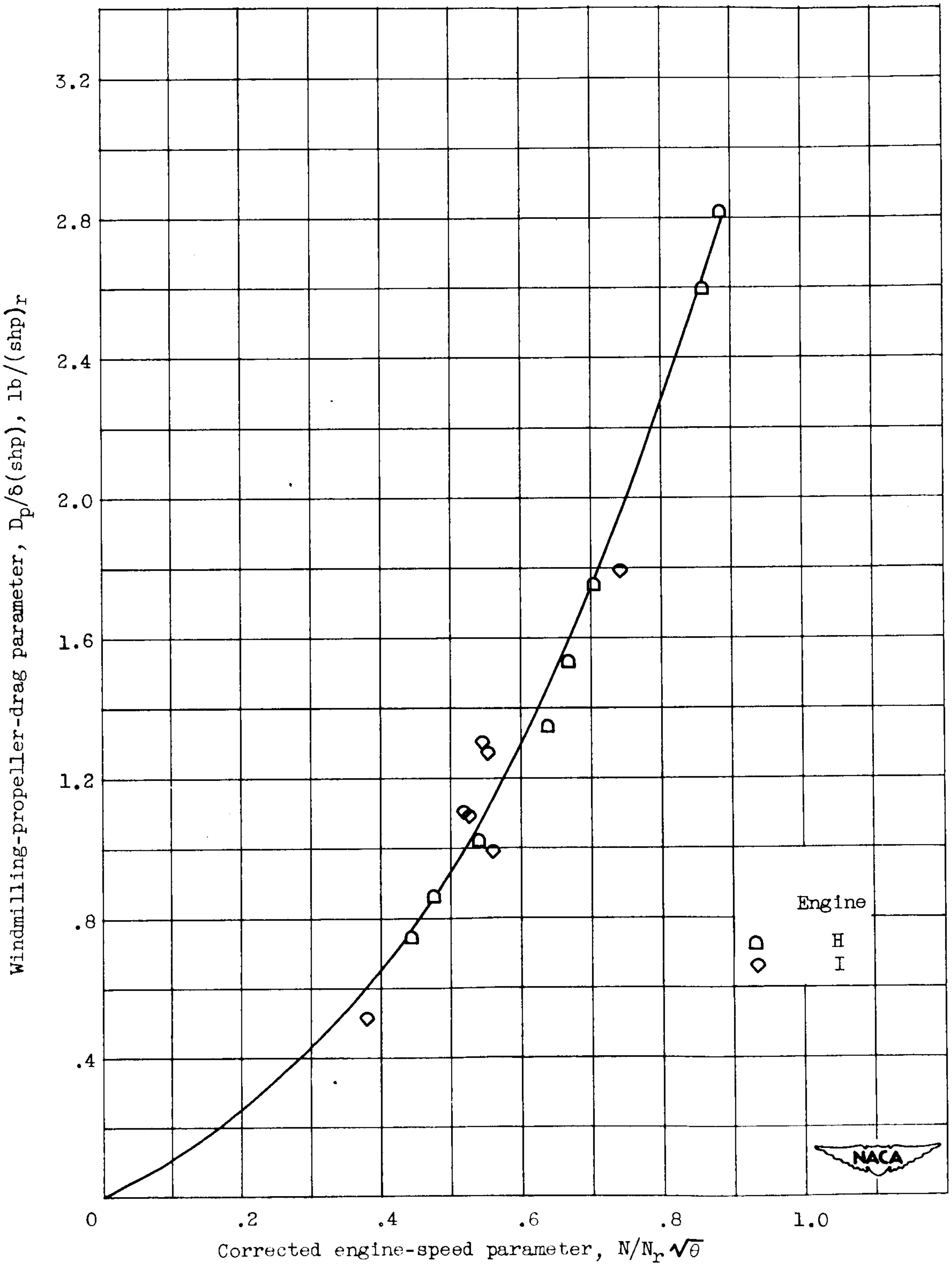

Figure 9. - Variation of windmilling-propeller-drag parameter with engine-speed parameter for two turbine-propeller engines at altitudes from 5000 to 40,000 feet; propeller blade angle set for maximum windmilling speed.

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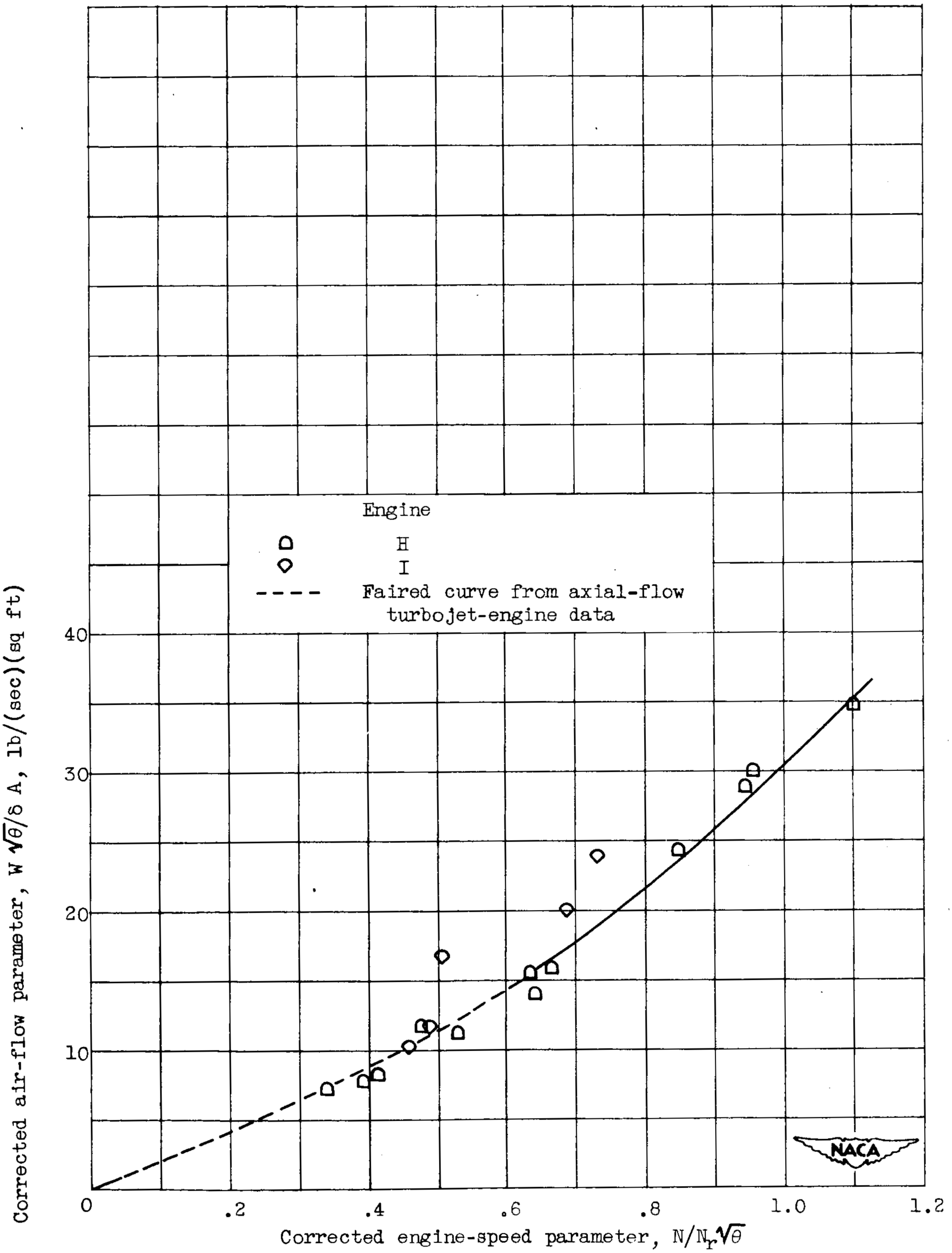

Figure 10. - Variation of air-flow parameter with corrected engine-speed parameter for two turbine-propeller engines in windmilling condition. Data obtained at altitudes between 5000 and 40,000 feet.

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