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RESEARCH MEMORANDUM

INVESTIGATION OF POWER EXTRACTION CHARACTERISTICS AND BRAKING REQUIREMENTS OF A WINDMILLING TURBOJET ENGINE

By Curtis L. Walker and David B. Fenn

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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INVESTIGATION OF POWER EXTRACTION CHARACTERISTICS AND BRAKING REQUIREMENTS OF A WINDMILLING TURBOJET ENGINE

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SUMMARY

An investigation was conducted in an altitude chamber at the NACA Lewis laboratory to determine the power extraction and braking characteristics of a windmilling single-spool axial-flow turbojet engine of the 5000-pound thrust class over a range of altitudes from 5000 to 50,000 feet and flight Mach numbers from 0.2 to 1.0. The maximum corrected power available for accessory drive with the engine investigated was found to increase from 3 horsepower at a flight Mach number of 0.2 to 178 horsepower at a flight Mach number of 1.0.

The constant applied torque required to stop the rotation of a windmilling engine in 0.2 minute at a simulated altitude of 40,000 feet was found to be 99 foot-pounds at a flight Mach number of 0.2 and 620 foot-pounds at a flight Mach number of 1.0. The torque required to stop the engine in 0.2 minute at a flight Mach number of 0.4 decreased from 290 foot-pounds to 160 foot-pounds as altitude was increased from 5000 to 50,000 feet.

INTRODUCTION

In modern aircraft there are many accessories such as the flight controls and landing-gear mechanisms that must be powered from the engine. In the event of engine flame-out or failure on a single-engine aircraft it is desirable to know the amount of power that would be available from the windmilling engine for these essential accessories. In the case of a multiengine aircraft, it is also desirable to prevent a damaged engine from windmilling. For example, a badly unbalanced engine, if allowed to continue its rotation, could cause failure of the supporting structure. It has been found in a previous investigation (reference 1) that the internal drag of a turbojet engine when allowed to windmill is greater than when rotation is prevented; a knowledge of the torque and time required to brake the engine rotor at various flight conditions is therefore also desirable.

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An investigation was accordingly conducted in an altitude test chamber at the NACA Lewis laboratory to determine the power available for accessory drive with a windmilling engine over a range of altitudes from 5000 to 50,000 feet and flight Mach numbers from 0.2 to 1.0. This investigation also included a determination of the time to stop the engine from free windmilling speed when a constant braking torque was applied. A study of speed decay from engine speeds above free windmilling speed has been presented in reference 2 from an investigation of a similar engine.

Data are presented in tabular and graphical form showing the effects of altitude, flight Mach number, and engine speed on the extractable power and the effect of engine speed on the total pressure gradient through the engine. In addition, generalized data are presented permitting prediction of power-extraction data at flight conditions other than those simulated in this investigation. A method of predicting the time to brake the engine from free windmilling speeds with constant applied torque is also presented. Symbols used in this report and methods used in calculations are given in the appendixes A and B, respectively.

APPARATUS

A turbojet engine incorporating an eleven-stage axial-flow compressor and a single-stage turbine was used in this investigation. The polar moment of inertia of the rotating parts was 440 pound-feet^2. At sea-level static conditions and rated engine speed of 8000 rpm, the engine had an inlet-air flow of 91 pounds per second. The engine was installed in an altitude test chamber 10 feet in diameter and 60 feet long. A sketch of the installation, including pressure and temperature measuring stations, is shown in figure 1. A bulkhead with a labyrinth seal around the front of the engine was used to separate the inlet and exhaust sections of the chamber. The desired conditions of inlet total pressure and temperature and exhaust static pressure were established in the chamber by controlling the flow of air from the laboratory compressors through the engine to the laboratory exhaust system.

The power available for accessory drive was absorbed with a 50-horsepower direct-current dynamometer mounted in the inlet section of the chamber and coupled to the main shaft of the engine through the take-off supplied by the manufacturer. The rotor of this dynamometer had a polar moment of inertia of 56 pound-feet^2. In order to protect the dynamometer from harmful overheating and brush arc caused by the low pressures encountered at high altitudes, it was sealed within a separate chamber vented to the atmosphere and supplied with dry air from the laboratory air system. The dynamometer was mounted on trunion bearings and equipped with an electric strain gage to measure the torque and hence the power transmitted to it from the engine.

PROCEDURE

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In order to evaluate its steady-state characteristics, the windmilling engine was operated over a range of altitudes from 5000 to 50,000 feet and flight Mach numbers from 0.2 to 1.0. At each condition, engine speed was decreased by increasing the torque applied by the dynamometer. In this manner, data were obtained showing the effects of altitude, flight Mach number, and engine speed on the power available for accessory drive, and the effect of engine speed on the total pressure gradient through the engine. Furthermore, it was of interest to know the relative work contributed by the compressor and turbine. Therefore, data were obtained of the extractable power available from the windmilling compressor when the turbine was removed from the engine. This brief investigation was conducted at several constant corrected windmilling speeds over a range of compressor pressure ratios, no attempt being made to determine Reynolds number effects.

In order to determine the time required to stop the engine from free windmilling speed, a nearly constant torque was applied to the engine with the dynamometer, and a photographic time history of applied torque and elapsed revolutions of the engine was taken. From these records, plots of elapsed revolutions versus time were made for each run. The slope of these curves plotted as a function of time gave curves of rpm versus time which provided a means of evaluating the time required to change the speed of the engine and dynamometer with a given torque at a given flight condition. To find the time required to stop the engine alone from free windmilling speed at a specified flight condition with a constant applied torque, a graphical computation method was used (see appendix C). The time required to change the speed of the engine and dynamometer combination for several of the flight conditions at which time histories were taken was computed to verify the methods of computation.

RESULTS AND DISCUSSION

Power Extraction

<u>Extractable horsepower from windmilling engine</u>. - The relation of extracted horsepower to windmilling engine speed is shown in figure 2. The extracted horsepower available at altitudes from 5000 to 50,000 feet and a flight Mach number of 0.4 is shown in figure 2(a). As altitude was increased, the horsepower available rapidly decreased because of the decrease in weight flow. Because the dynamometer imposed a windage and friction load even with no electrical load, it was necessary to

extrapolate the data to free windmilling engine speed. At a flight Mach number of 0.4, the free windmilling engine speed was 1600 rpm at an altitude of 5000 feet and decreased to 1420 rpm at 50,000 feet.

As torque was applied to the engine, the speed was reduced; maximum extracted horsepower was obtained at about one-half of free windmilling speed. These curves peak because horsepower is the product of torque and engine speed and, as mentioned previously, windmilling engine speed was decreased by increasing torque. The maximum power extracted at an altitude of 5000 feet was 14.2 horsepower as compared with only 1.9 horsepower at 50,000 feet.

The relation of extracted horsepower to windmilling engine speed for flight Mach numbers from 0.2 to 1.0 at an altitude of 40,000 feet is shown in figure 2(b). As flight Mach number was increased, there was an increase in the pressure drop across the engine and an increase in air flow whereby the horsepower available from the engine was increased. At a flight Mach number of 0.2, only 2.0 horsepower were available as compared to nearly 28 horsepower at a flight Mach number of 0.8.

In order to make the extracted horsepower data more useful, the data have been corrected to static sea-level pressure and temperature in figure 3. These data show a tendency to generalize for altitude but not for Mach number. At a given flight Mach number, the spread in extracted horsepower is primarily a result of changes in the inlet Reynolds number. The corrected power curve for a Mach number of 1.0 at 50,000 feet was extrapolated to zero. In order to permit the use of these data at intermediate flight Mach numbers, the maximum corrected power available for accessory drive at 40,000 feet is presented as a function of flight Mach number in figure 4 which is a cross plot of figure 3. Above a flight Mach number of 0.7 there was apparently a nearly linear increase in maximum corrected extracted horsepower with increasing flight Mach number.

The over-all efficiency of the windmilling engine is defined as the ratio of the measured extractable horsepower to the ideal horsepower available from adiabatic expansion of the measured weight flow. This over-all efficiency is presented in figure 5 as a function of corrected windmilling engine speed for various flight conditions. These data show a reduction in efficiency with increasing altitude at a constant flight Mach number, and the highest efficiency obtained in this investigation was 0.36 at a flight Mach number of 0.2 and an altitude of 5000 feet. As flight Mach number was increased at a constant altitude, peak efficiency showed a tendency to increase. This increase may be attributed to higher component efficiencies encountered as the components approach their design condition at higher speeds.

The scatter in these data at the low Mach numbers is primarily due to the inability to accurately measure the low-power output of the windmilling engine and the low ram-pressure ratios encountered at these flight conditions.

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Total pressure gradient through a windmilling engine. - The effect of windmilling engine speed on the total pressure gradient throughout the engine is illustrated in figure 6. At the 0.8 flight Mach number conditions (figs. 6(a) and 6(b)), a continuous drop in total pressure through the engine occurred at all windmilling engine speeds. However, at rotative speeds near free windmilling speed and a flight Mach number of 1.0, there was a pressure rise across the compressor (station 2 to 3) as shown in figure 6(c) and 6(d). Unpublished data from a previous investigation of the pressure from stage to stage in a similar compressor has shown that under windmilling conditions the first stages produce a pressure rise and the last stages produce a pressure drop. The net result can be a compressor pressure ratio greater than unity at the high windmilling engine speeds.

Contribution of compressor to extracted horsepower. - In order to determine the contribution of the compressor to extracted horsepower, an investigation was conducted with the turbine removed. The variation of corrected compressor horsepower with corrected windmilling engine speed is shown in figure 7 for various compressor pressure ratios. These data were obtained with the turbine removed from the engine and no attempt was made to determine the Reynolds number effects. Negative horsepower on this curve was obtained with the dynamometer driving the compressor. A comparison of corrected extracted horsepower from the windmilling engine with the corrected power of the compressor is presented in figure 8. These values of compressor power (solid lines) were obtained from figure 7 with the compressor pressure ratio and corrected windmilling speed from windmilling engine data. The dashed lines of corrected extracted power from the windmilling engine were taken from figure 3 at 0.4 Mach number for all altitudes investigated and at 0.8 Mach number for 30,000 and 40,000 feet. At a flight Mach number of 0.4, the compressor power was nearly equal to the total power of the engine, which means that at this condition the turbine was contributing very little power. At a flight Mach number of 0.8, the compressor power increased as corrected windmilling speed was increased from 0 to 1400 rpm. Maximum extracted power from the engine was obtained at a corrected windmilling speed of about 1700 rpm, at which point the compressor was supplying approximately half of the power available from the windmilling engine. As windmilling speed was increased beyond this point, the rapid decrease in compressor power caused the turbine to supply all of the extractable power plus the power required to drive the compressor above a corrected windmilling speed of 2170 rpm.

Braking of the Windmilling Engine

The investigation of the braking requirements of the windmilling engine provided time-history data that included the torque required to decelerate both the engine rotor and the rotor of the dynamometer. Furthermore, it was found that when the dynamometer was used, constant torque during deceleration generally could not be maintained. Because of these two difficulties, it was impossible to use the experimental data directly to determine the time history of the braking of the windmilling engine alone at a constant torque. Therefore, a graphical method of computing deceleration time using experimental steady-state data was developed and is presented in appendix C. 2566

The method is based on the two factors affecting the time required to change rotative speed: moment of inertia of the rotating mass and the steady-state windmilling torque of the engine. The steady-state windmilling torque of the engine must be obtained from an engine calibration such as that shown in figure 9. Figure 9(a) presents the torque-speed characteristics of this windmilling turbojet engine at a flight Mach number of 0.8 for altitudes from 5000 to 50,000 feet. At any constant engine speed, windmilling torque decreased with increasing altitude. For example, at 2400 rpm an increase in altitude from 30,000 to 50,000 feet decreased the windmilling torque from 67.5 to 19 foot pounds.

The effect of flight Mach number on the torque-speed characteristics of the windmilling engine is shown in figure 9(b) for a constant altitude of 40,000 feet. At a given speed, an increase in flight Mach number requires an increase in brake torque to maintain that speed. At 1200 rpm an increase in flight Mach number from 0.4 to 0.8 raised the torque requirement from 9 to 111 foot-pounds. The torque-speed characteristics were generalized for altitude by use of the conventional factors δ and θ to provide a means of computing time-to-stop for flight conditions other than those investigated (see fig. 10). The curves of figure 10 were extrapolated both to locked rotor torque and to free windmilling speed because these conditions were not obtainable with the dynamometer.

After the necessary torque-speed characteristics had been obtained, a check of the validity of the graphical method was made by use of experimentally determined speed-decay curves. In this verification, the moment of inertia used in the graphical method included the moment of inertia of the dynamometer. The computational method appeared reliable and the times required to stop the rotation of the engine alone for several applied torques and flight conditions were computed and are presented in figure 11. The applied torque is presented in figure 11(a) as a function of time-to-stop from free windmilling speed at a flight

Mach number of 0.4 over a range of altitudes from 5000 to 50,000 feet. This relation is also presented in figure 11(b) for an altitude of 40,000 feet over a range of flight Mach numbers from 0.2 to 1.0.

In order to provide a means of determining the torque required to stop the engine in shorter lengths of time than those presented in figures 11(a) and 11(b), these data were replotted on logarithmic coordinates and are presented in figures 11(c) and 11(d). The relation between applied torque and time-to-stop for a constant altitude of 40,000 feet (fig. 11(c)) shows that the applied torque required to stop the engine in 0.2 minute increased from 99 foot-pounds to 620 foot-pounds as flight Mach number was increased from 0.2 to 1.0. At a constant flight Mach number of 0.4 (fig. 11(d)), the applied torque required to stop the engine in 0.2 minute increased from 160 foot-pounds at an altitude of 50,000 feet to 290 foot-pounds at 5000 feet. The primary advantage of plotting braking data on logarithmic coordinates is that the computed data become asymptotic to a straight line (dashed) which relates applied torque and time-to-stop from free windmilling speed if only the inertia of the rotating masses is considered. Because it is physically impossible to stop the engine with an applied torque less than locked rotor torque, these curves also become asymptotic to a value equal to locked rotor torque. These relations provide a simple means of estimating the time-to-stop curve for any engine when the following three characteristics are known: the locked rotor torque and the free windmilling speed at the desired flight condition, and the polar moment of inertia of the engine. While locked rotor torque and free windmilling speed must be obtained experimentally, these quantities are more easily determined than the relation between steady-state windmilling torque and windmilling engine speed.

CONCLUDING REMARKS

From a steady-state power-extraction investigation of a single-spool axial-flow turbojet engine of the 5000-pound thrust class, it was found that the windmilling turbojet engine is an available but inefficient source of power for accessory drive. At a flight Mach number of 0.4, only 1.9 horsepower could be extracted at an altitude of 50,000 feet, whereas at 5000 feet, 14.2 horsepower were available for accessory drive. At an altitude of 40,000 feet, the maximum extractable power increased from about 1.0 to 20.7 horsepower at flight Mach numbers of 0.2 and 0.8, respectively. The maximum power available for accessory drive at flight conditions closely approximating landing conditions, 5000 feet and 0.2 flight Mach number, was found to be about 2.6 horsepower.

The steady-state windmilling power-extraction data were found to generalize rather well for altitude but not for flight Mach number variation. The maximum corrected horsepower obtainable from the turbojet engine used in this investigation increased from 1.5 to 178 horsepower as flight Mach number was raised from 0.2 to 1.0.

The maximum over-all efficiency of the windmilling engine as a power source was found to be about 0.36 for a flight Mach number of 0.2 at an altitude of 5000 feet and tended to decrease with increasing altitude at constant flight Mach number. As flight Mach number was increased at a constant altitude, efficiency showed a tendency to increase.

From an evaluation of the time required to stop the engine from free windmilling speed at a given flight condition with a constant applied torque, it was found that to stop the engine in 0.2 minute at an altitude of 40,000 feet required an increase in applied torque from 99 foot-pounds at 0.2 Mach number to 620 foot-pounds at a flight Mach number of 1.0. At a flight Mach number of 0.4, the applied torque required to stop the engine from free windmilling speed in 0.2 minute increased from 160 to 290 foot-pounds as altitude was decreased from 50,000 to 5000 feet. It is possible to estimate with reasonably good accuracy the time-to-stop curve for any engine if the locked rotor torque and free windmilling speed for the desired flight condition and the polar moment of inertia of the rotor are known.

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

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A	area, sq ft
c_p	specific heat of air at constant pressure = 0.24 Btu/lb-°F
g	gravitational constant = 32.2 ft/sec^2
hp_a	extracted horsepower or horsepower available for accessory drive
hp_I	ideal horsepower available with isentropic expansion assumed
I	polar moment of inertia, lb-ft^2
J	mechanical equivalent of heat, 778 ft-lb/Btu
M	flight Mach number
N	engine speed, rpm
P	total pressure, lb/sq ft abs
p	static pressure, lb/sq ft abs
R	gas constant
Q_a	constant applied torque for braking the engine, ft-lb
Q_d	decelerating torque, $Q_d = Q_a - Q_s$, ft-lb
Q_s	steady-state windmilling torque of the engine, ft-lb
T	total temperature, °R
t	time, min
W_a	air flow, lb/sec
γ	ratio of specific heats for air, 1.4
δ	compressor-inlet total pressure divided by NACA standard sea-level static pressure of 2116 lb/sq ft

η over-all windmilling engine efficiency, hp_a/hp_I

θ compressor-inlet total temperature divided by NACA standard sea-level static temperature, 519° R

Subscripts: 2566

f final conditions

i initial conditions

0 ambient conditions

1 venturi throat

2 compressor inlet

3 compressor outlet

4 turbine inlet

5 exhaust-nozzle inlet

APPENDIX B

METHODS OF CALCULATION

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Flight Mach number. - In the calculation of flight Mach number, complete ram pressure recovery at the engine inlet was assumed and the following formula was used:

$$M = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_2}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (1)$$

Extracted horsepower. - The horsepower available for accessory drive was computed from the measured steady-state torque and engine speed.

$$hp_a = \frac{2\pi\, Q_s\, N}{33,000} \qquad (2)$$

Ideal horsepower and efficiency. - The ideal horsepower available was calculated from the isentropic relation:

$$hp_I = \frac{Jc_pT_2}{550}\left[1 - \left(\frac{p_0}{P_2}\right)^{\frac{\gamma-1}{\gamma}}\right]W_a \qquad (3)$$

and the weight flow W_a from the relation:

$$W_{a,1} = \frac{A_1p_1}{\sqrt{RT}}\sqrt{2g\,\frac{\gamma}{\gamma-1}\left[\left(\frac{P_1}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\left(\frac{P_1}{p_1}\right)^{\frac{\gamma-1}{\gamma}}} \qquad (4)$$

The over-all efficiency of the windmilling engine η is defined as:

$$\eta = \frac{hp_a}{hp_I} \qquad (5)$$

APPENDIX C

GRAPHICAL METHOD FOR CALCULATING BRAKING REQUIREMENTS

OF A WINDMILLING TURBOJET ENGINE

At a given flight condition and applied torque greater than locked rotor torque, there are two factors, moment of inertia and steady-state windmilling torque, which affect the time required to stop the engine. The moment of inertia of the system is related to decelerating torque, engine speed, and time by Newton's second law:

$$Q_d = -\frac{2\pi I}{g \times 3600}\frac{\Delta N}{\Delta t} \tag{6}$$

where $\Delta t = t_f - t_i$ is the time required to make the speed change $\Delta N = N_f - N_i$ with a constant decelerating torque Q_d available to overcome the inertia forces of the rotating masses. However, the steady-state windmilling torque of the engine Q_s is a function of engine speed and acts in a direction opposing the applied torque Q_a. Thus, equation (6) becomes:

$$Q_a - Q_s = \frac{-2\pi I}{g \times 3600}\frac{(N_f - N_i)}{(t_f - t_i)} \tag{7}$$

A mathematical solution of this expression is impossible unless the equation of the steady-state windmilling torque-versus-engine-speed curve (similar to fig. 9) for the flight condition in question is known. However, a graphical solution is possible and is believed to be sufficiently accurate.

Arbitrary values were chosen for ΔN over the engine-speed range from free windmilling speed to zero speed. An average steady-state windmilling torque Q_s was then obtained from a curve such as figure 9 each value of ΔN. For a constant applied torque Q_a a value of Δt was obtained from equation (7) for each ΔN. The sum of these values of Δt yields the time-to-stop from free windmilling speed at the given flight condition and applied torque.

The accuracy of the results obtained by this graphical solution will, of course, depend upon the number of speed increments used. Equation (7) was solved mathematically by writing equations for the steady-state windmilling torque-versus-speed characteristic of the engine and integrating $\frac{1}{Q_d}\,dN$ for Mach numbers of 0.8 and 1.0 at

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40,000 feet. From these equations, which were tedious to derive, it was found that the graphical method was accurate to within 2 percent when speed increments of 6 percent of free windmilling speed were used.

In order to compute the time required to brake the engine at flight conditions other than those included in this investigation, the uncorrected torque-speed characteristic of the engine can be obtained from the corrected torque-speed curves of figure 10.

REFERENCES

1. Vincent, K. R., Huntley, S. C., and Wilsted, H. D.: Comparison of Locked-Rotor and Windmilling Drag Characteristics of an Axial-Flow-Compressor Type Turbojet Engine. NACA RM E51K15, 1952.

2. Sobolewski, A. E., and Farley, J. M.: Steady-State Engine Windmilling and Engine Speed Decay Characteristics of an Axial-Flow Turbojet Engine. NACA RM E51I06, 1951.

TABLE 1. - POWER EXTRACTION CHARACTERISTICS OF WINDMILLING TURBOJET ENGINE AT VARIOUS FLIGHT CONDITIONS

Run	Flight Mach number M	Ram pressure ratio P_2/p_0	Compressor-inlet total pressure P_2 (lb/sq ft)	Compressor-inlet total temperature T_2 (°R)	Actual windmilling engine speed N (rpm)	Corrected windmilling engine speed $N/\sqrt{\theta}$ (rpm)	Steady-state windmilling torque Q_s (ft-lb)	Corrected steady-state windmilling torque Q_s/δ (ft-lb)	Extracted horsepower hp_a (hp)	Corrected extracted horsepower $\frac{hp_a}{\delta\sqrt{\theta}}$ (hp)	Compressor-inlet air flow $W_{a,1}$ (lb/sec)	Corrected ideal horsepower $\frac{hp_I}{\delta\sqrt{\theta}}$ (hp)	Over-all windmilling engine efficiency η
Altitude, 5000 feet.													
1	0.209	1.031	1813	510	146	147	43.8	51.1	1.2	1.4	3.63	6.5	0.220
2	.199	1.028	1812	507	274	278	31.2	36.5	1.8	1.9	3.63	5.8	.335
3	.206	1.030	1810	505	449	455	28.2	33.0	2.4	2.9	4.68	7.9	.362
4	.206	1.030	1813	499	579	590	23.8	27.8	2.6	3.1	5.51	9.3	.334
5	.202	1.029	1808	508	736	744	9.5	11.1	1.3	1.6	5.81	9.6	.167
6	0.397	1.115	1954	509	103	104	141.1	152.8	2.8	3.2	-----	-----	-----
7	.396	1.114	1960	517	255	256	137.5	148.5	6.7	7.2	-----	-----	-----
8	.396	1.114	1960	516	643	645	105.9	143.7	13.0	14.1	-----	-----	-----
9	.394	1.113	1960	514	984	989	75.0	110.8	14.0	15.2	-----	-----	-----
10	.401	1.117	1963	514	1280	1286	44.7	48.2	10.9	11.8	-----	-----	-----
11	.397	1.115	1963	516	1577	1582	3.3	3.5	1.0	1.1	-----	-----	-----
12	0.784	1.523	2685	533	3015	2975	83.5	65.8	48.0	37.3	32.79	523.1	0.071
13	.797	1.520	2677	534	3069	3025	66.6	52.6	38.9	30.3	33.15	528.6	.057
14	.800	1.524	2680	534	3112	3068	50.3	39.7	29.8	23.2	33.45	530.7	.044
15	.797	1.519	2675	534	3150	3105	34.0	26.9	20.4	15.9	33.73	532.3	.030
16	.801	1.526	2690	533	3209	3167	16.3	12.8	10.0	7.7	34.79	551.1	.014
Altitude, 20,000 feet.													
17	0.206	1.030	1000	457	114	122	25.1	53.2	0.6	1.3	2.41	7.1	0.185
18	.199	1.028	1001	457	194	206	21.4	45.2	.8	1.8	2.52	6.9	.259
19	.199	1.028	1000	451	218	234	19.1	40.4	.8	1.8	2.84	7.7	.234
20	.195	1.027	1000	454	310	332	16.6	35.2	1.0	2.2	2.97	7.8	.287
21	.199	1.028	1000	452	384	412	13.8	29.2	1.0	2.3	3.27	8.9	.258
22	.202	1.029	1000	452	484	518	11.6	24.4	1.1	2.4	3.36	9.5	.255
23	.136	1.027	998	450	520	558	9.9	20.9	1.0	2.2	3.36	8.8	.254
24	.192	1.026	998	452	555	594	9.2	19.5	1.0	2.2	3.30	8.3	.267
25	.202	1.029	1000	450	665	714	3.9	8.4	.5	1.1	3.36	9.5	.120
26	0.399	1.118	1085	466	202	213	88.3	172.1	3.4	7.0	3.77	37.9	0.184
27	.397	1.115	1082	464	447	473	74.7	146.1	6.4	13.2	4.42	44.4	.296
28	.396	1.114	1084	460	737	783	52.6	102.7	7.4	15.3	5.27	51.8	.295
29	.398	1.114	1085	460	1098	1166	34.3	66.9	7.2	14.8	6.38	62.7	.237
30	.402	1.118	1090	464	1448	1532	10.5	20.5	2.9	6.0	7.64	77.6	.077
31	0.797	1.520	1481	504	2717	2758	84.6	120.8	43.7	83.4	17.18	477.6	0.133
32	.797	1.520	1480	507	2788	2821	68.2	97.6	36.2	52.4	17.47	487.1	.108
33	.799	1.522	1482	505	2854	2894	53.3	76.1	29.0	42.0	17.95	500.1	.084
34	.800	1.525	1482	502	2974	3025	34.3	49.0	19.4	28.2	14.41	401.4	.072
35	.802	1.528	1484	506	3088	3138	14.6	20.8	8.6	12.4	18.64	524.2	.024
36	1.004	1.901	1844	534	3925	3869	67.9	76.0	50.8	57.4	28.85	984.1	0.058
37	.996	1.884	1835	534	3962	3906	44.8	51.7	33.8	38.4	29.21	988.6	.039
38	1.000	1.894	1845	534	4067	4009	33.6	38.6	26.0	29.4	30.55	1037.0	.028
39	.995	1.883	1838	534	4084	4026	18.0	20.7	14.0	15.9	30.17	1019.0	.016
Altitude, 30,000 feet.													
40	0.219	1.034	648	440	95	112	18.8	54.8	0.3	1.2	2.59	12.9	0.090
41	.206	1.030	646	441	205	222	13.2	43.1	.5	1.8	2.58	11.7	.158
42	.195	1.027	646	439	399	434	8.2	26.9	.6	2.2	2.66	10.8	.206
43	.195	1.027	645	432	510	559	5.3	17.3	.5	1.8	2.78	11.2	.165
44	0.408	1.120	700	426	118	143	56.6	171.1	1.4	4.6	2.88	44.2	0.105
45	.394	1.113	701	428	321	354	44.7	135.1	2.7	9.1	3.01	43.8	.208
46	.402	1.118	700	423	605	670	41.4	125.3	4.8	16.0	3.35	50.5	.316
47	.398	1 114	701	425	834	922	26.3	79.5	4.2	13.9	3.52	51.6	.270
48	.396	1.114	702	424	112	1244	13.8	41.6	3.0	9.9	3.86	56.5	.175
49	.410	1.123	703	422	137	1517	5.9	17.8	1.5	5.1	4.24	66.1	.078
50	0.797	1.520	956	464	2074	2194	97.4	215.5	38.4	90.0	7.34	302.7	0.297
51	.803	1.529	957	463	2250	2383	82.2	181.9	35.2	82.4	7.77	323.7	.255
52	.795	1.517	956	463	2522	2671	45.7	101.2	22.0	51.5	8.39	345.0	.149
53	.797	1.519	957	465	2744	2898	22.4	49.5	11.7	27.3	8.94	368.6	.074
54	.801	1.526	955	462	2893	3067	2.6	5.8	1.4	3.4	9.38	390.7	.087
55	1.003	1.899	1189	491	3515	3611	63.2	112.4	42.2	77.3	13.31	674.1	0.115
56	1.003	1.900	1191	494	3601	3691	55.3	98.2	37.9	69.0	13.56	687.9	.100
57	.996	1.883	1188	494	3628	3719	40.8	72.7	28.2	51.4	13.66	685.5	.075
58	1.000	1.895	1190	495	3757	3847	26.3	46.8	18.8	34.3	14.21	720.3	.048
59	.996	1.884	1187	494	3838	3934	9.2	16.4	6.7	12.3	14.56	733.2	.017
Altitude, 40,000 feet.													
60	0.24	1.036	406	448	104	122	16.4	85.7	0.4	2.0	3.77	32.2	0.082
61	.21	1.031	404	446	298	321	11.5	60.3	.7	3.7	3.86	28.4	.130
62	.21	1.028	404	445	446	482	8.2	43.1	.7	4.0	4.01	26.4	.150
63	.17	1.023	402	444	518	559	6.9	36.4	.7	3.8	4.06	21.6	.178
64	0.391	1.111	439	435	118	140	38.2	188.9	0.9	4.8	4.29	97.7	0.050
65	.382	1.106	437	430	380	418	29.6	143.4	2.1	11.4	4.31	94.3	.121
66	.406	1.120	439	427	692	762	27.8	133.2	3.6	19.3	4.49	110.3	.175
67	.400	1.117	438	426	973	1076	17.1	82.6	3.2	16.9	4.72	113.6	.149
68	.392	1.112	437	430	1249	1373	7.6	36.6	1.8	9.8	4.51	104.8	.091
69	0.801	1.528	598	445	210	226	149.7	529.8	6.0	22.8	4.75	311.5	0.073
70	.806	1.534	600	445	793	857	130.9	461.7	19.8	75.4	5.10	338.2	.223
71	.804	1.531	600	443	1324	1434	103.0	363.3	26.0	99.2	5.60	368.9	.268
72	.799	1.522	598	446	1813	1956	75.7	267.7	26.1	99.7	5.99	391.7	.255
73	.802	1.526	599	446	2250	2428	51.3	181.3	22.0	83.8	6.58	433.9	.193
74	.802	1.528	599	444	2732	2953	10.2	36.0	5.3	20.3	7.02	457.5	.044
75	1.002	1.898	740	470	3011	3165	80.3	229.5	46.0	138.3	8.55	682.2	0.203
76	1.005	1.905	745	470	3175	3337	63.8	181.3	38.6	115.2	8.86	706.3	.163
77	.999	1.890	741	471	3382	3551	37.2	106.2	23.9	71.8	9.27	736.3	.098
78	1.000	1.893	742	475	3681	3847	10.5	30.0	7.4	22.0	9.84	789.7	.028
Altitude, 50,000 feet.													
79	0.438	1.141	275	446	118	138	27.3	210.2	0.7	5.5	2.46	114.6	0.048
80	.412	1.124	272	447	295	318	22.4	174.0	1.3	10.5	2.51	104.5	.108
81	.406	1.120	271	446	606	654	15.1	118.1	1.7	14.7	2.56	103.8	.142
82	.397	1.115	272	446	871	940	12.2	94.7	2.0	17.0	2.60	100.9	.168
83	.375	1.102	270	434	1113	1218	5.9	4.6	1.3	10.8	2.68	93.0	.116
84	0.806	1.533	374	453	114	132	87.4	551.0	0.2	14.3	2.52	270.1	0.053
85	.790	1.510	370	459	548	580	78.3	447.8	8.1	49.5	2.86	301.8	.164
86	.804	1.531	372	462	905	959	73.0	415.4	12.6	75.9	2.97	322.6	.235
87	.797	1.519	389	460	1248	1325	64.5	369.7	15.3	93.3	3.08	330.7	.282
88	.799	1.522	370	461	1630	1729	52.6	301.0	16.3	99.2	3.29	353.4	.281
89	.788	1.506	369	460	2060	2188	31.6	181.2	12.4	75.4	3.54	372.4	.203
90	.793	1.514	368	460	2705	2905	4.6	26.5	2.4	14.6	-----	-----	-----
91	1.000	1.892	458	474	2365	2472	79.0	364.8	35.5	171.7	4.40	566.9	0.303
92	1.000	1.893	460	473	2699	2826	58.6	269.4	30.1	144.9	4.64	593.4	.244
93	.998	1.889	459	472	2942	3086	39.2	180.5	21.9	106.1	4.85	625.6	.170
94	.997	1.885	460	470	3380	3552	15.1	69.6	9.7	47.1	5.41	688.6	.068
95	1.005	1.905	461	474	3588	3753	3.3	15.1	2.2	10.8	5.72	738.1	.015

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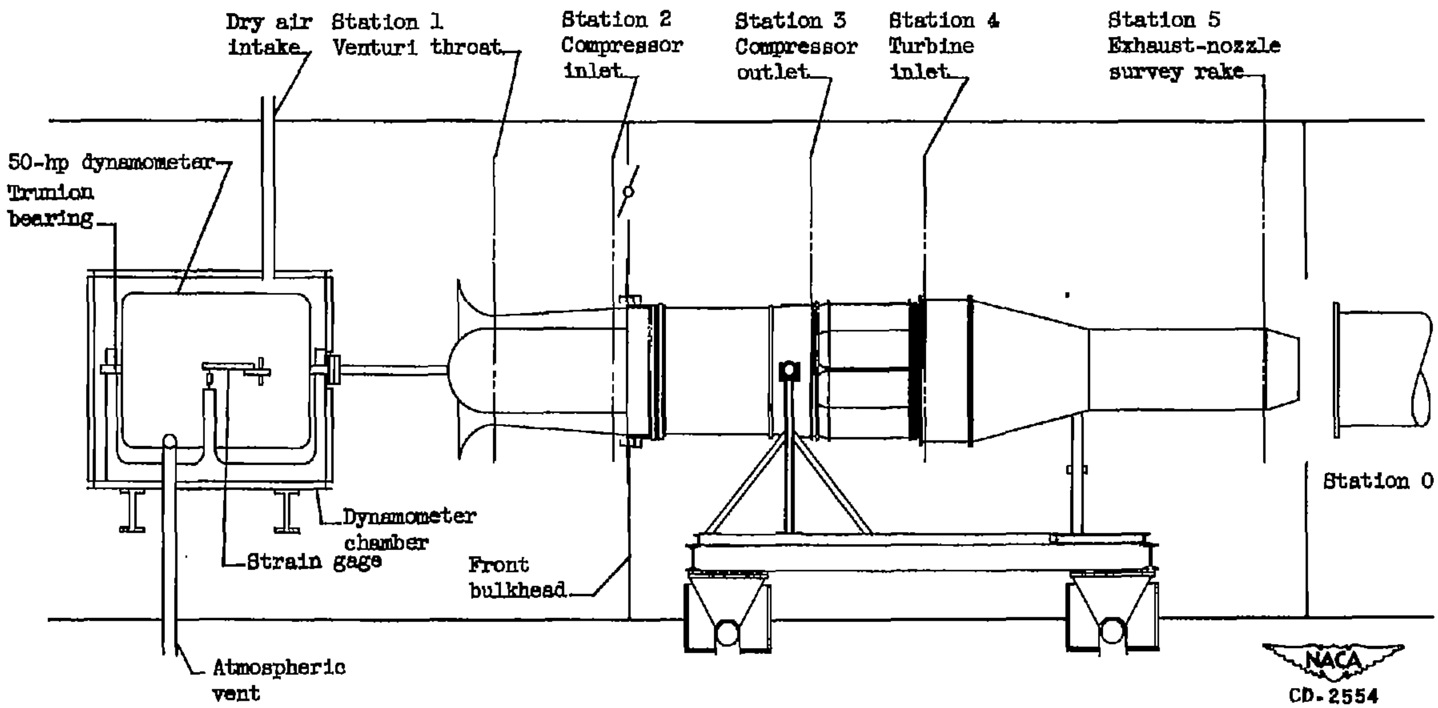
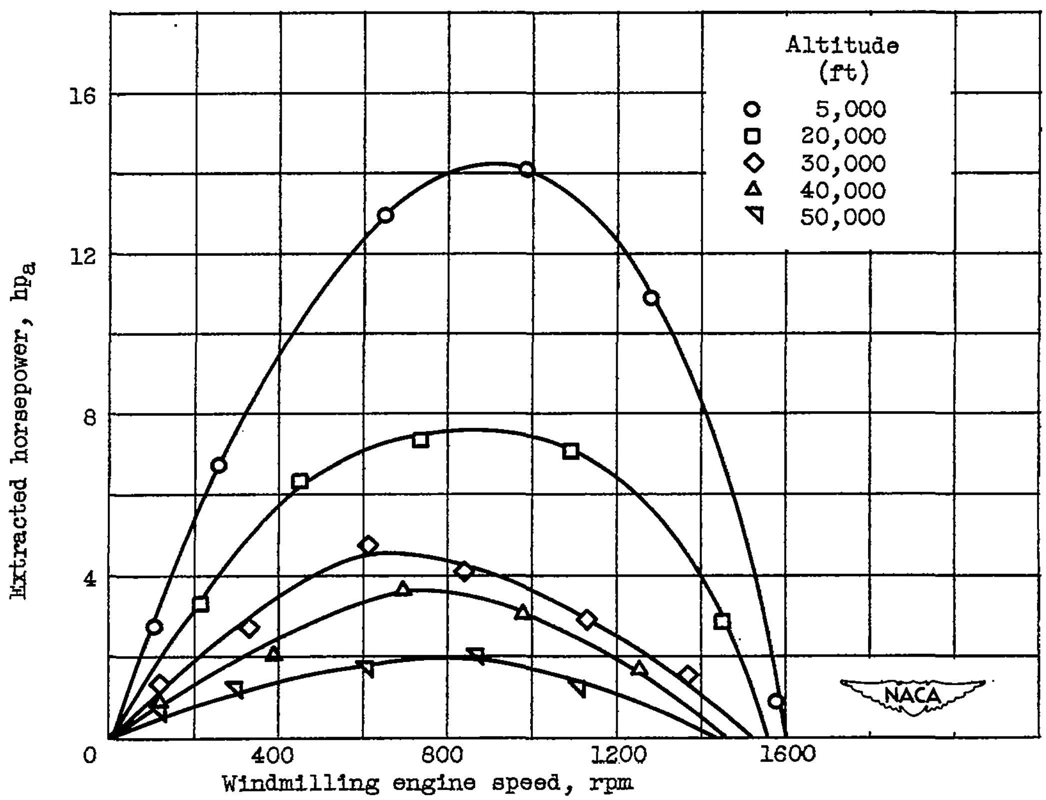
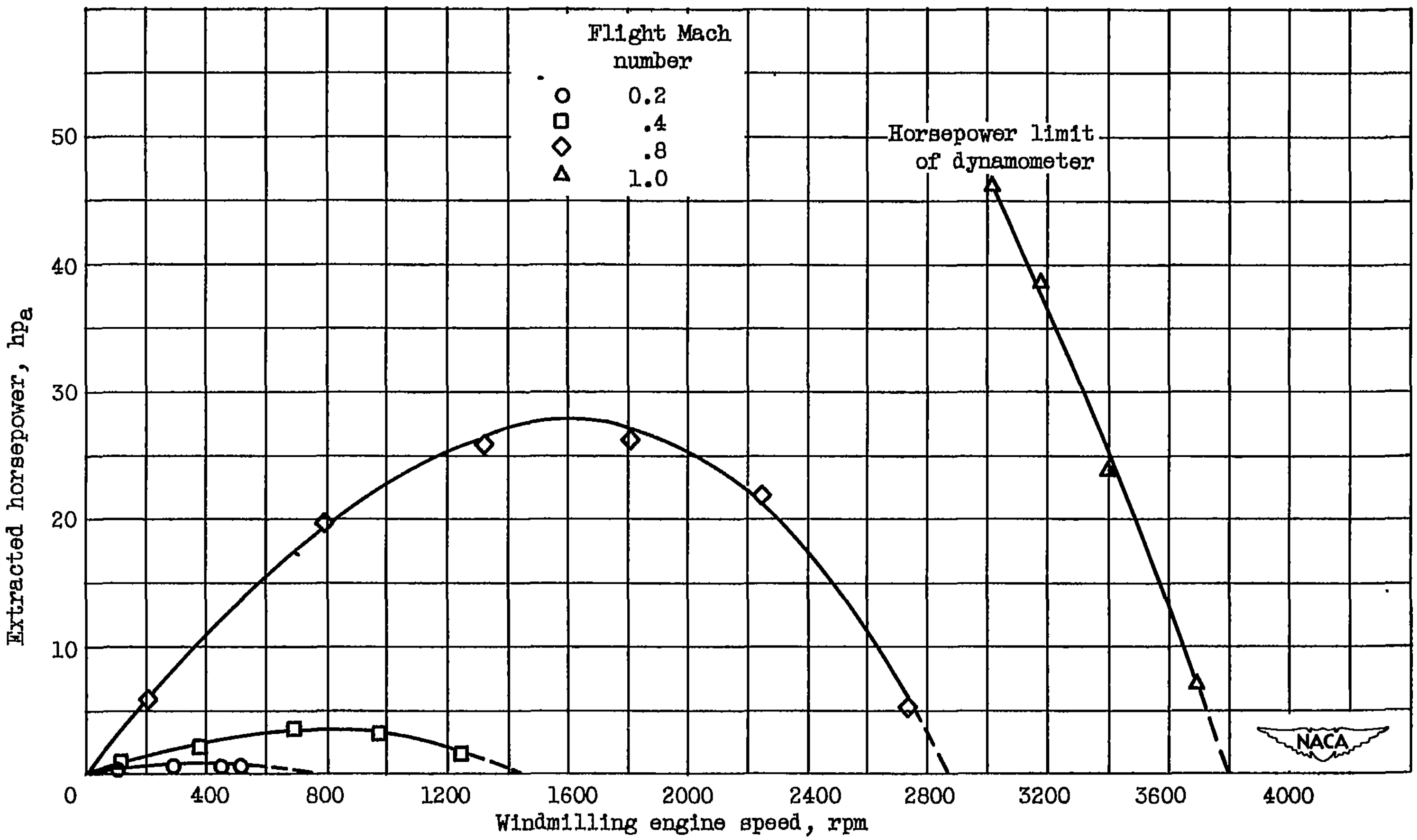


Figure 1. - Schematic drawing of engine and dynamometer installation in altitude test chamber.



(a) Effect of altitude. Flight Mach number, 0.4.

Figure 2. - Extracted power from windmilling turbojet engine.



(b) Effect of flight Mach number. Altitude, 40,000 feet.

Figure 2. - Concluded. Extracted power from windmilling turbojet engine.

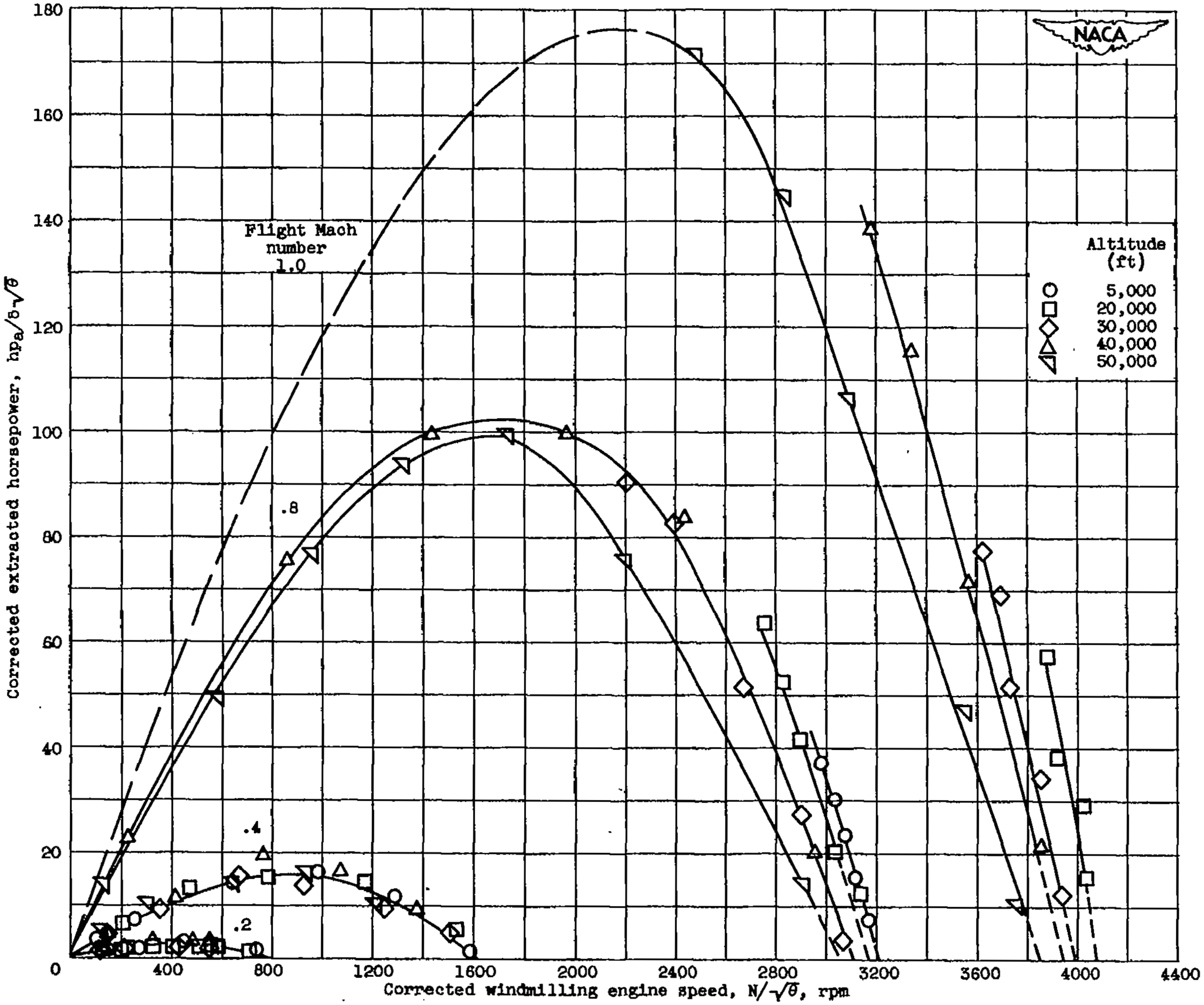


Figure 3. - Generalization of windmilling power-extraction data.

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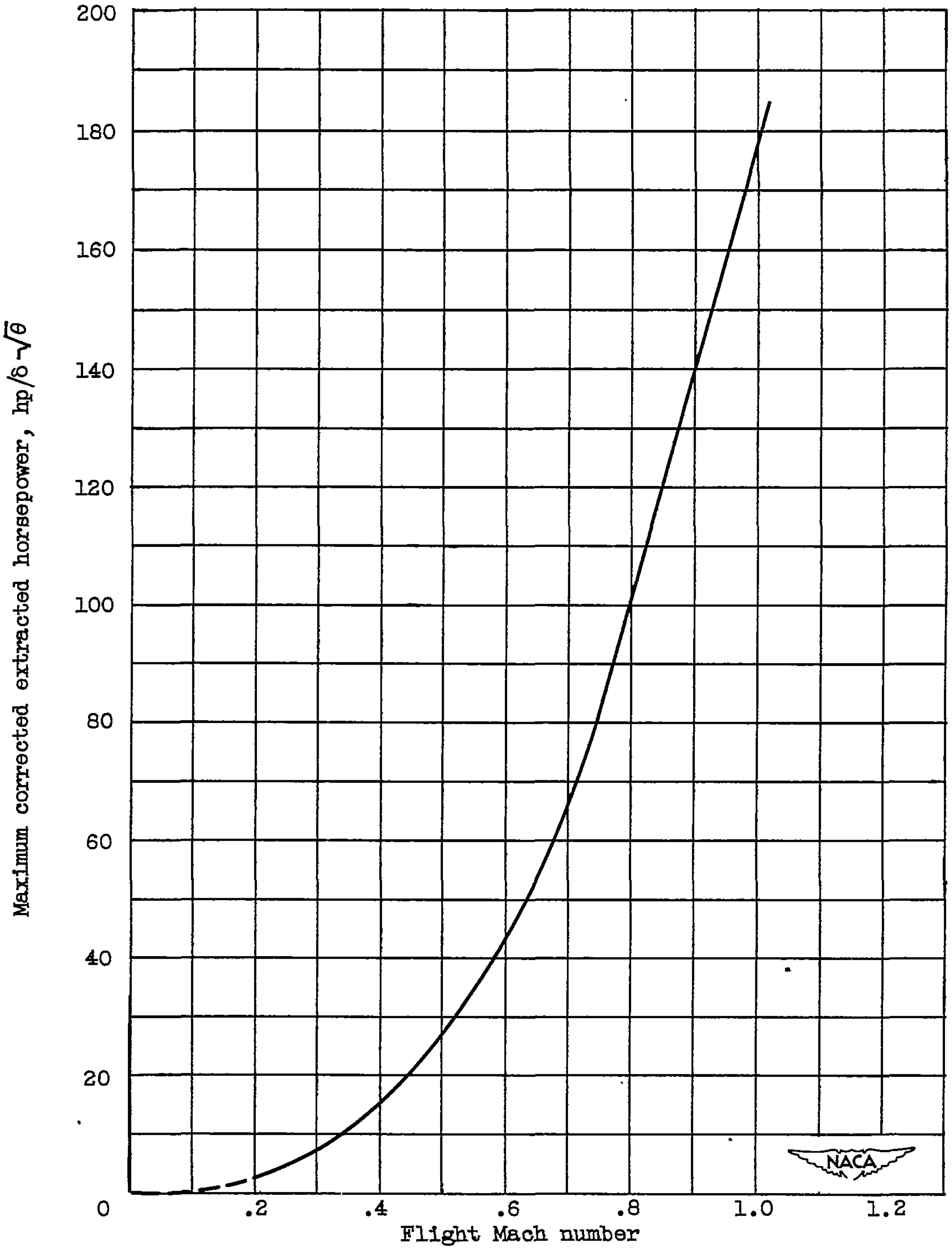

Figure 4. - Effect of flight Mach number on maximum corrected horsepower extractable from windmilling turbojet engine. Altitude, 40,000 feet.

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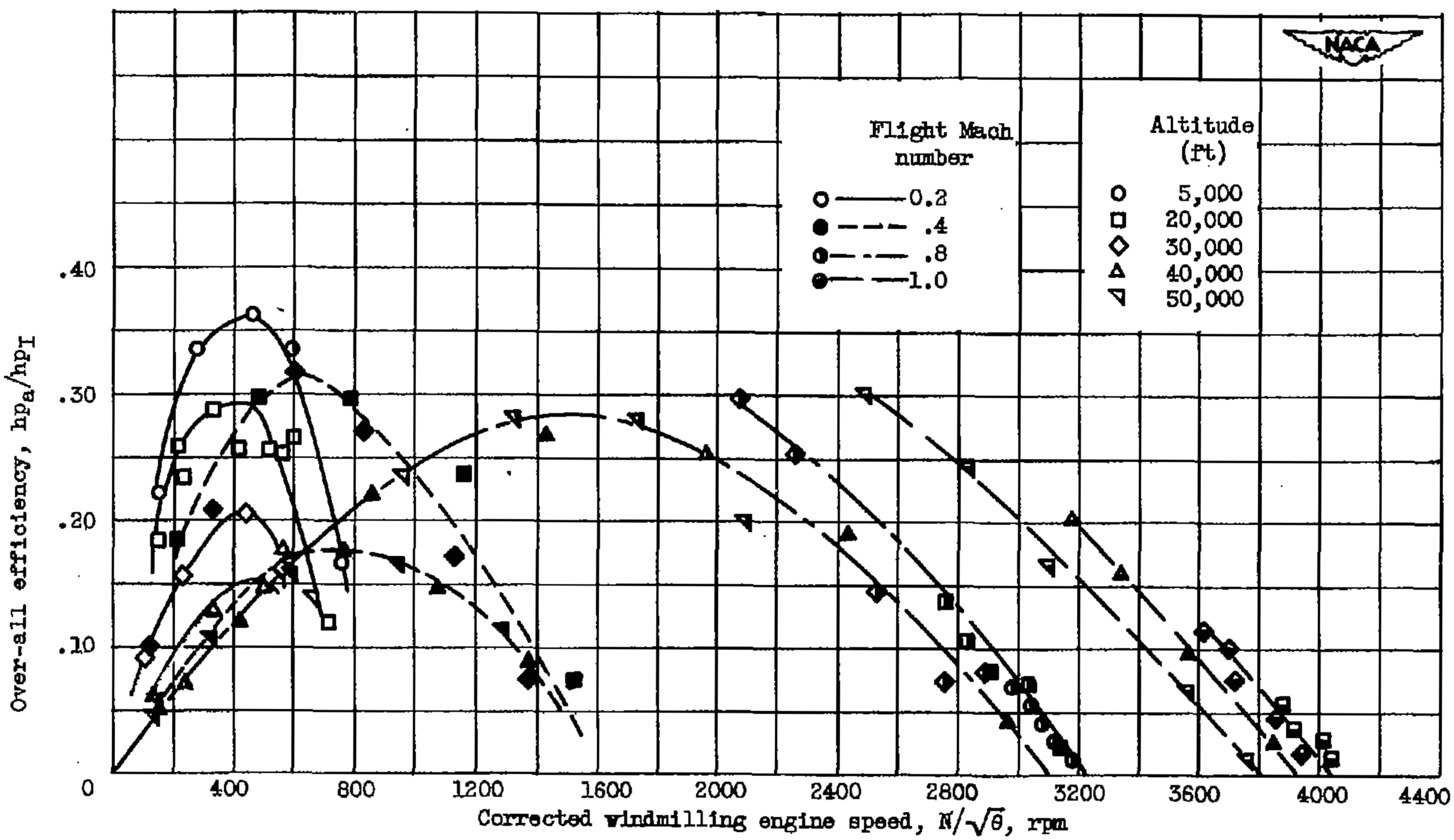

Figure 5. - Over-all efficiency of windmilling turbojet engine used as power source.

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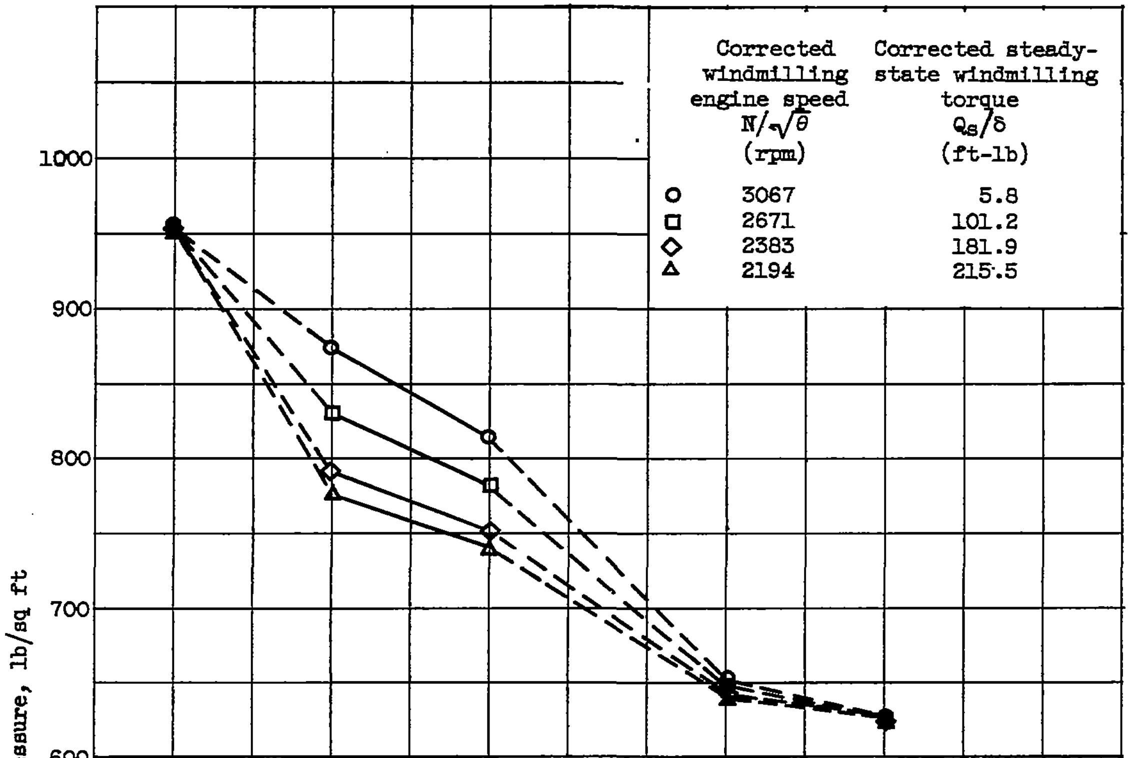
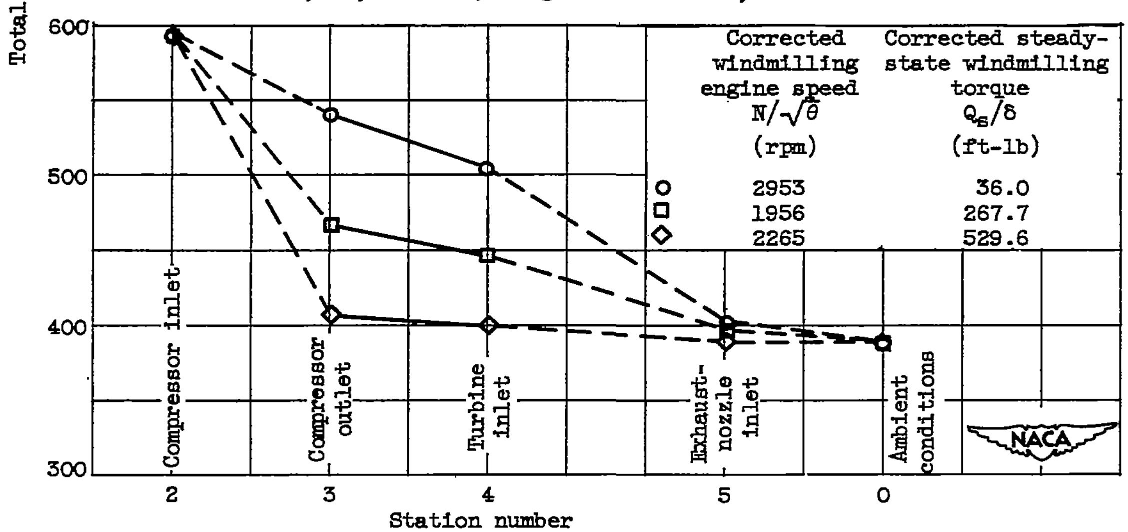
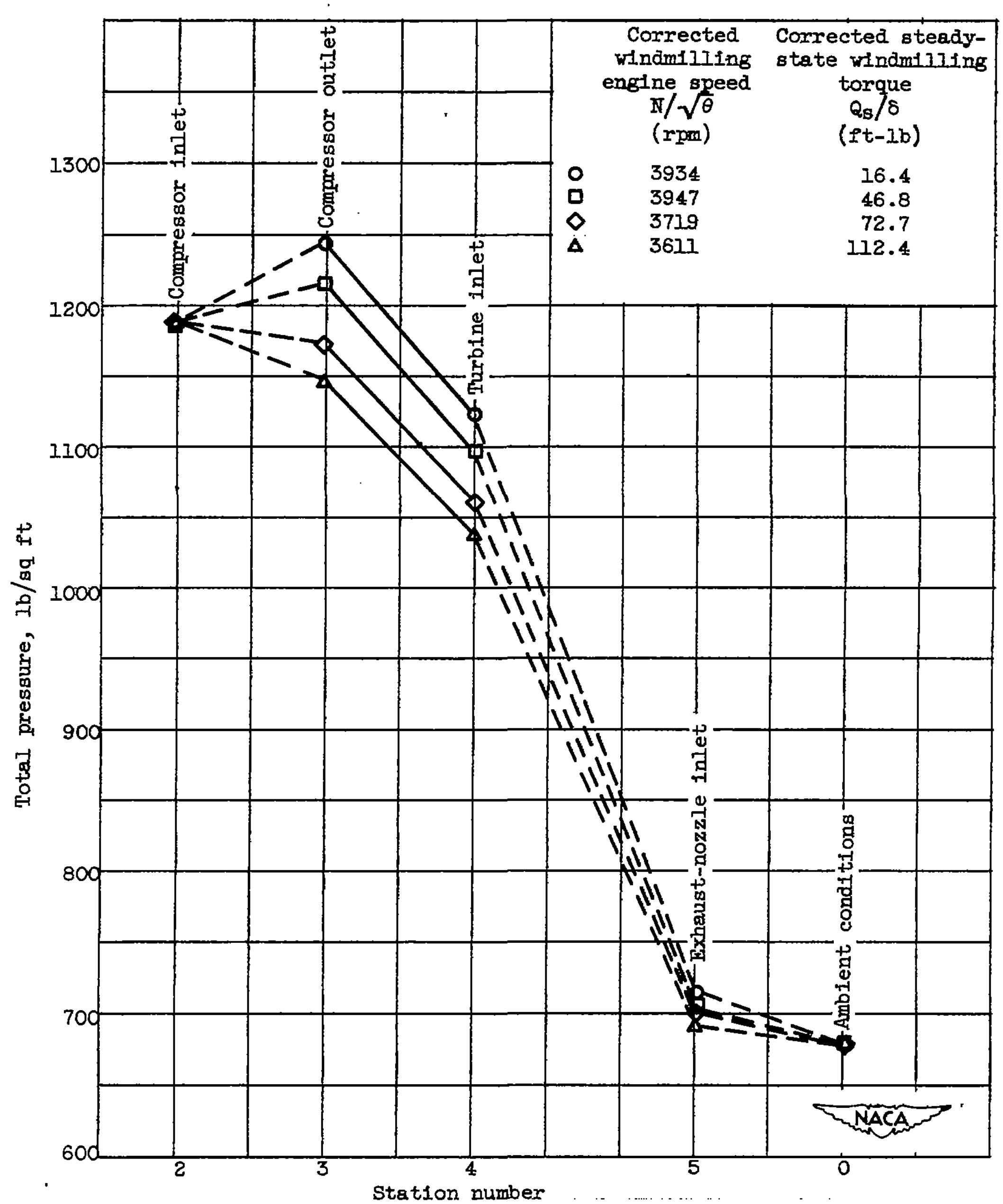


(a) Altitude, 30,000 feet; flight Mach number, 0.8.



(b) Altitude, 40,000 feet; flight Mach number, 0.8.

Figure 6. - Effect of windmilling engine speed on total pressure gradient throught engine.



(c) Altitude, 30,000 feet; flight Mach number, 1.0.

Figure 6. - Continued. Effect of windmilling engine speed on total pressure gradient through engine.

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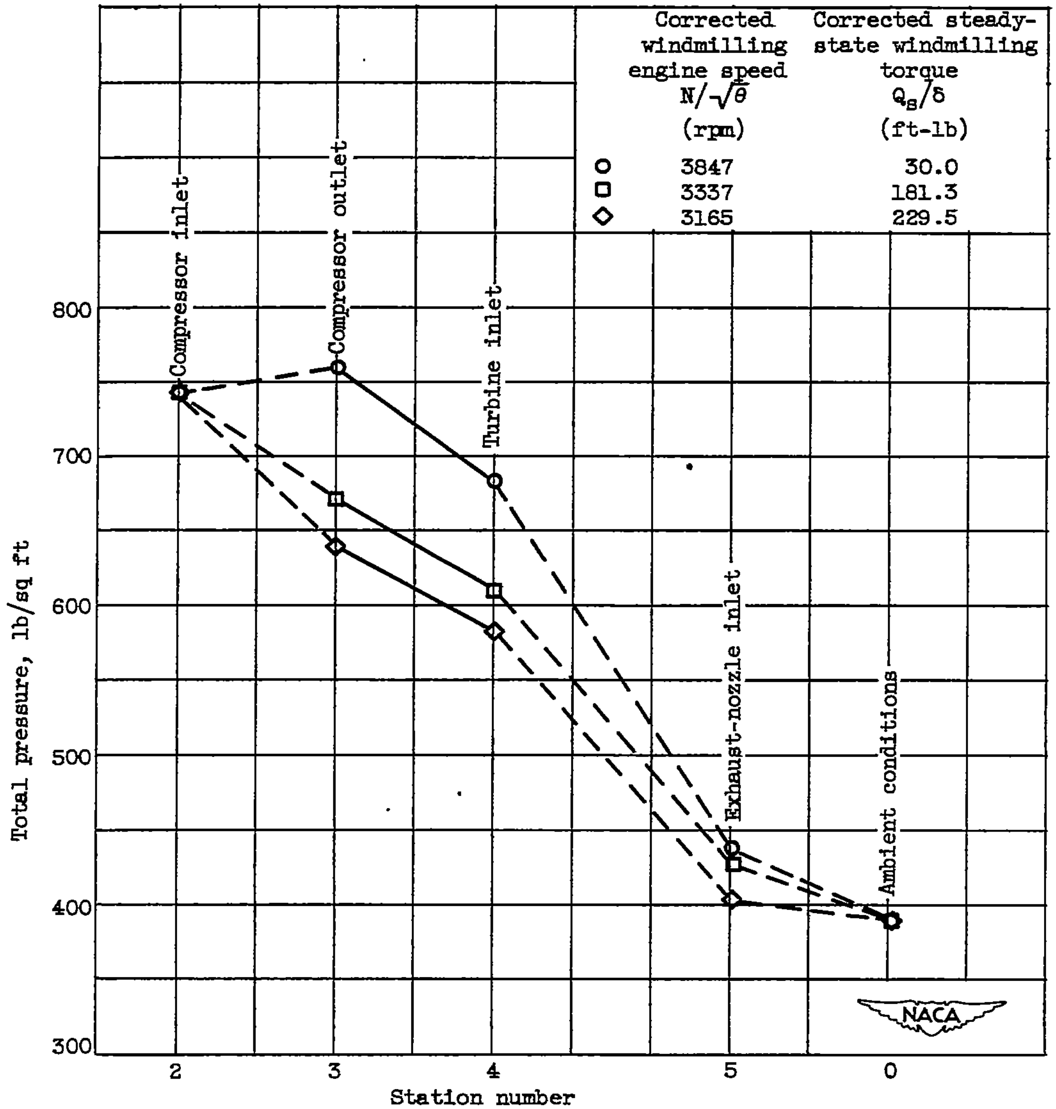


(d) Altitude, 40,000 feet; flight Mach number, 1.0.

Figure 6. - Concluded. Effect of windmilling engine speed on total pressure gradient through engine.

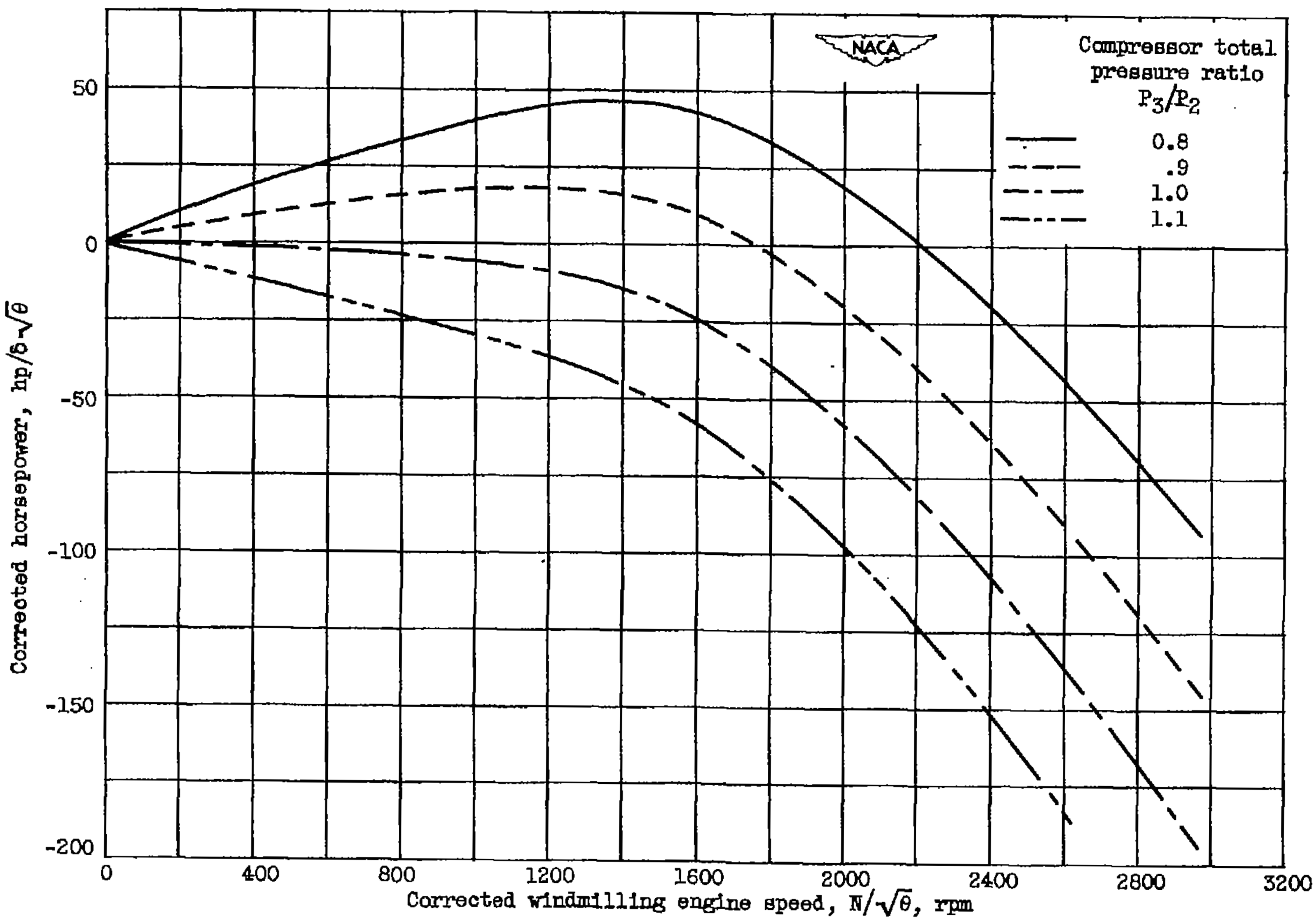


Figure 7. - Variation of corrected compressor horsepower with corrected windmilling engine speed at various compressor pressure ratios.

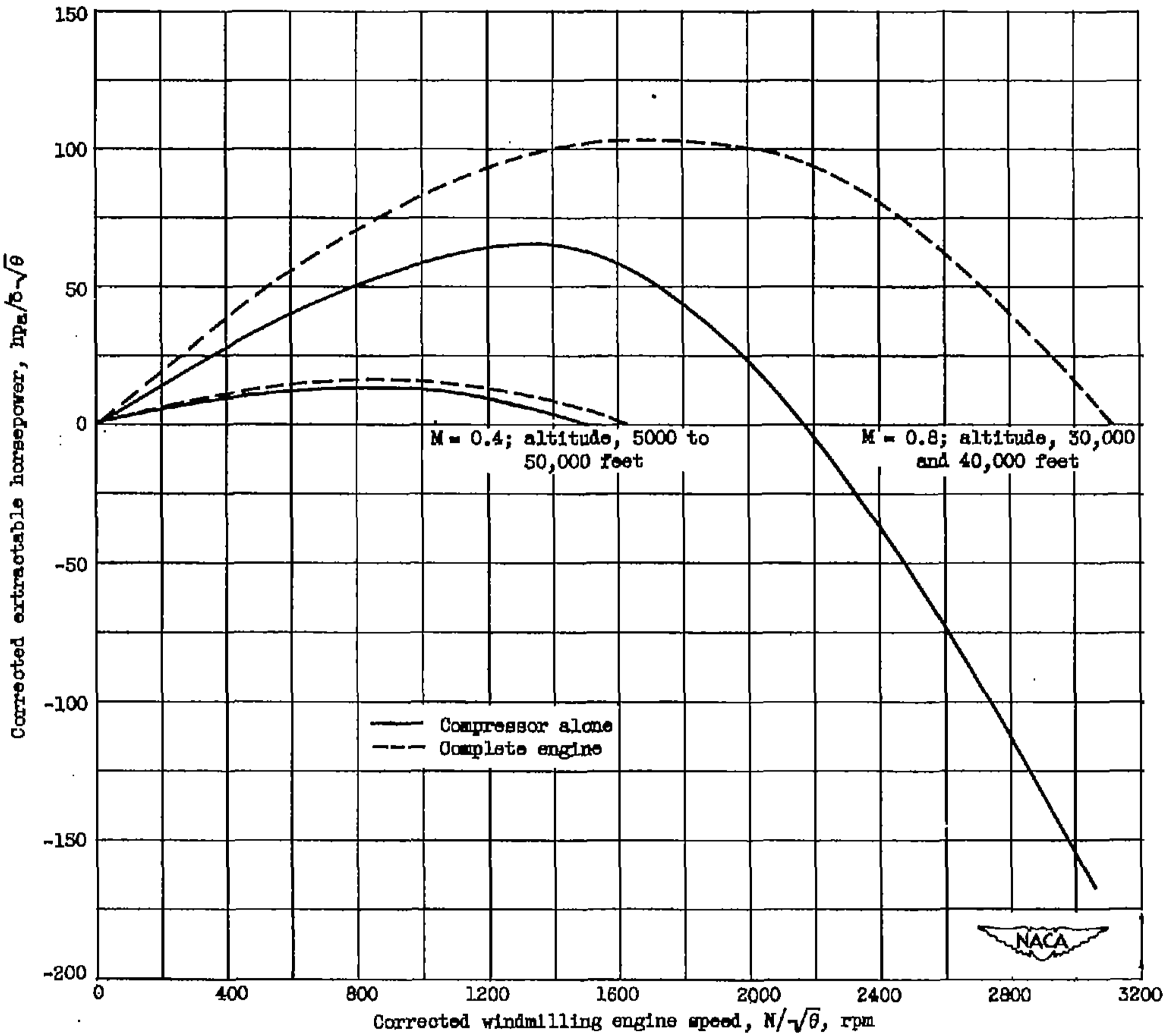
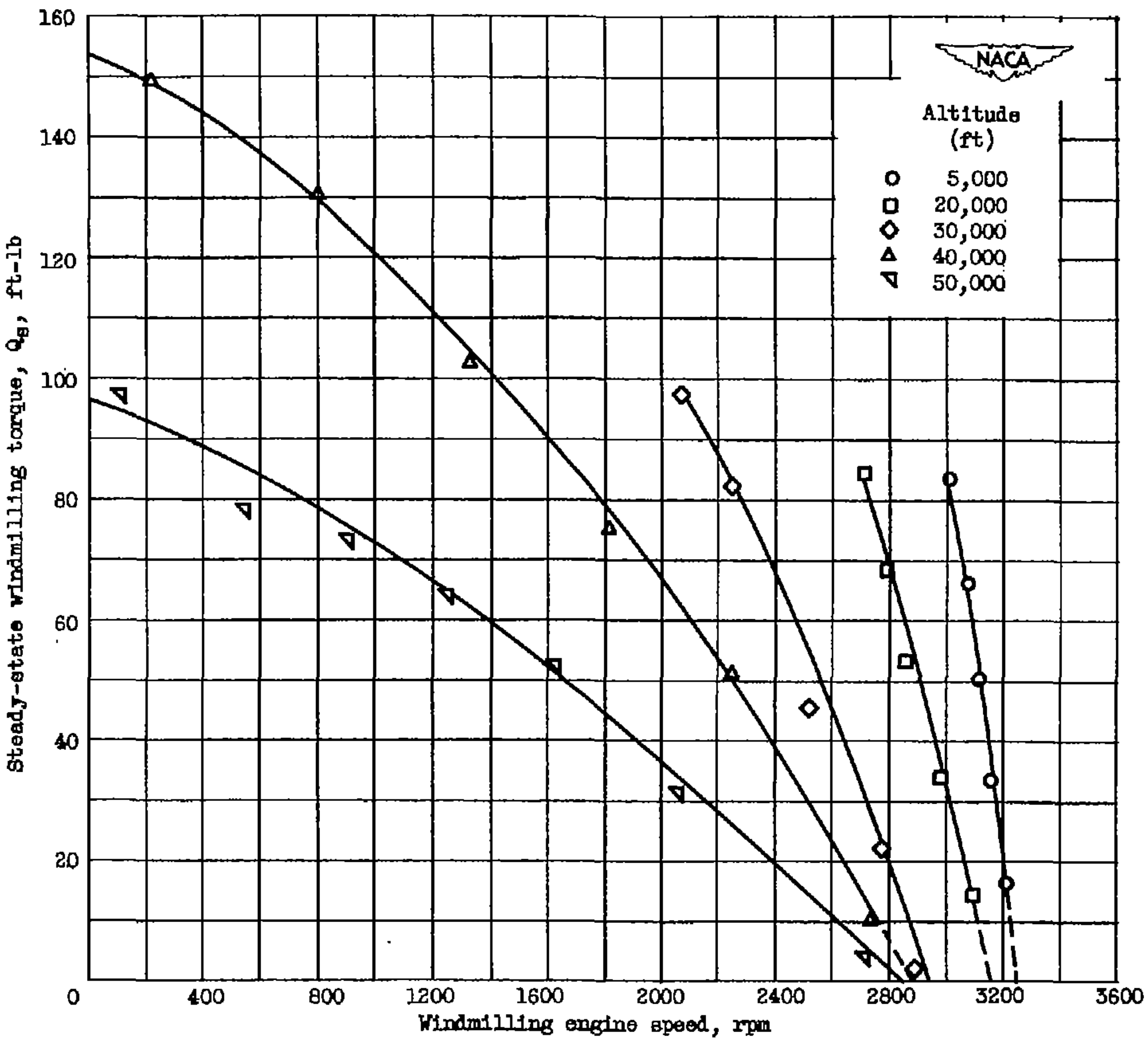
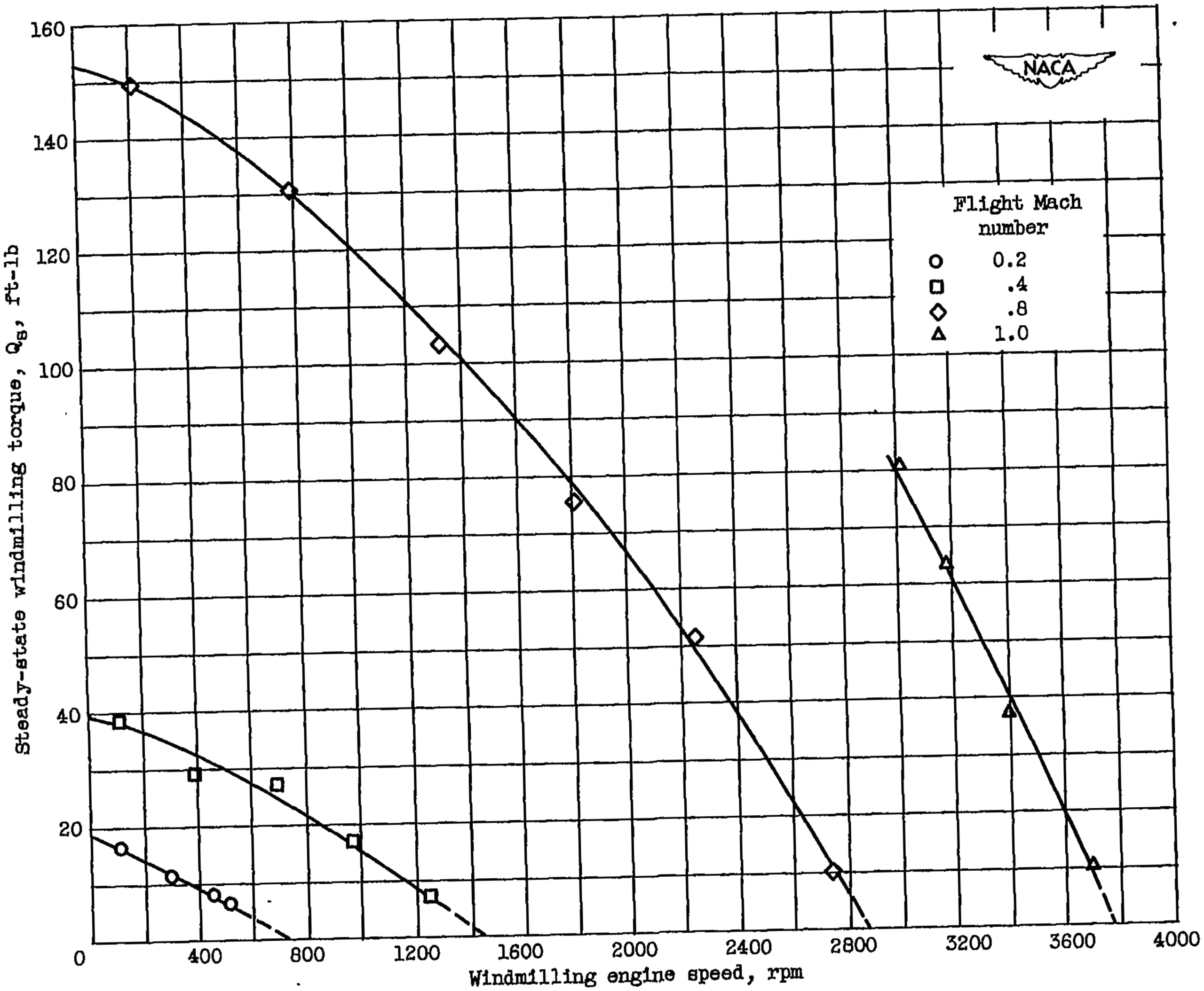


Figure 8. - Comparison of corrected horsepower output from engine and compressor.



(a) Effect of altitude. Flight Mach number, 0.8.

Figure 9. - Steady-state torque as a function of windmilling engine speed.



(b) Effect of flight Mach number. Altitude, 40,000 feet.

Figure 9. - Concluded. Steady-state torque as a function of windmilling engine speed.

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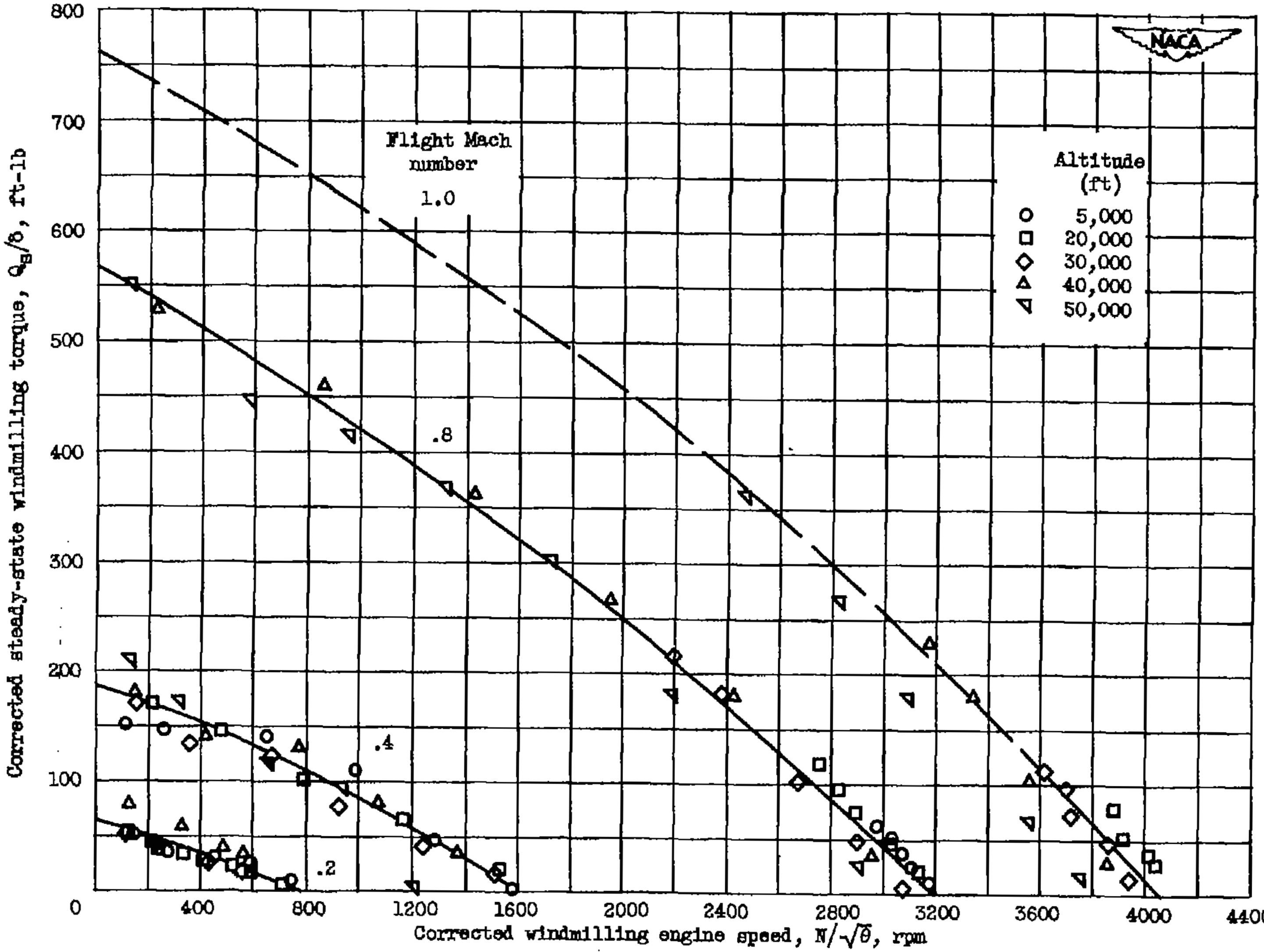

Figure 10. - Corrected steady-state torque as a function of corrected windmilling engine speed.

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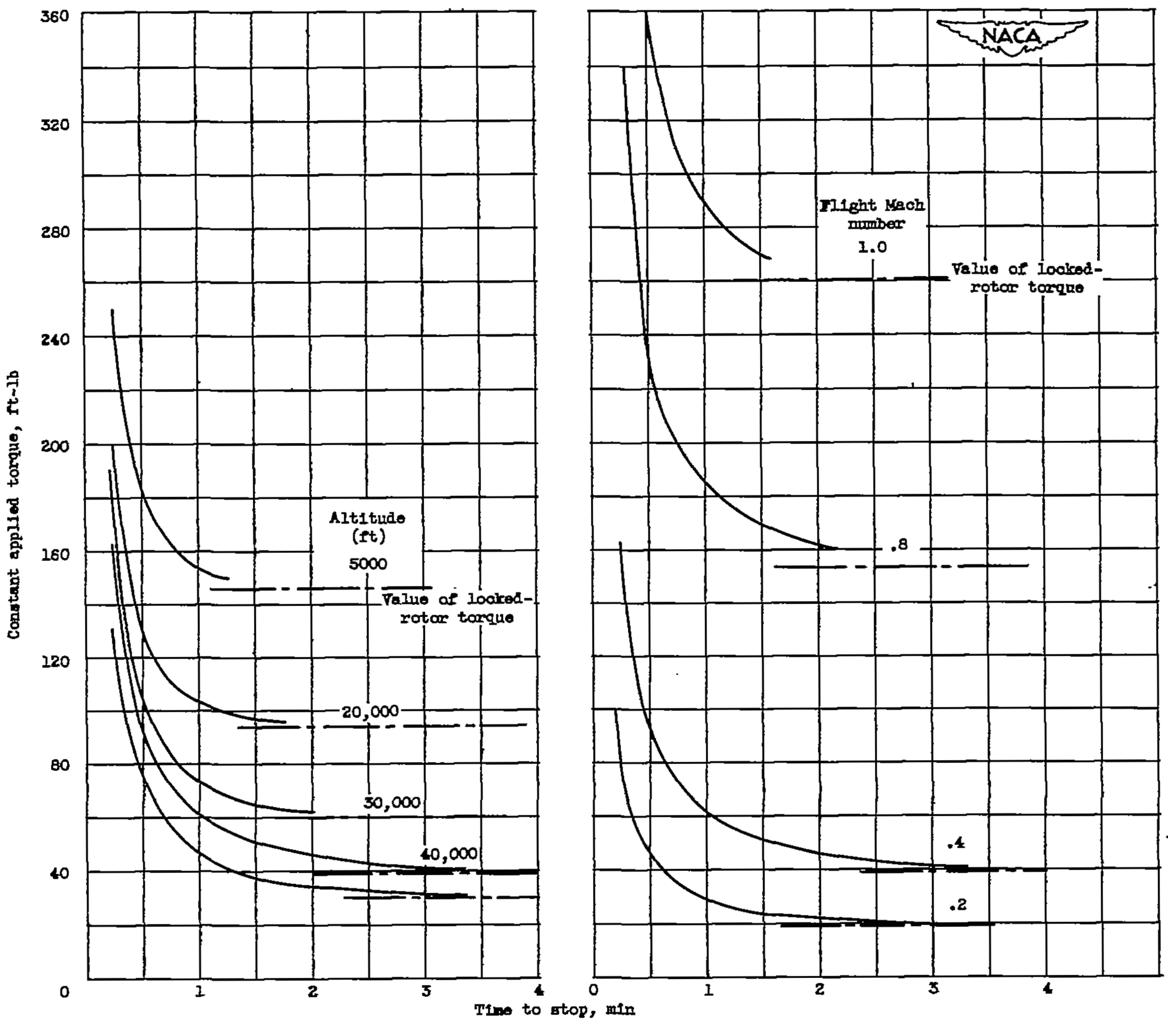

(a) Effect of altitude.
Flight Mach number, 0.4.

(b) Effect of flight Mach number.
Altitude, 40,000 feet.

Figure 11. - Variation of constant applied torque with time required to stop engine from free windmilling speed.

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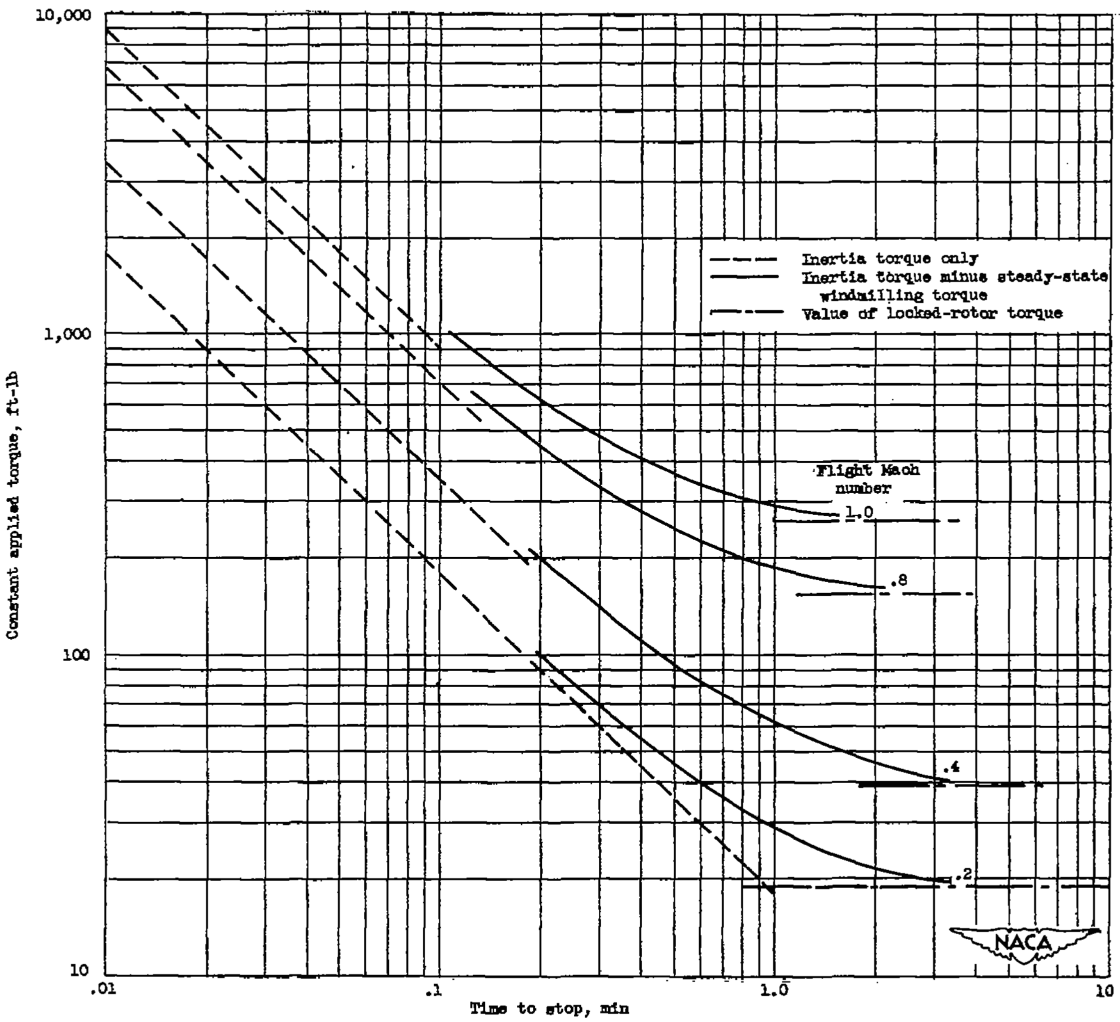

(c) Effect of flight Mach number. Altitude, 40,000 feet; logarithmic scale.

Figure 11. - Continued. Variation of constant applied torque with time required to stop engine from free windmilling speed.

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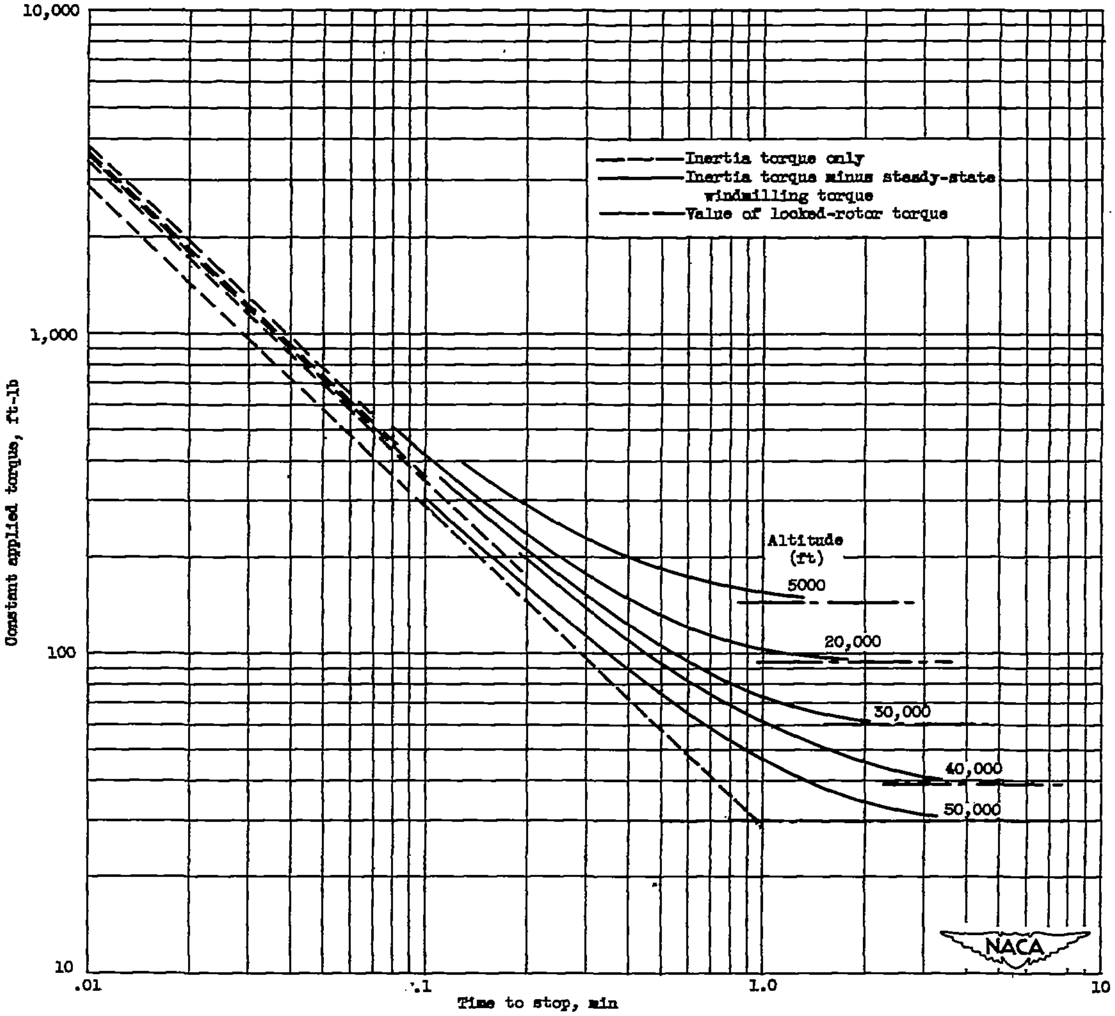

(d) Effect of altitude. Flight Mach number, 0.4; logarithmic scale.

Figure 11. - Concluded. Variation of constant applied torque with time required to stop engine from free windmilling speed.

SECURITY INFORMATION

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