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TECHNICAL NOTE

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FLIGHT INVESTIGATION IN CLIMB AND AT HIGH SPEED OF A TWO-BLADE AND A THREE-BLADE PROPELLER

By Jerome B. Hammack

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SUMMARY

As part of a flight program at the NACA to obtain information on general propeller aerodynamic characteristics, an investigation has been made of a two-blade and a three-blade propeller on a slender-nose fighter airplane in climb and at high speed.

In climbs, the propeller efficiency varied with both change in operating engine power and change in blade number. For normal rated engine power (900 hp and 2600 rpm) the propeller efficiency was higher than for military power (1200 hp and 3000 rpm), being on the order of 4 percent higher at 12,000 feet with a three-blade propeller. With a two-blade propeller, the propeller efficiency was approximately the same for normal rated and military power at altitudes below 12,000 feet. At altitudes above 12,000 feet, the propeller efficiency for the military-power condition increased by about 6 percent at 20,000 feet because of the power drop when the critical altitude was exceeded. A change in blade number from three to two resulted in a decrease in propeller efficiency from 8 to 14 percent for the normal-rated-power condition and about 6 to 7 percent for the military-power condition. This loss in efficiency was due to increasing the power loading per blade which took place when the blade number was changed.

In high-speed flight at a Mach number of 0.7, propeller efficiency increased 17 percent when the power coefficient per blade was increased from 0.07 to 0.17 at the normal engine rotational speed of 2600 rpm; thus the propeller efficiency is shown to increase with power coefficient at higher speeds. Further improvement might have been obtained if the propeller had been tested at higher loadings, since the values of efficiency continued to increase up to the highest loadings used in the tests. Compressibility losses occurred at high speed whenever a tip Mach number of 0.9 was reached and increased in severity with further increases in tip Mach number. The main sources of efficiency loss were the shank and tip sections of the blade. Tip compressibility losses could be minimized by reducing rotational speed. When the tip Mach number was reduced from 0.96 to 0.82 at the same blade power coefficient (0.13) and advance ratio (2.5), the propeller efficiency increased by 4 percent.

INTRODUCTION

As part of a flight program to determine the aerodynamic characteristics of various propellers, tests have been made of two-blade and three-blade propellers on a high-speed fighter airplane.

The unrestricted free-stream flow about the spinner and nose of the airplane used for the tests is especially suited to the study of propeller shanks. The shank problem has been discussed in reference 1 from some of the data obtained in this series of tests. Complete results of the tests on this propeller are presented; and climb and high-speed characteristics, as affected by blade loading, are discussed.

SYMBOLS

B	number of blades
b	blade width (chord), feet
C_P	power coefficient $\left(\frac{P}{\rho n^3 D^5}\right)$
C_{P_2}	power coefficient per blade for a two-blade propeller
C_{P_3}	power coefficient per blade for a three-blade propeller
c_l	section lift coefficient
c_{l_d}	design section lift coefficient
$c_{l_{0.7R}}$	lift coefficient at 0.7 radius
C_T	thrust coefficient $\left(\frac{T}{\rho n^2 D^5}\right)$
$\frac{dC_T}{d(x_s^2)}$	element thrust coefficient
c	speed of sound in air, feet per second
D	propeller diameter, feet
D	drag, pounds
h	blade section maximum thickness, feet

J	advance ratio (V/nD)
L	lift, pounds
M	airplane Mach number (V/c)
M_t	helical tip Mach number
n	propeller rotational speed, revolutions per second
P	engine power, foot-pounds per second
R	propeller tip radius, feet
r	radius to a blade element, feet
r_s	radius to a survey point, feet
T	thrust, pounds
V	true airspeed, feet per second
x	fraction of propeller tip radius (r/R)
$x_s = \frac{r_s}{R}$	
β	blade angle at any radius, degrees
η	efficiency $\left(\frac{JC_T}{C_P}\right)$
ρ	density, slugs per cubic foot

PROPELLER AND TEST EQUIPMENT

Blade-form curves for the propeller tested are shown in figure 1. The shanks are characterized by a rapid transition from thin sections along the blade to round sections at the roots. The airplane used was a fighter-type airplane having an engine installation which permits a slender nose shape. A photograph of the airplane in flight is shown in figure 2.

Other pertinent propeller and engine specifications are as follows:

Propeller characteristics:

Propeller diameter, feet	11.08
Design lift coefficient	0.5
Blade activity factor	130
Blade sections	NACA 16 series
Calculated design advance ratio	2.5
Calculated design power coefficient per blade	0.12

Engine characteristics:

Designation	Allison V-1710-93
Propeller gear ratio	2.23:1
Normal power rating:	
Engine speed, rpm	2600
Manifold pressure, inches of mercury	38
Horsepower	900
Critical altitude (approximately), feet	24,000
Military power rating:	
Engine speed, rpm	3000
Manifold pressure, inches of mercury	50
Horsepower	1200
Critical altitude (approximately), feet	16,000

Propeller torque was measured by an NACA hydraulic torquemeter. The hydraulic torquemeter was similar to the torquemeter used in reference 2 and measured torque by balancing propeller counter torque against a hydraulic piston, the oil pressure within the hydraulic cylinder being proportional to propeller torque. Torquemeter operation was checked frequently by several recalibrations during the test program. From these checks the torquemeter measurements were beleived to be accurate to within ±2 percent.

Propeller thrust was measured by the slipstream-survey method described in reference 3. The survey rake was located about $3\frac{1}{2}$ feet (0.32D) behind the plane of the propeller and can be seen mounted on the airplane with the two-blade propeller installation in figure 3. Standard NACA recording instruments were used to determine engine speed, impact pressure, static pressure, and free-air temperature.

TEST PROCEDURES

Climb tests.- With engine speed, manifold pressure, and indicated airspeed held at desired values, short records were taken at prescribed intervals as the airplane climbed from sea level to altitude.

Data were obtained in the following conditions, all at an indicated airspeed of 165 miles per hour:

(1) Normal rated power, three blades.

(2) Military power, three blades.

(3) Normal rated power, two blades.

(4) Military power, two blades.

High-speed tests.- All high-speed runs were at an altitude of 20,000 feet. Each run was made at values of engine speed, torque, and indicated airspeed selected to produce a desired combination of values of airplane Mach number, propeller advance ratio, and power coefficient. Because the airplane was usually climbing or diving during each run, only engine speed, torque, and airspeed could be fixed. These values were held constant as the airplane passed through an altitude of 20,000 feet, where a short record was taken.

REDUCTION OF DATA

The methods for reduction of recorded data were similar to those outlined in reference 3. In calculating values of propeller efficiency, the effect of slipstream rotation on the total-pressure measurement was neglected. This effect, which is discussed in reference 4, is a function of advance ratio, number of blades, and power loading. The uncorrected values, although from 3 to 4 percent too high, are nevertheless sufficiently accurate for comparative purposes, in that differences in correction are small over the test range.

RESULTS AND DISCUSSION

Climb tests.- The behavior of the propeller in both a three-blade and a two-blade configuration in climbs at an indicated airspeed of 165 miles per hour is shown in figures 4 to 7. These figures show the effect of increasing the power coefficient per blade by approximately 50 percent in climbs at both normal rated and military power.

Exact values of the amount of increase in power loading per blade plotted as the ratio C_{P_2}/C_{P_3} against advance ratio J are shown in figure 8.

For the normal-rated-power condition with three blades the measured data are shown in figure 4. Derived values of section lift coefficient are shown in figure 9(a). For the range of section lift coefficient covered the lift-drag ratio (L/D) is increasing with increasing lift coefficient (reference 5). The propeller efficiency varies from 88 to 90 percent.

Decreasing the number of blades from three to two increases the power per blade as shown in figure 8. In the normal-rated-power climb condition this increase in power loading is accompanied by a decrease in efficiency (fig. 5). The decrease of propeller efficiency with altitude is due primarily to increasing the lift coefficients beyond the most favorable L/D range into the stall region. The slight increase at the end of the climb is due to a reduction in power loading, accompanied by reduced blade lift coefficients which resulted in decreased profile drag losses. The variations in lift coefficient are shown in figure 9(b). The efficiency varies from 74 to 82 percent through the climb range, a decrease of 8 to 14 percent from the lower blade loading. Efficiencies calculated by means of references 6 and 7 show a loss of the same magnitude under these conditions. This decrease in operating efficiency is caused by (a) reduction in the number of blades which increased the induced losses and (b) increased profile drag losses, both because of the higher angle of attack of the blade element and because of the approach of the blade element to the stall region.

Results obtained with the three-blade propeller in a military-power climb are shown in figure 6. Propeller efficiency varies from 83 to 87 percent. The increase at altitude is attributed to a reduction in axial energy losses with increase in forward speed. When the power coefficient per blade is increased by using a two-blade propeller (fig. 7) instead of a three-blade propeller the efficiency drops to values between 77 and 80 percent through the same range, a difference of 6 to 7 percent. Variation of section lift coefficients for military-power climb in both a three-blade and two-blade configuration can be seen in figures 9(c) and 9(d).

Changing the blade number from three to two for normal rated power was found to decrease the efficiency by 8 to 14 percent, depending on altitude. This same change in blade number for the military-power condition produces a decrease in efficiency of only 6 to 7 percent. This smaller efficiency drop results from the fact that the power loading on the blade is not changed so drastically in the military-power condition, as can be seen in figure 8.

A comparison of the efficiency of the three-blade propeller at normal power (fig. 4) and military power (fig. 6) in climb shows that the efficiency is higher at normal power, being of the order of 4 percent higher at 12,000 feet. Figure 10 shows a comparison of the propeller characteristics in the normal-rated and military power conditions. As shown

in figure 10, this higher efficiency at normal power is to be expected because, at any given altitude, the propeller at normal power operates at lower tip Mach numbers, higher values of J, and at approximately the same value of $c_{l_{0.7R}}$ as the propeller at military power. The efficiency at military power increases from 83 percent at 4000 feet ($J = 1.06$) to approximately 87 percent at 16,000 feet ($J = 1.28$) in spite of an increase in tip Mach number from 0.73 to 0.78 and an increase in $c_{l_{0.7R}}$ from 0.75 to 0.83. This increase of efficiency with altitude indicates that the increase in J (fig. 10) has the principal effect and that the sections are apparently operating at subcritical Mach numbers. Similarly, reduction in efficiency at military power from that at normal power at a given altitude must be ascribed chiefly to the lower values of J at military power in the climbing range. Similarly, a comparison of the efficiency of the two-blade propeller at both normal power and military power shows that the propeller efficiency was approximately constant at altitudes below 12,000 feet. At altitudes above 12,000 feet, the propeller efficiency increased when military power was used to the extent that at 20,000 feet a gain in efficiency of the order of 6 percent was obtained as a result of the decrease in power when critical altitude was exceeded.

Thrust gradient curves obtained at military power for both three-blade and two-blade operation are shown in figures 11 and 12. The curves show no compressibility effects. Neither were compressibility losses evident in normal-rated-power climbs.

High-speed tests.- For the high-speed investigation, the airplane was flown at speeds from a Mach number of 0.3 to a Mach number of 0.7 for a range of power coefficient per blade from 0.07 to 0.17. The high end of this range was made possible by reducing the number of blades from three to two.

The effect of blade power loading on propeller efficiency is shown in figures 13 and 14. Runs for figure 13 were made at an engine speed of 2600 rpm and runs for figure 14 at an engine speed of 3000 rpm to determine the effect of tip Mach number. The effect of blade loading on efficiency at a Mach number 0.7 is presented in figure 15. At a forward Mach number of 0.7, the efficiency of the propeller increases with power coefficient per blade. Figure 15(a) shows the variation of propeller efficiency with shank losses included. As pointed out in reference 1, shank losses reduce propeller efficiency for this propeller less as power loading is increased at high speeds, and this fact accounts for most of the improvement shown. Figure 15(b) presents the variation in propeller efficiency when shank losses are omitted. Data for shank losses were obtained from reference 1. The improvement in propeller efficiency with blade loading as shown in figure 15(b) results from the decreased profile drag resulting from propeller sections operating at more favorable L/D ratios. Lift coefficient values for a typical

run are shown in figure 16. These data show that, at a blade power coefficient of 0.17, the blade sections are operating at very nearly the design lift coefficient of 0.5. Figure 15(a) shows that, at an engine speed of 2600 rpm, increasing the power coefficient per blade from 0.07 to 0.17 (an increase of 0.10) increases the propeller efficiency at a Mach number of 0.7 from 65 percent to 82 percent or an increase of 17 percent. At an engine speed of 3000 rpm, increasing the power coefficient per blade from 0.07 to 0.13 (0.13 being the maximum value obtainable at an engine speed of 3000 rpm) increased the efficiency at a Mach number of 0.7 from 69 percent to 74 percent. The decreased efficiency at an engine speed of 3000 rpm as compared with that at 2600 rpm is due to the higher tip Mach numbers associated with the higher rotational speed. At an airplane Mach number of 0.7, the tip Mach number is 0.95 for an engine speed of 2600 rpm and 1.03 for an engine speed of 3000 rpm.

The main sources of efficiency loss in high-speed flight with this blade design are present at the tip and shank sections of the blade. Compressibility losses are generally known to begin at the tip and to proceed inboard progressively with increasing speed. This shift in load unloads the outer sections of the blade and reduces the part of the disk area that carries the load; the load on the inboard section is thus increased. Tip losses can be seen graphically in figures 17 and 18, which are typical thrust distributions. Figure 17 is for the lowest power coefficient per blade obtained, and figure 18 is for the highest. Losses due to compressibility are evident whenever tip Mach numbers of the order of 0.9 are attained. These losses could be reduced by reducing tip speed. For example, at an advance ratio of 2.5 and power coefficient per blade of 0.13, a reduction in tip Mach number from 0.95 to 0.82 increases the propeller efficiency by approximately 4 percent. For higher advance ratios, larger gains would be realized. The data of figures 17 and 18 show that the shank sections account for a large part of the efficiency loss. The negative area shown represents drag and varies principally with airplane Mach number. This loss appears to be relatively independent of power loading. Losses due to the shanks of this propeller have been discussed fully in reference 1, which points out that the losses are caused by thick airfoil sections in the shank region. As was stated in reference 1, shank losses account for an efficiency loss of approximately 9 percent at a Mach number of 0.7 at a test power coefficient of 0.17 per blade.

The propeller used in these tests has relatively high efficiency at a forward Mach number of 0.7 when operated at the highest test power coefficient. This efficiency might be further improved by increasing the power loading and aerodynamically improving the shank sections. An increase in power loading, however, would be detrimental for climbing performance as shown in the section on "Climb tests." Shank sections could be improved either by increasing the spinner diameter as reported in reference 1 or possibly by carrying thin airfoil sections into the spinner. Both of these methods apply only to high-speed flight, as shank losses are neglible in climbs.

CONCLUSIONS

Flight investigations of a three-blade and a two-blade propeller mounted on a slender-nose fighter airplane indicated the following conclusions:

1. For three-blade operation, the propeller efficiency in climbs was higher for normal rated power than for military power, being about 4 percent higher at an altitude of 12,000 feet. For two-blade operation, the propeller efficiency was approximately constant at altitudes below 12,000 feet. At altitudes above 12,000 feet, the propeller efficiency increased when military power was used to the extent that at 20,000 feet a gain in efficiency of the order of 6 percent was obtained as a result of the decrease in power when critical altitude was exceeded.

2. When the blade number was changed from three to two, the propeller efficiency decreased about 8 to 14 percent for the normal-rated-power condition and about 6 to 7 percent for the military-power condition because of the increase in power loading per blade.

3. At a Mach number of 0.7 with an engine speed of 2600 rpm, propeller efficiency increased 17 percent as a result of increasing the power coefficient per blade from 0.07 to 0.17; thus the propeller efficiency is found to increase at high speeds with increased power loading per blade.

4. Compressibility losses appeared with this blade design at a tip Mach number of about 0.9.

5. The main sources of efficiency loss were present in the shank and tip sections of the blade. Tip losses could be minimized by reducing rotational speed, as when the tip Mach number was reduced from 0.95 to 0.82 at the same power coefficient per blade (0.13) and advance ratio (2.5) the propeller efficiency increased by 4 percent.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., November 3, 1948

REFERENCES

1. Hammack, Jerome B.: Investigation of Thrust Losses Due to Shanks of a Flared-Shank Two-Blade Propeller on a Slender-Nose Airplane. NACA TN No. 1414, 1947.

2. Vogeley, A. W.: Flight Measurements of Compressibility Effects on a Three-Blade Thin Clark Y Propeller Operating at Constant Advance-Diameter Ratio and Blade Angle. NACA ACR No. 3G12, 1943.

3. Vogeley, A. W.: Climb and High-Speed Tests of a Curtiss No. 714-1C2-12 Four-Blade Propeller on the Republic P-47C Airplane. NACA ACR No. L4L07, 1944.

4. Pankhurst, R. C.: Airscrew Thrust Grading by Pitot Traverse: Allowance for Rotation of Slipstream at High Rates of Advance. R & M No. 2049, British A.R.C., 1945.

5. Stack, John: Tests of Airfoils Designed to Delay the Compressibility Burble. NACA Rep. No. 763, 1943.

6. Hartman, Edwin P., and Feldman, Lewis: Aerodynamic Problems in the Design of Efficient Propellers. NACA ACR, Aug. 1942.

7. Crigler, John L., and Talkin, Herbert W.: Propeller Selection from Aerodynamic Considerations. NACA ACR, July 1942.

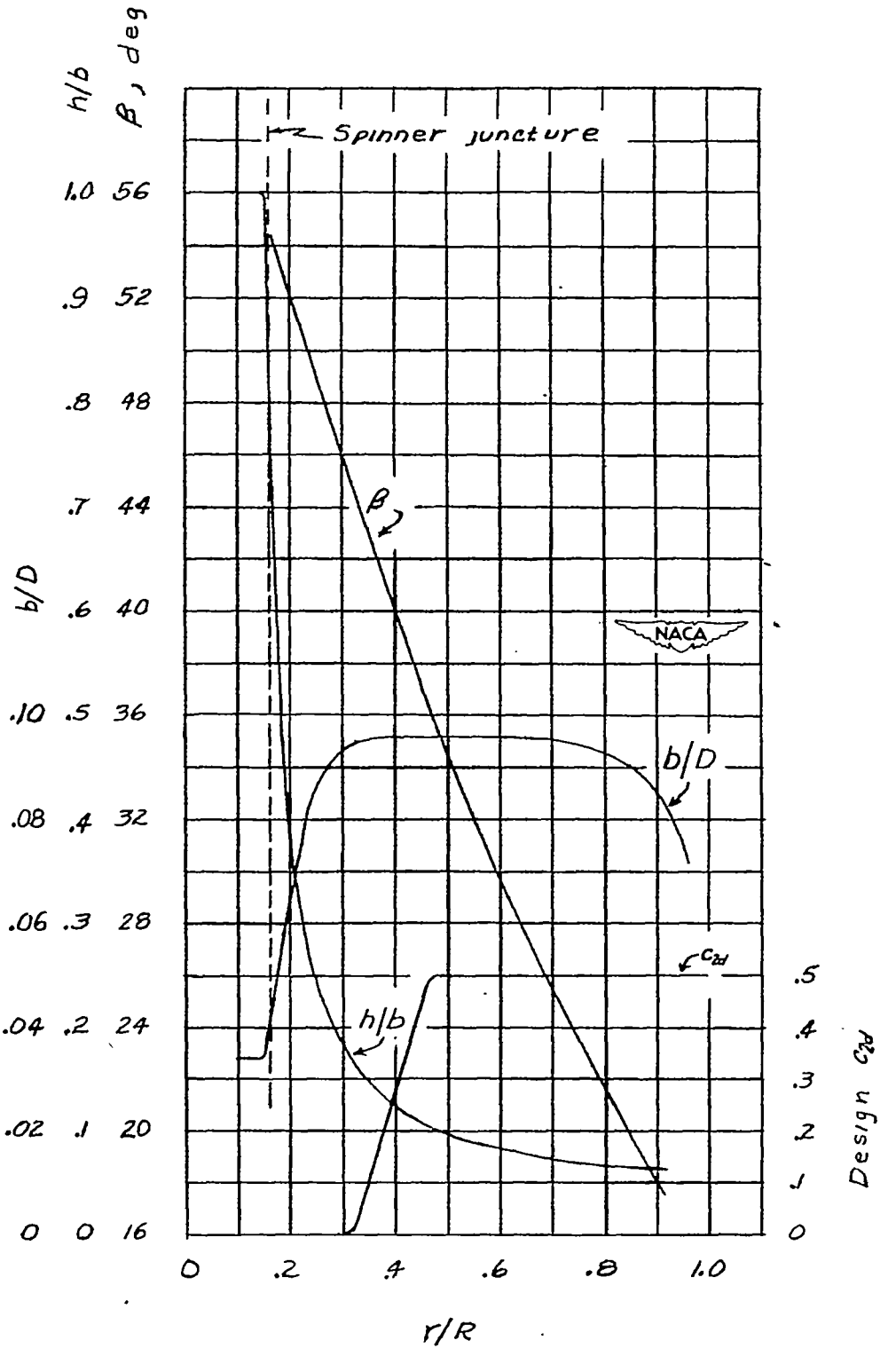


Figure 1.- Blade-form curves of propeller tested.

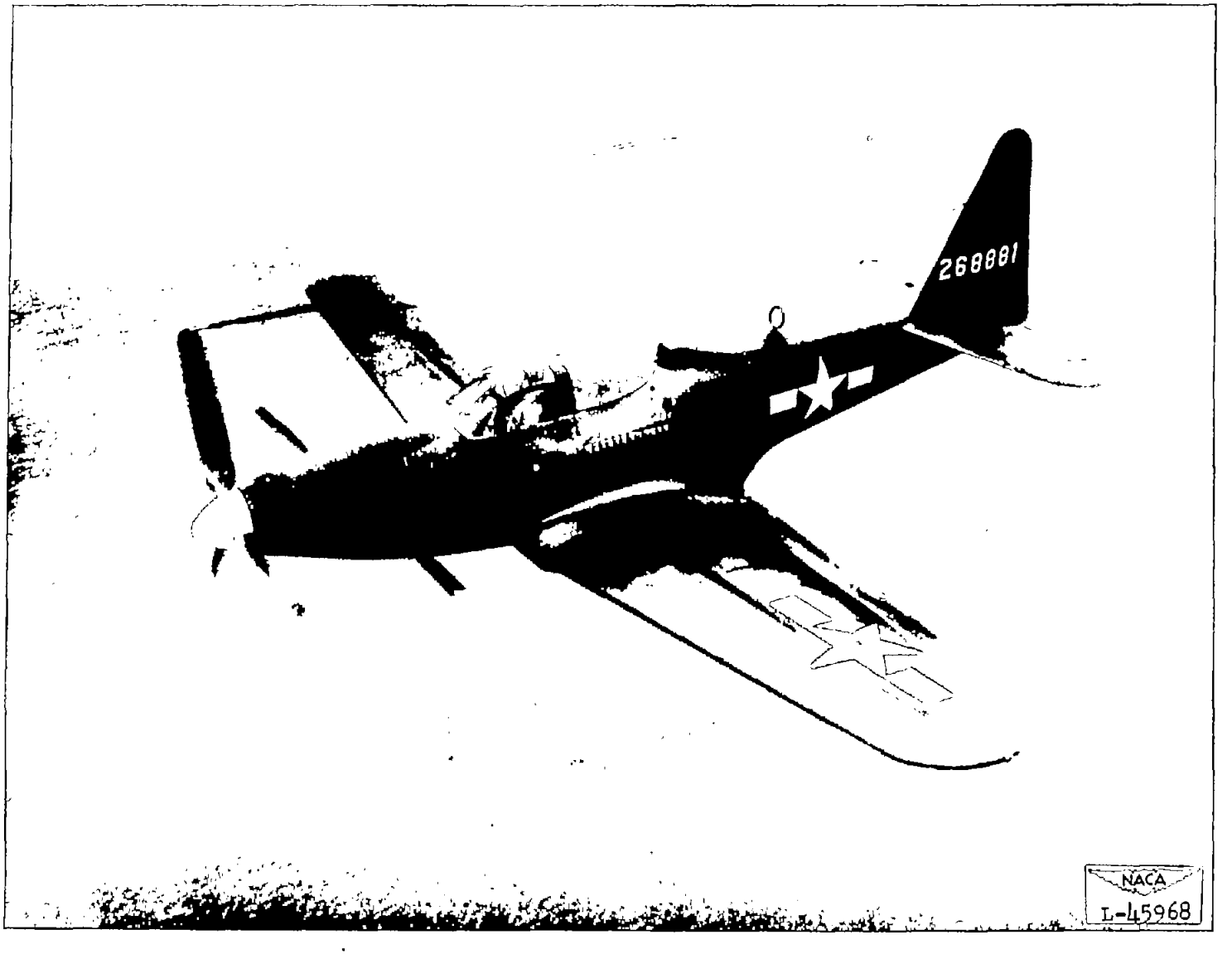


Figure 2.- Test airplane in flight with three-blade propeller. The survey rake and NACA airspeed boom are visible in this view.

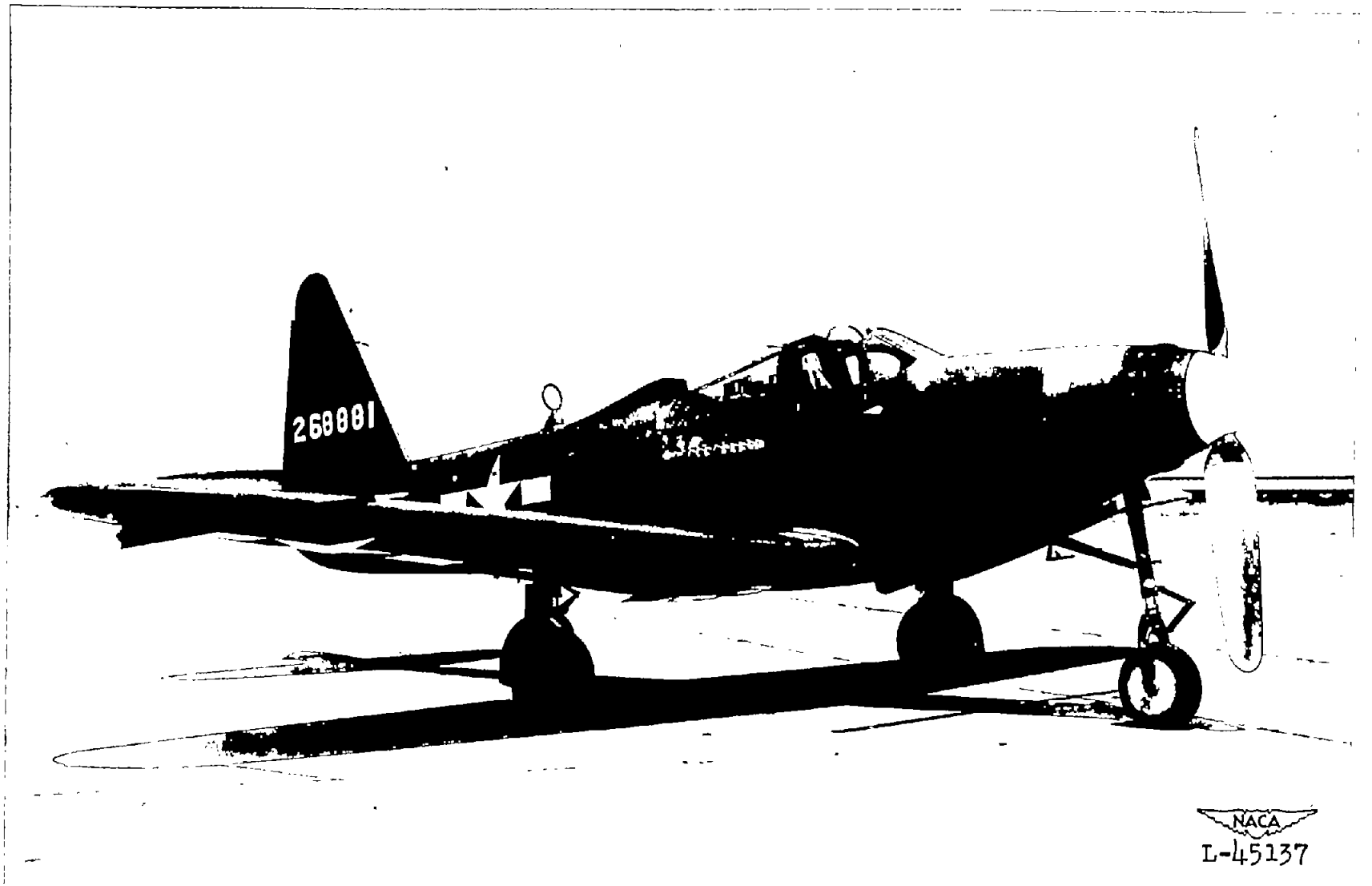


Figure 3.- Test airplane with a two-blade propeller.

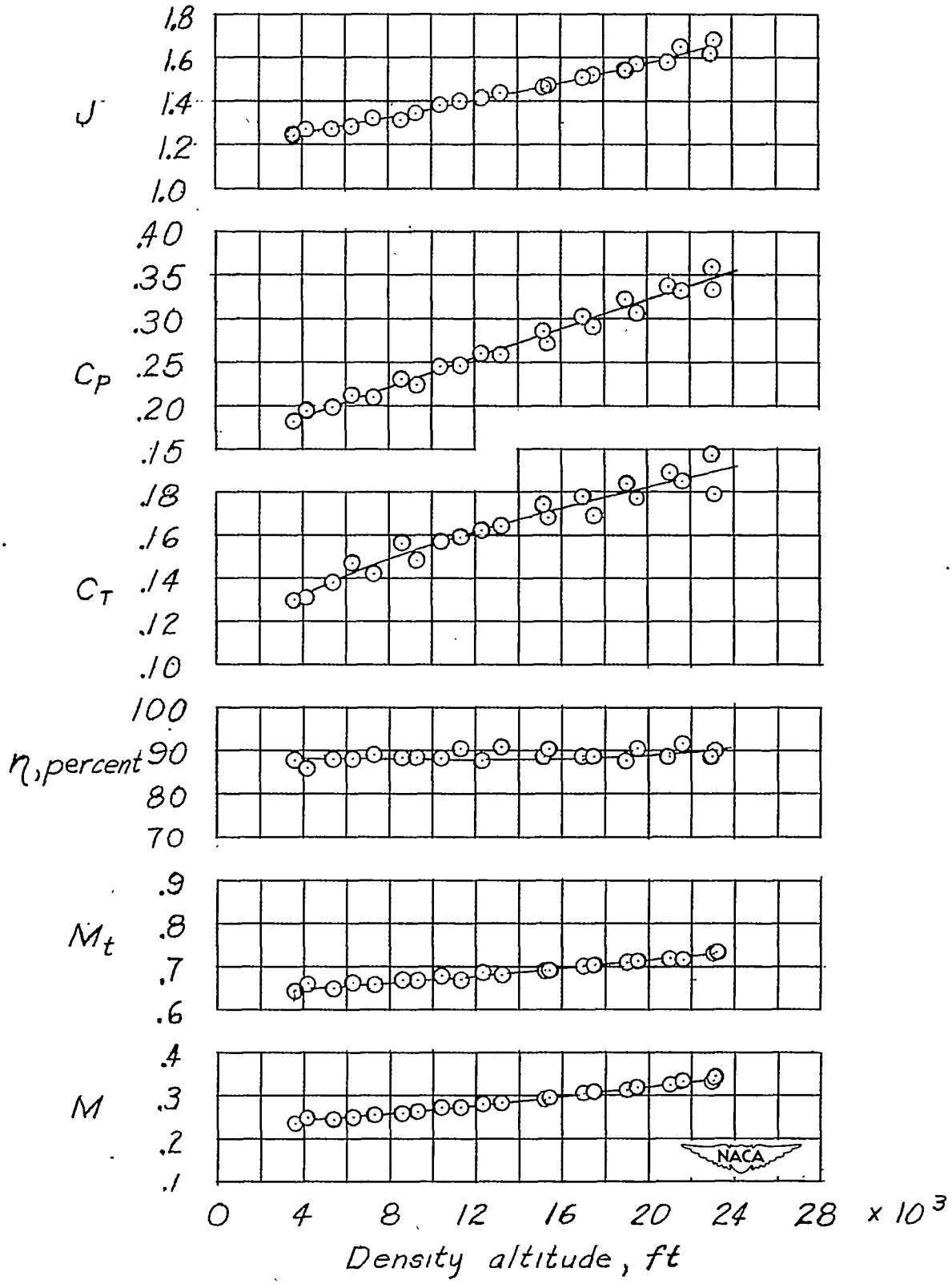


Figure 4.- Normal-rated-power climb at an indicated airspeed of 165 miles per hour with three-blade propeller on a fighter-type airplane.

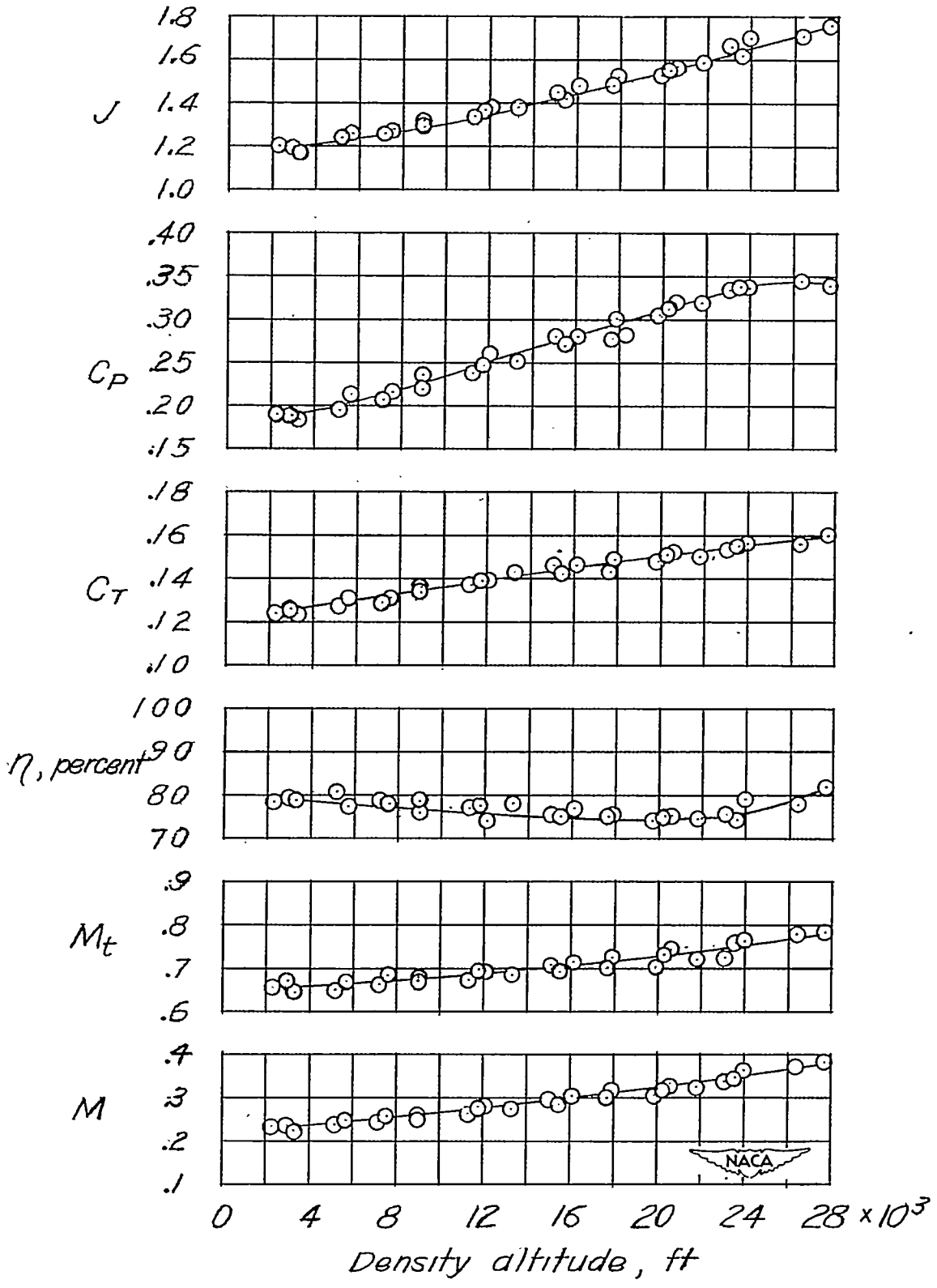


Figure 5.- Normal-rated-power climb at an indicated airspeed of 165 miles per hour with two-blade propeller on a fighter-type airplane.

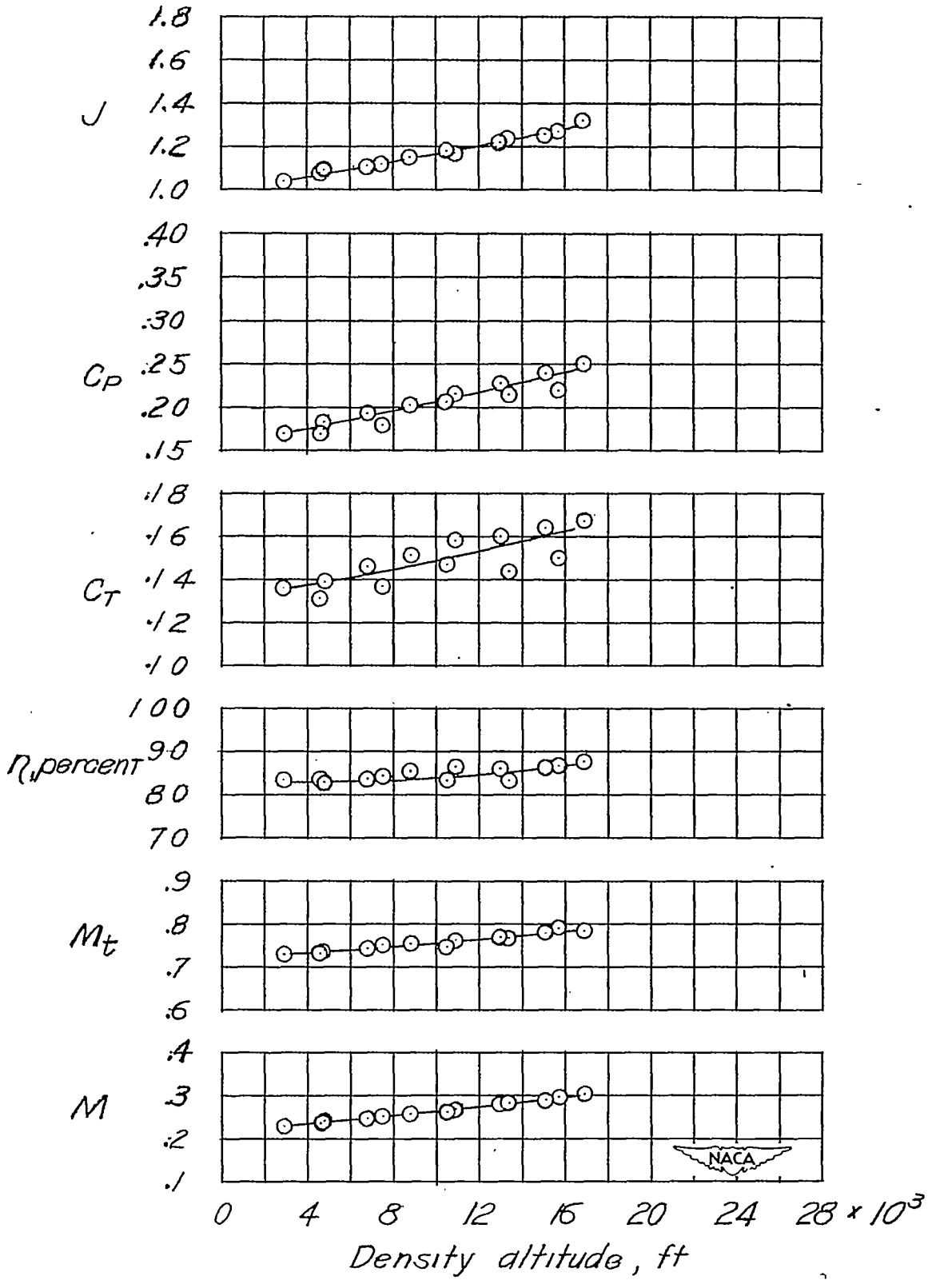


Figure 6.- Military-power climb at an indicated airspeed of 165 miles per hour with three-blade propeller on a fighter-type airplane.

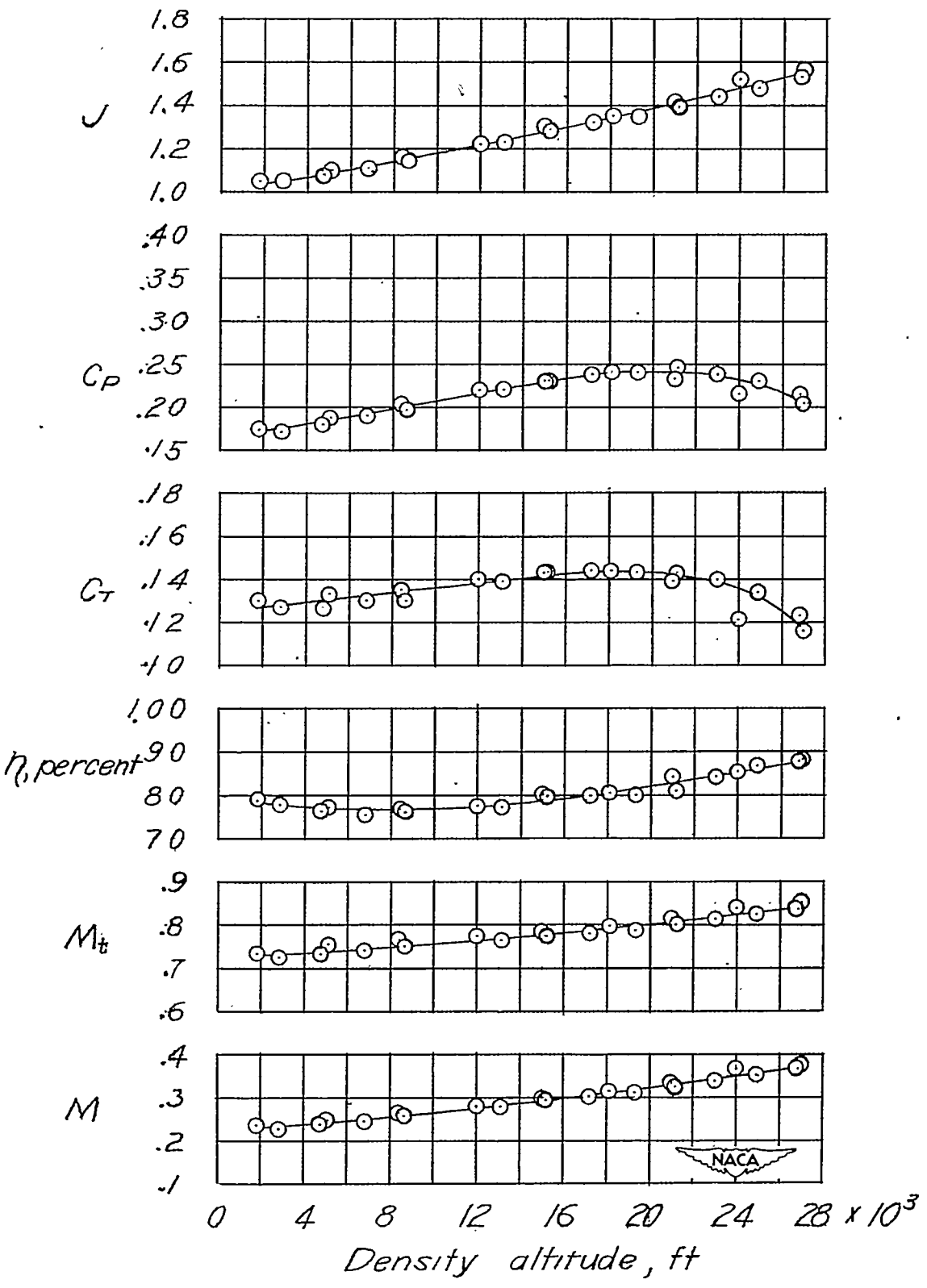


Figure 7.- Military-power climb at an indicated airspeed of 165 miles per hour with two-blade propeller on a fighter-type airplane.

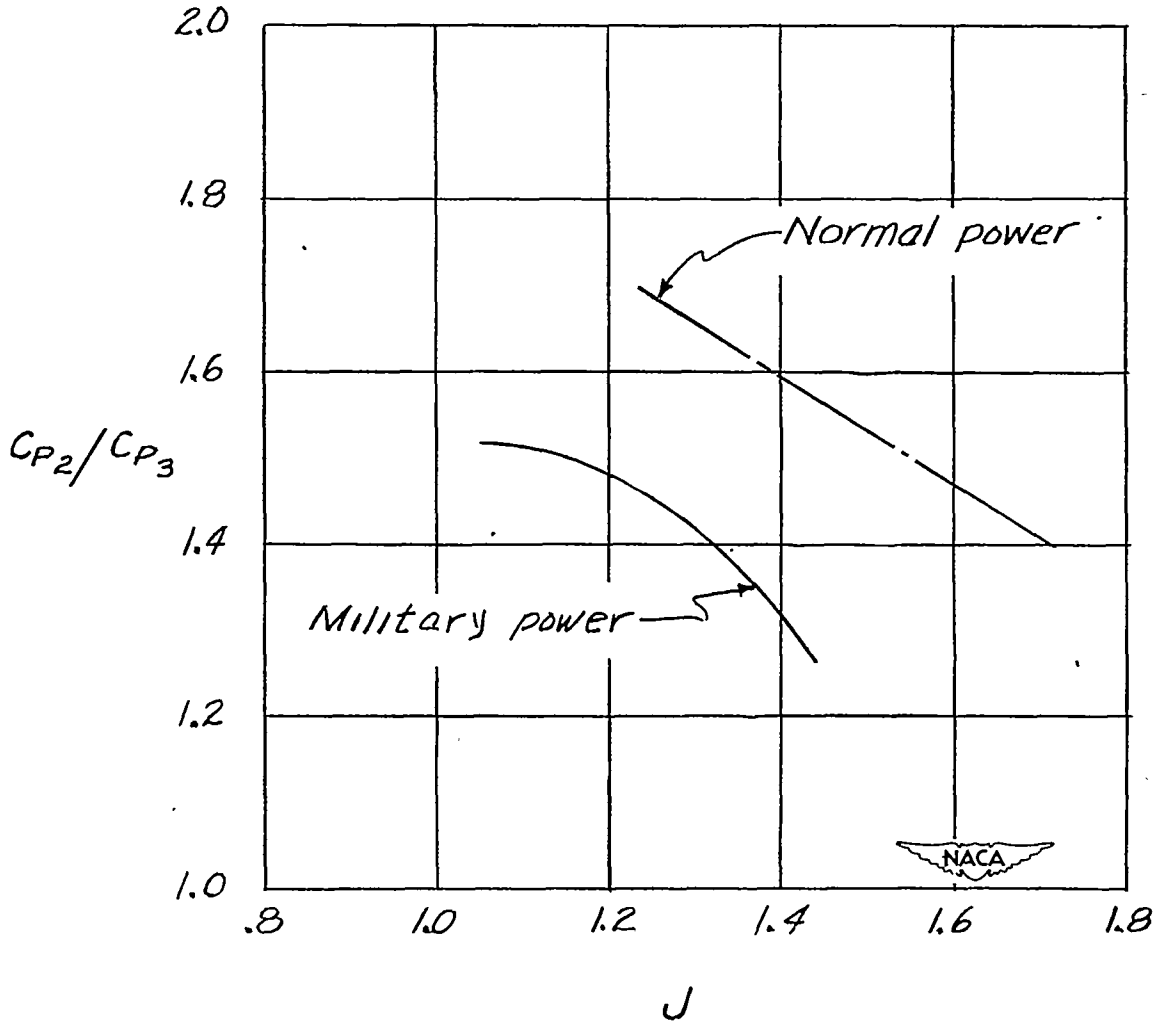


Figure 8.- Ratio of power coefficient per blade for two-blade operation to three-blade operation for various advance ratios in climbs.

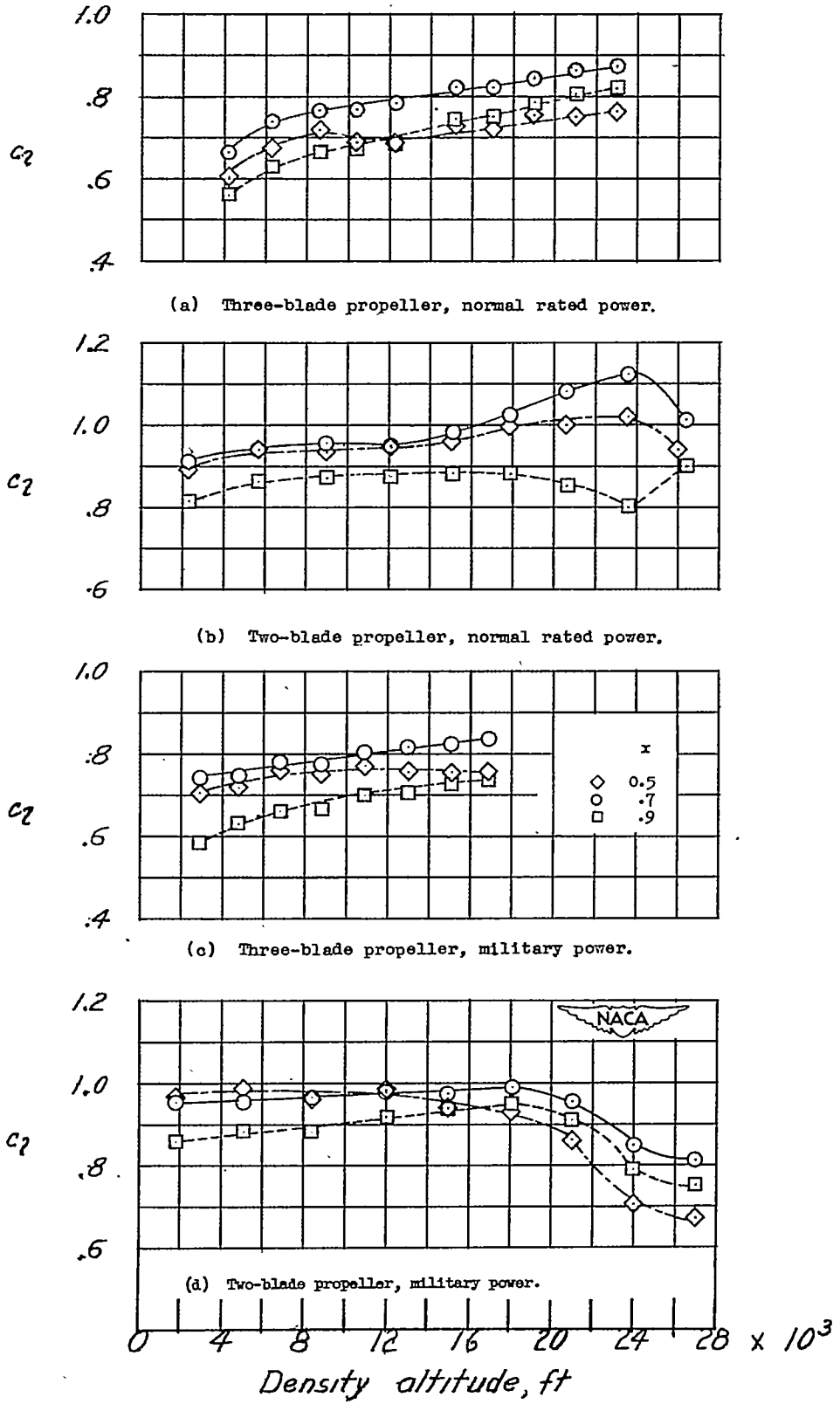


Figure 9.- Variation of c_η of tested propeller with altitude in climbs.

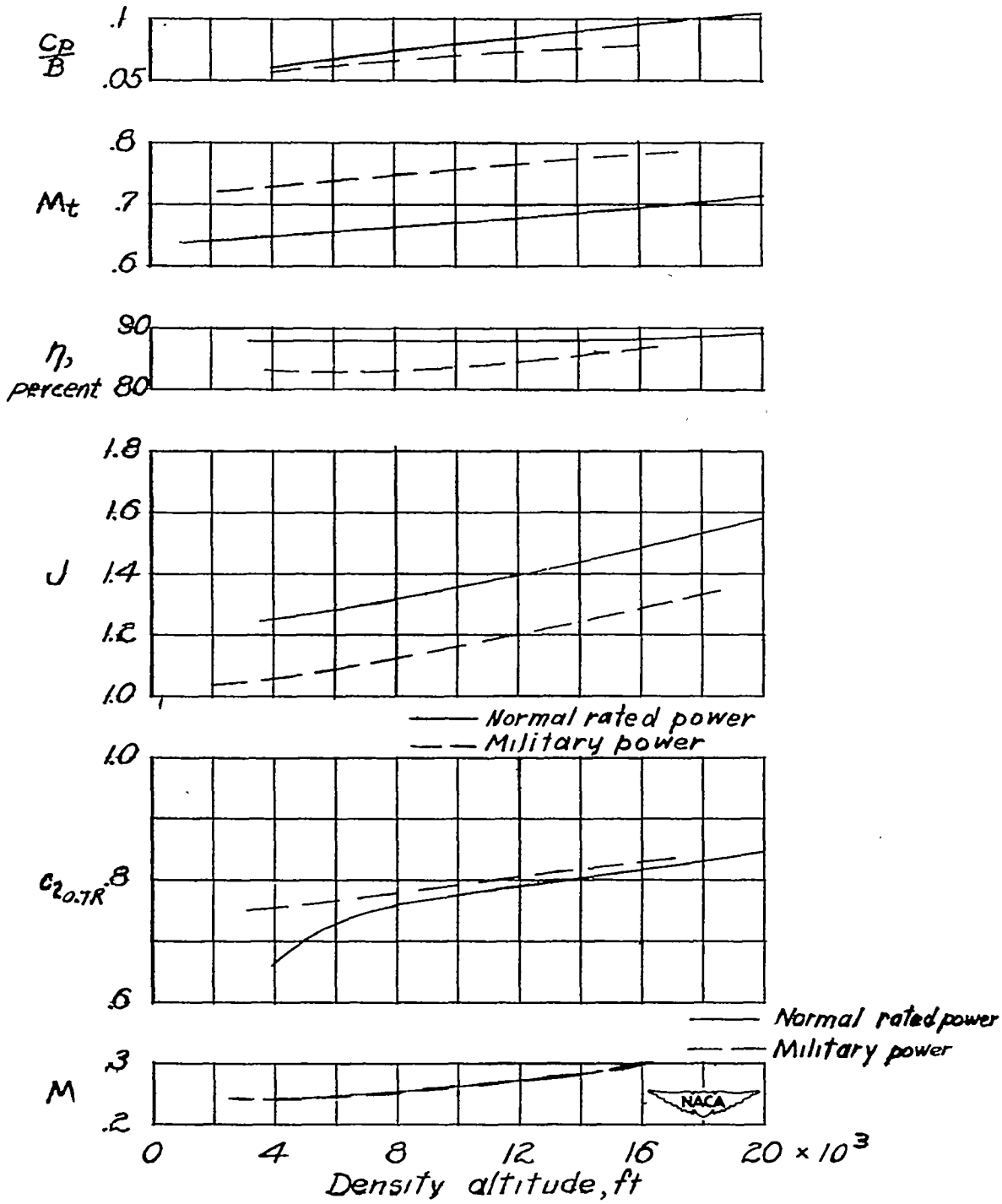
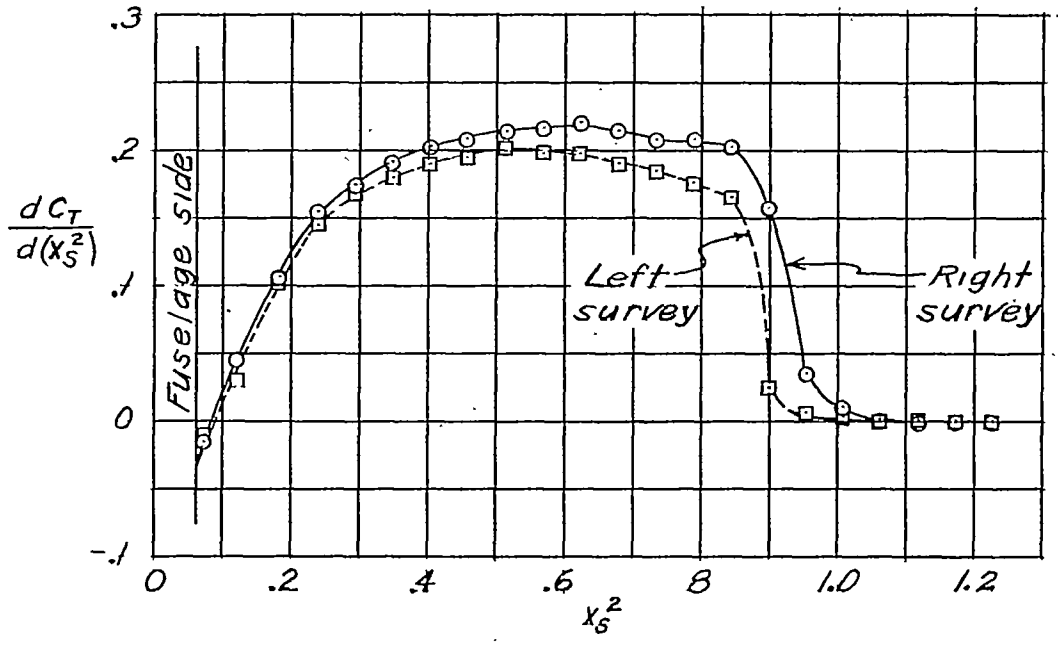
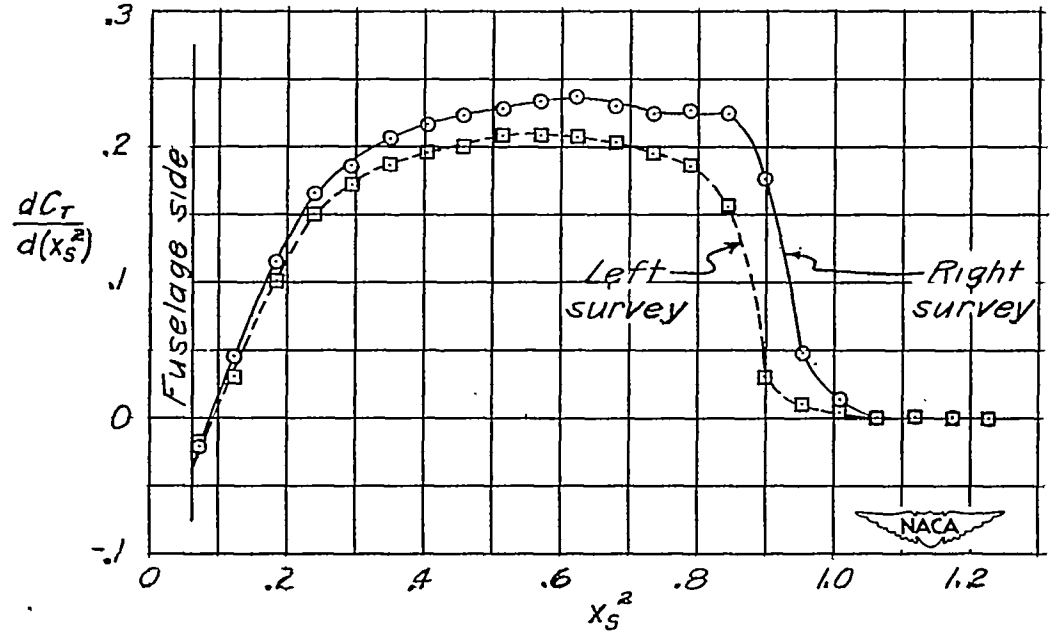


Figure 10.- Comparison of results for normal rated and military power in climb with three-blade propeller.

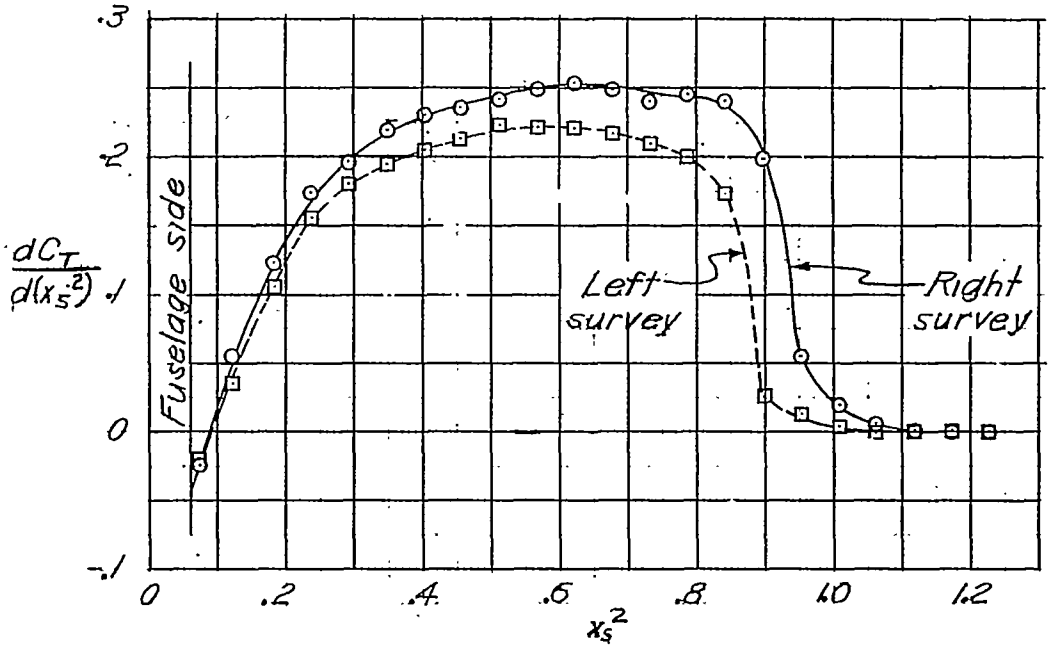


(a) Test conditions: η = 82.8 percent; J = 1.09; C_P = 0.183; C_T = 0.139; M = 0.242; M_t = 0.739.

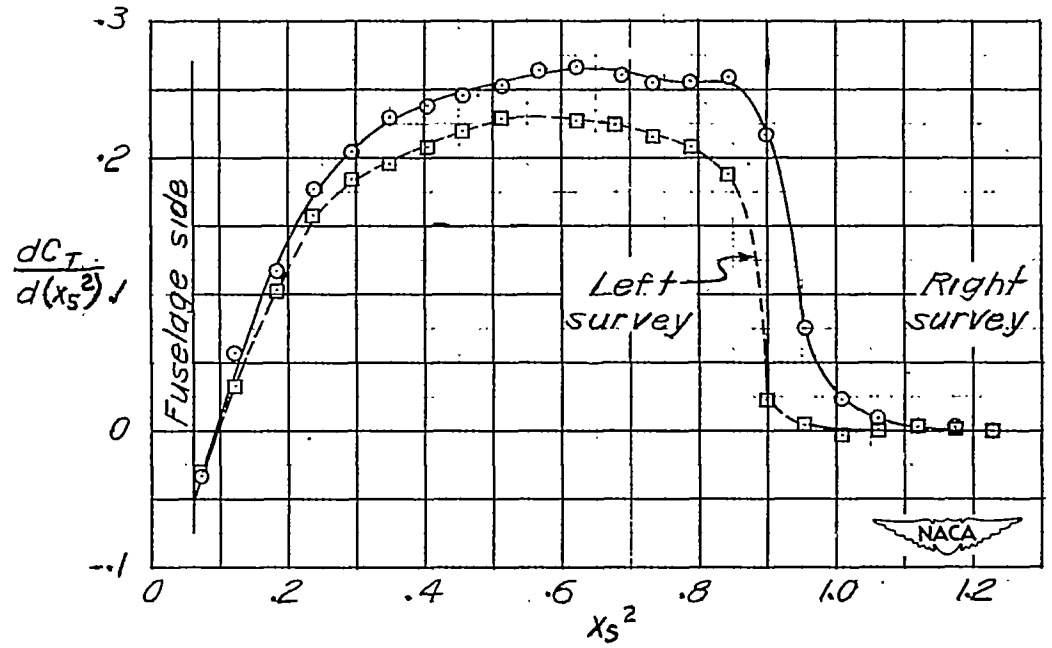


(b) Test conditions: η = 85.3 percent; J = 1.15; C_P = 0.202; C_T = 0.151; M = 0.259; M_t = 0.754.

Figure 11.- Thrust gradient curves for military-power climb with three-blade propeller.

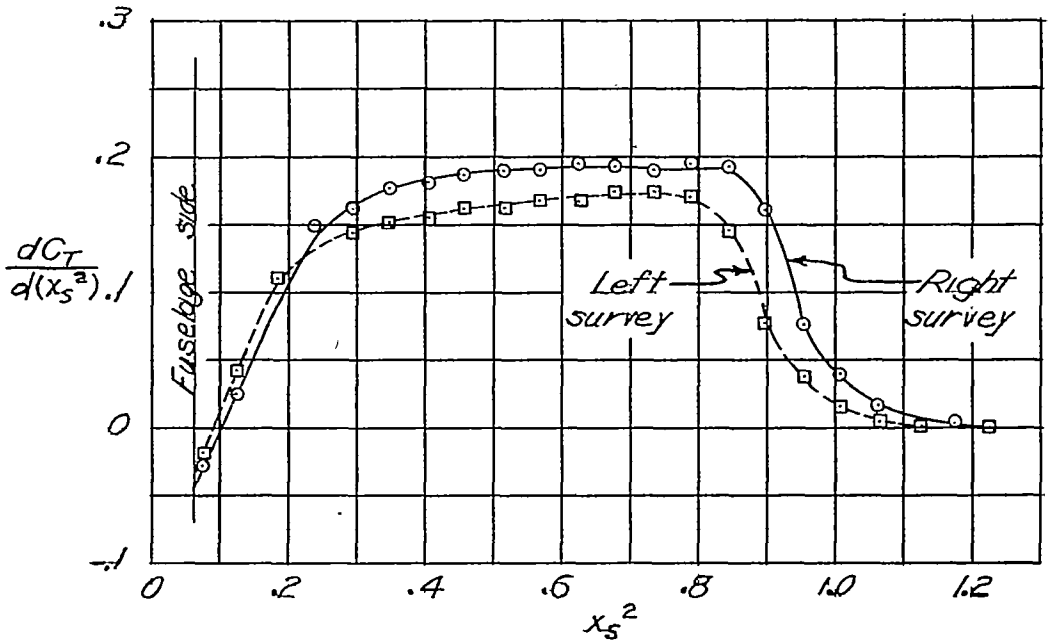


(c) Test conditions: η = 86.0 percent; J = 1.22; C_P = 0.228; C_T = 0.160; M = 0.280; M_t = 0.770.

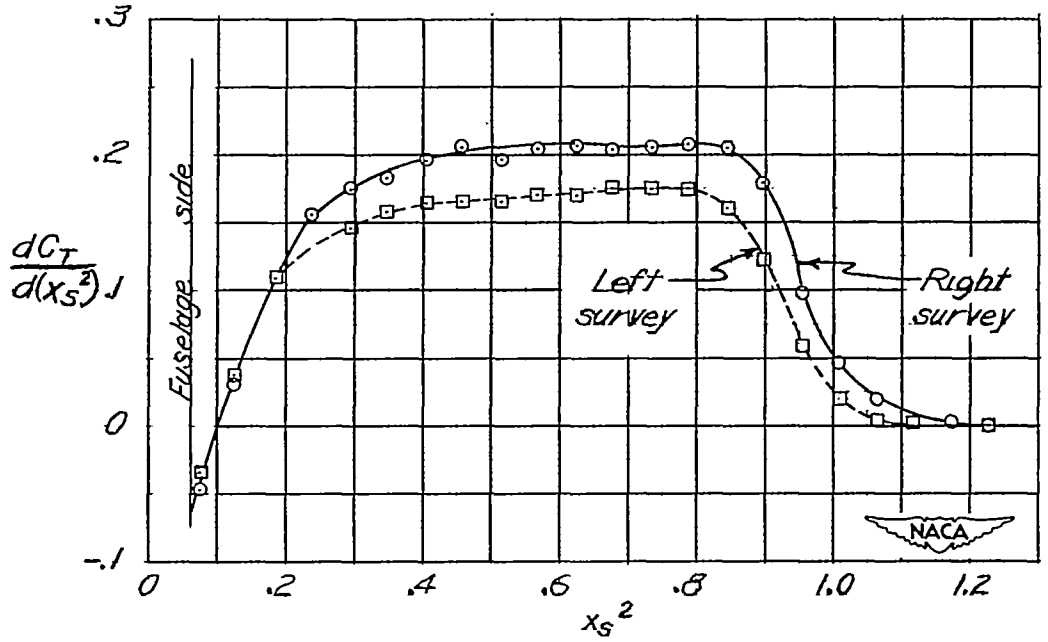


(d) Test conditions: η = 87.6 percent; J = 1.32; C_P = 0.251; C_T = 0.167; M = 0.303; M_t = 0.784.

Figure 11.– Concluded.

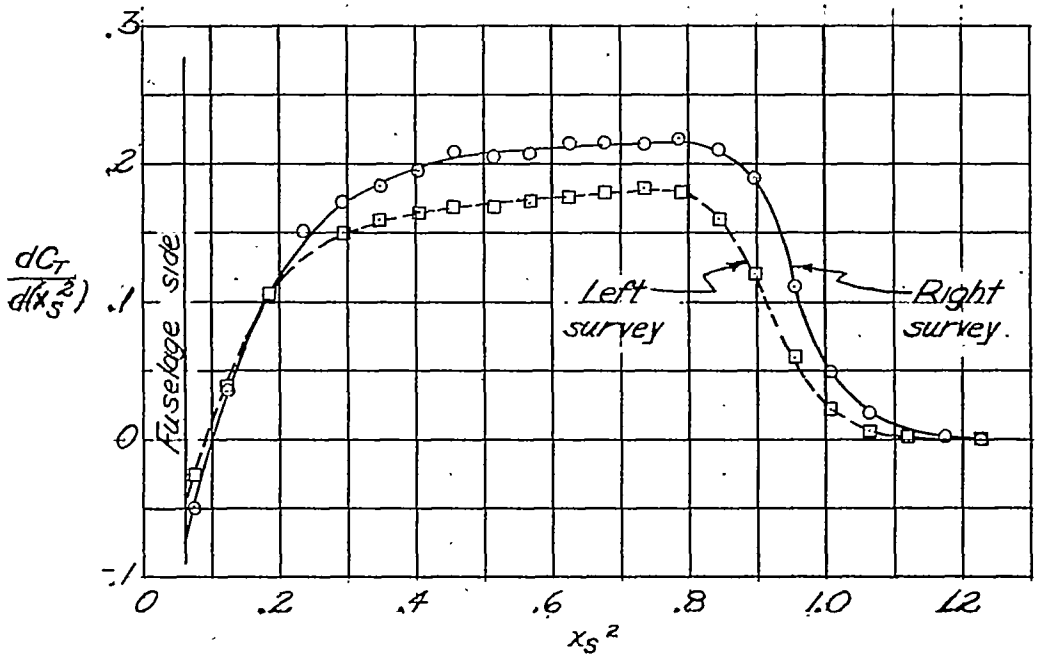


(a) Test conditions: η = 77.1 percent; J = 1.10; C_P = 0.188; C_T = 0.133; M = 0.249; M_t = 0.756.

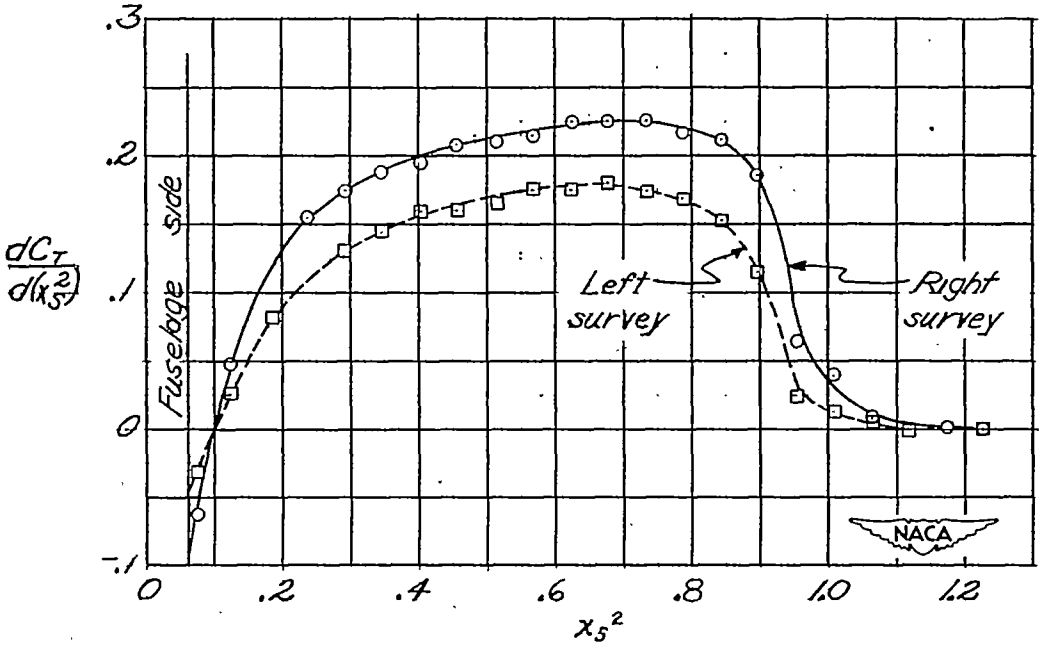


(b) Test conditions: η = 77.5 percent; J = 1.22; C_P = 0.220; C_T = 0.140; M = 0.280; M_t = 0.774.

Figure 12.- Thrust gradient curves for military-power climb with two-blade propeller.

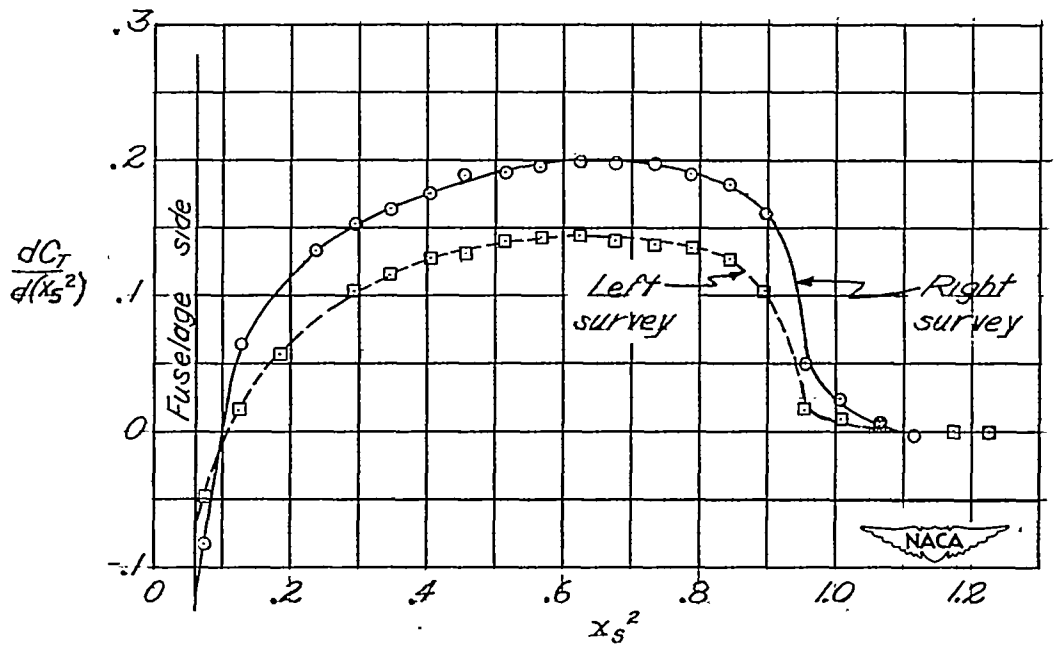


(c) Test conditions: η = 80.2 percent; J = 1.30; C_P = 0.231; C_T = 0.143; M = 0.300; M_t = 0.785.



(d) Test conditions: η = 84.2 percent; J = 1.41; C_P = 0.233; C_T = 0.139; M = 0.334; M_t = 0.815.

Figure 12. Continued.



(e) Test conditions: η = 88.2 percent; J = 1.56; C_P = 0.205; C_T = 0.116; M = 0.379; M_t = 0.851.

Figure 12.– Concluded.

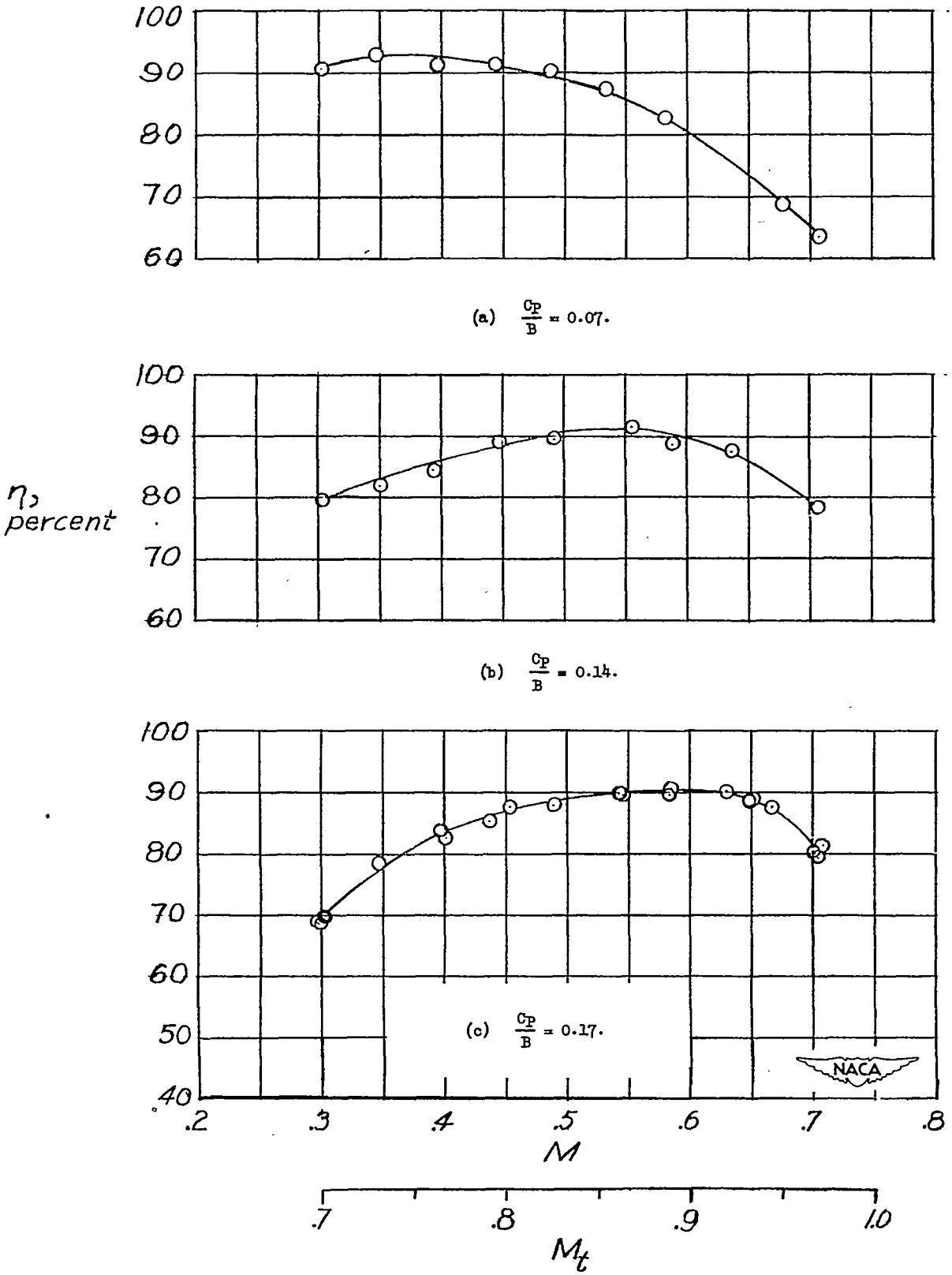


Figure 13.- Variation of efficiency of tested propeller with Mach number at engine speed of 2600 rpm.

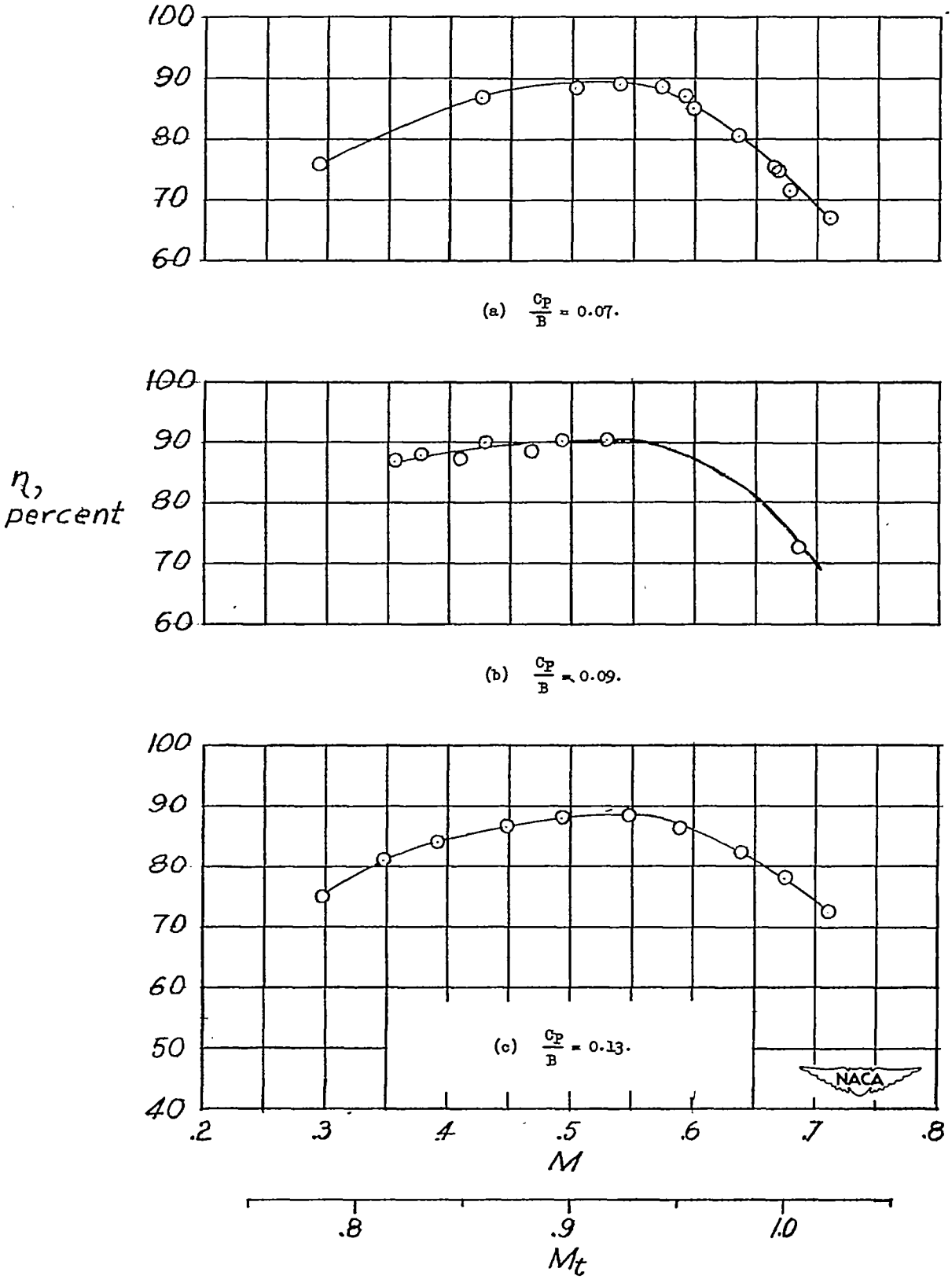
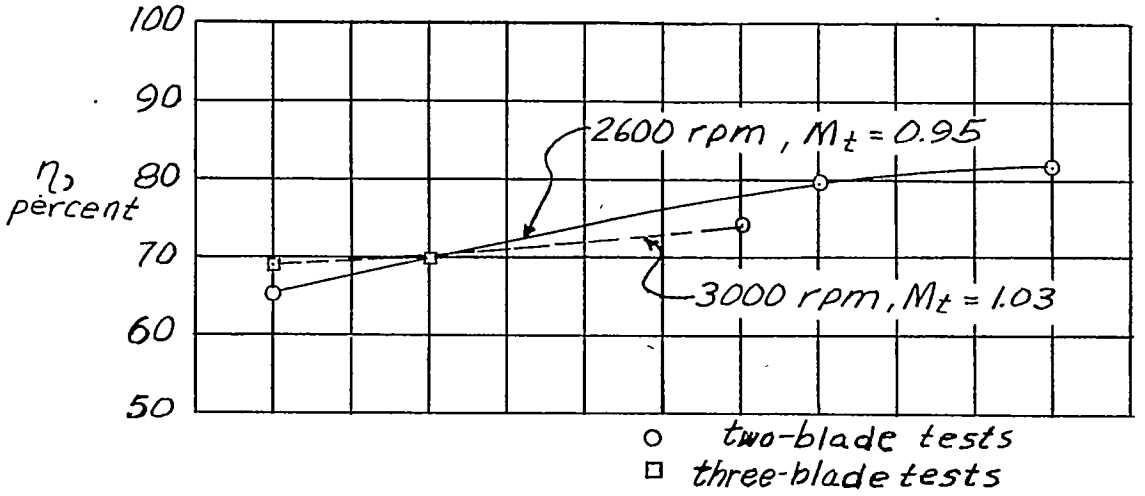
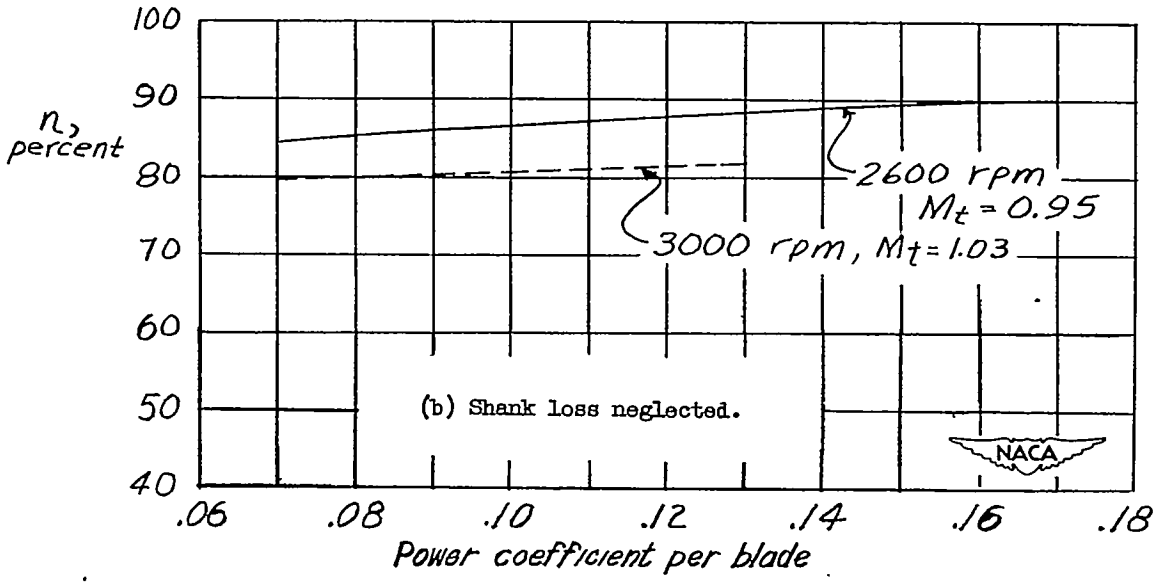


Figure 14.- Variation of efficiency of tested propeller with Mach number at engine speed of 3000 rpm.



(a) Propeller as tested, with shank loss.



(b) Shank loss neglected.

Figure 15.- Effect of power loading on efficiency of tested propeller at airplane Mach number of 0.7.

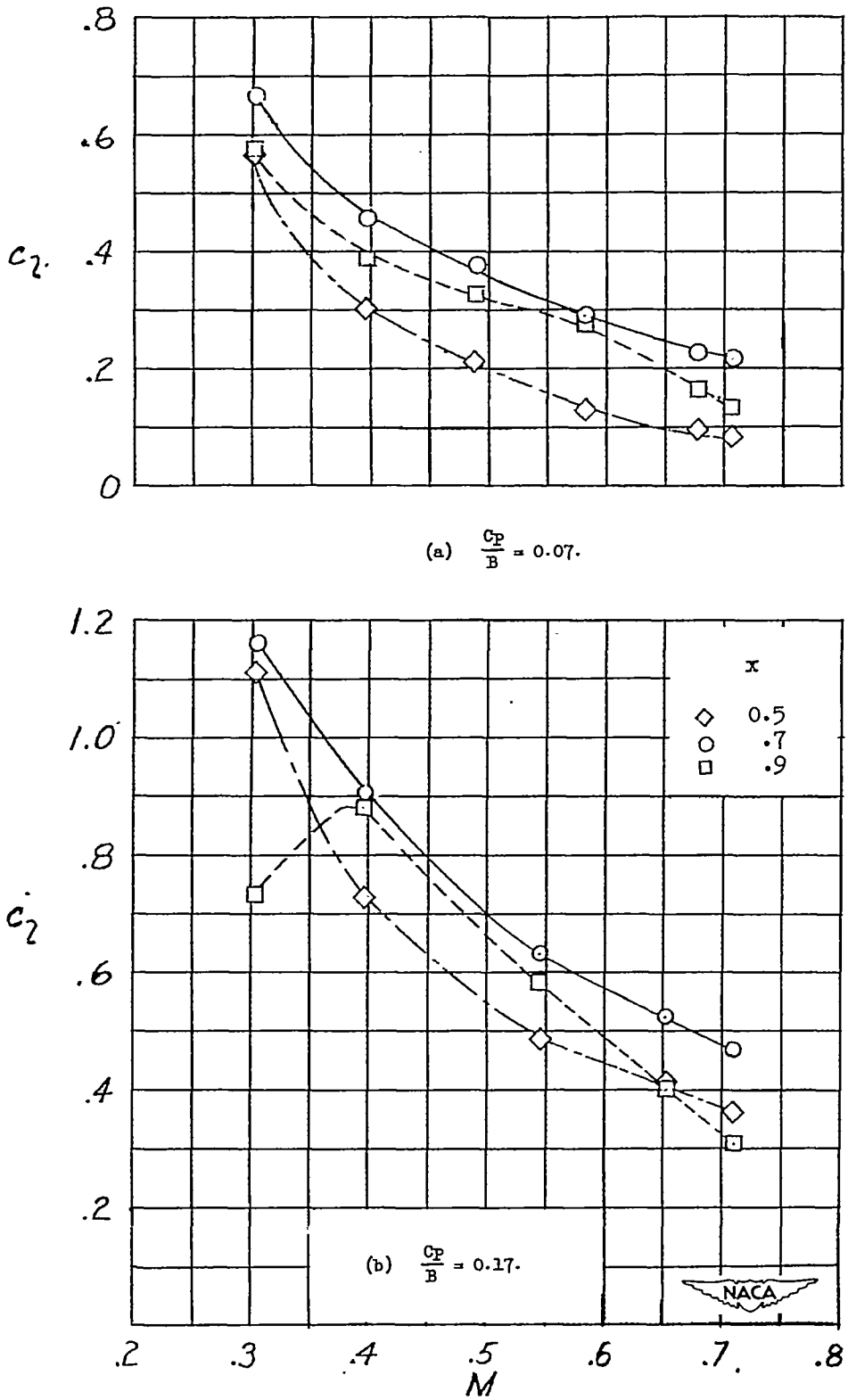
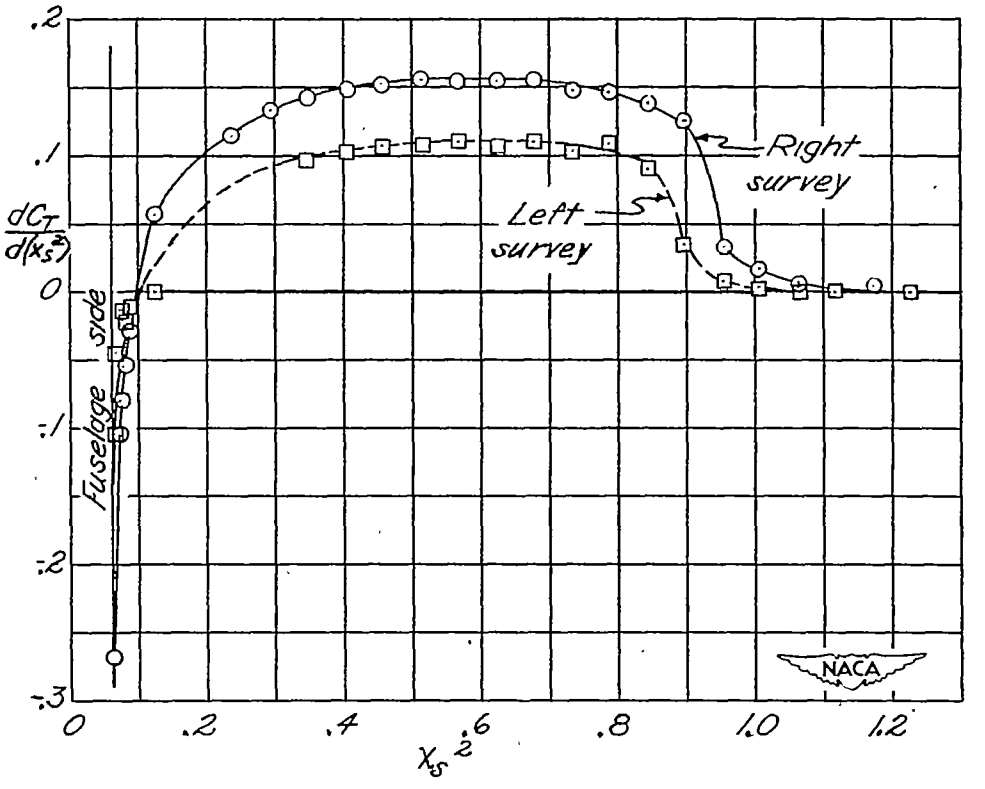
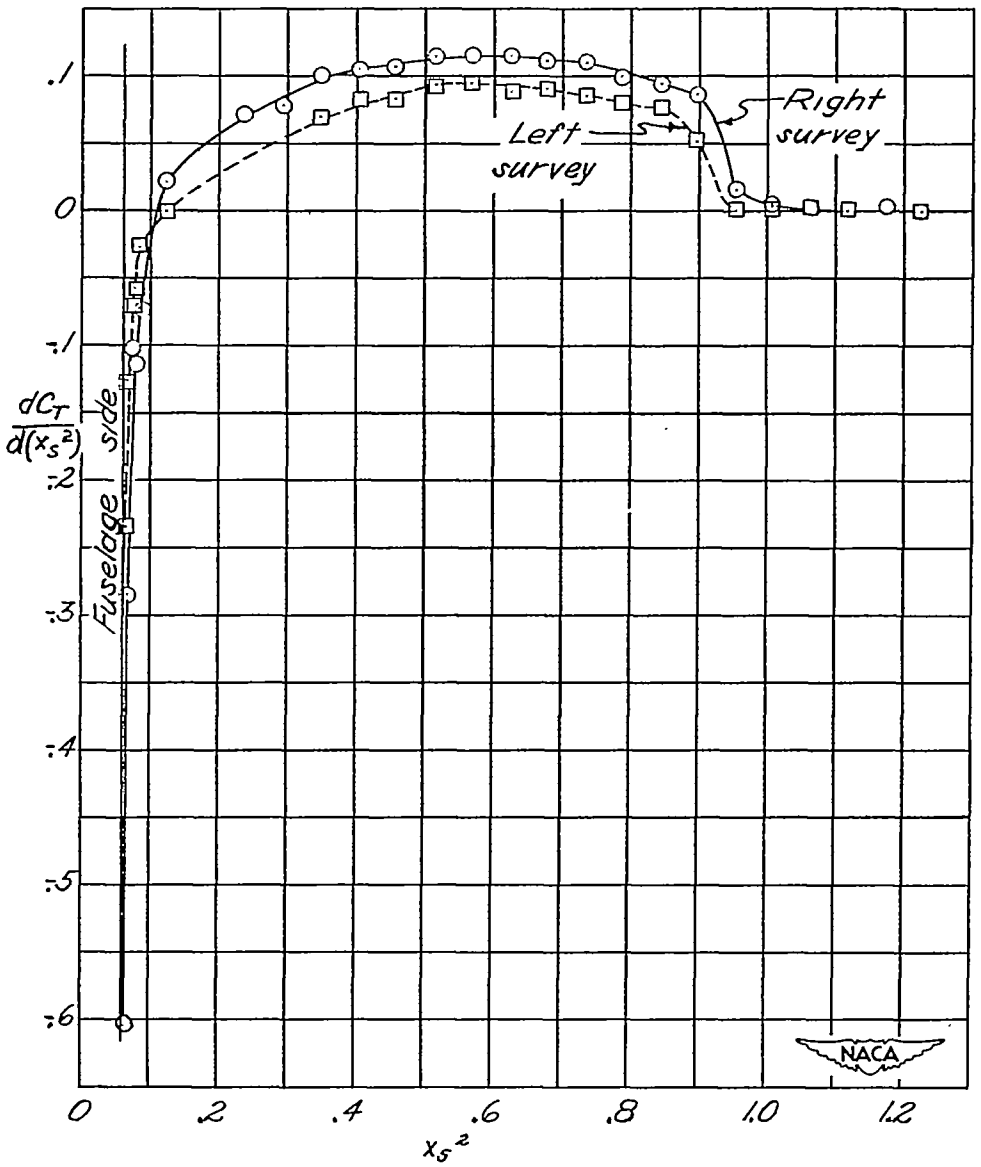


Figure 16.- Variation of c_l of propeller tested with Mach number at high speeds. Engine speed, 2600 rpm.



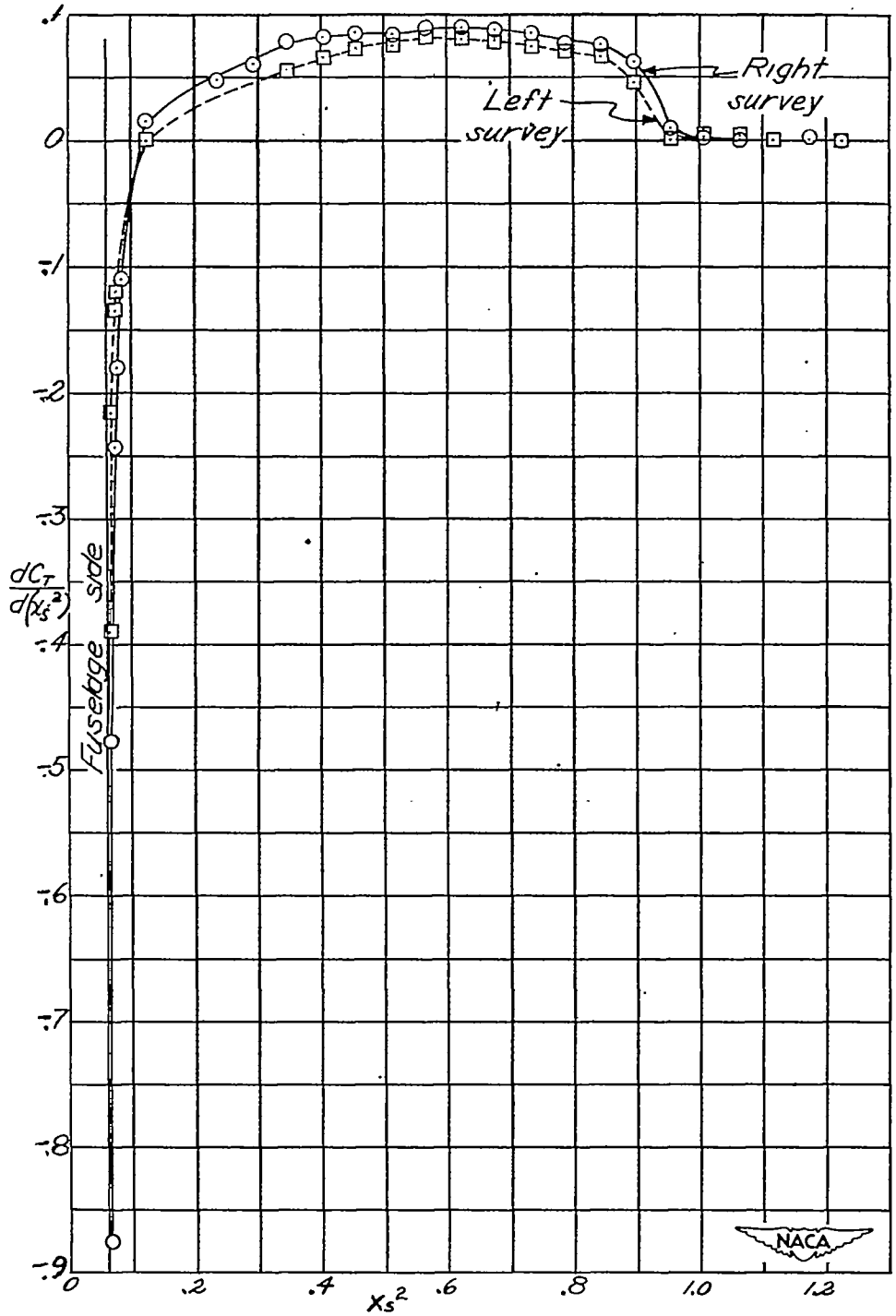
(a) Test conditions: η = 90.8 percent; J = 1.45; C_P = 0.147; C_T = 0.092; M = 0.301; M_t = 0.718.

Figure 17.- Thrust gradient curves of tested propeller at high speed. Power coefficient per blade of 0.07 at an engine speed of 2600 rpm.



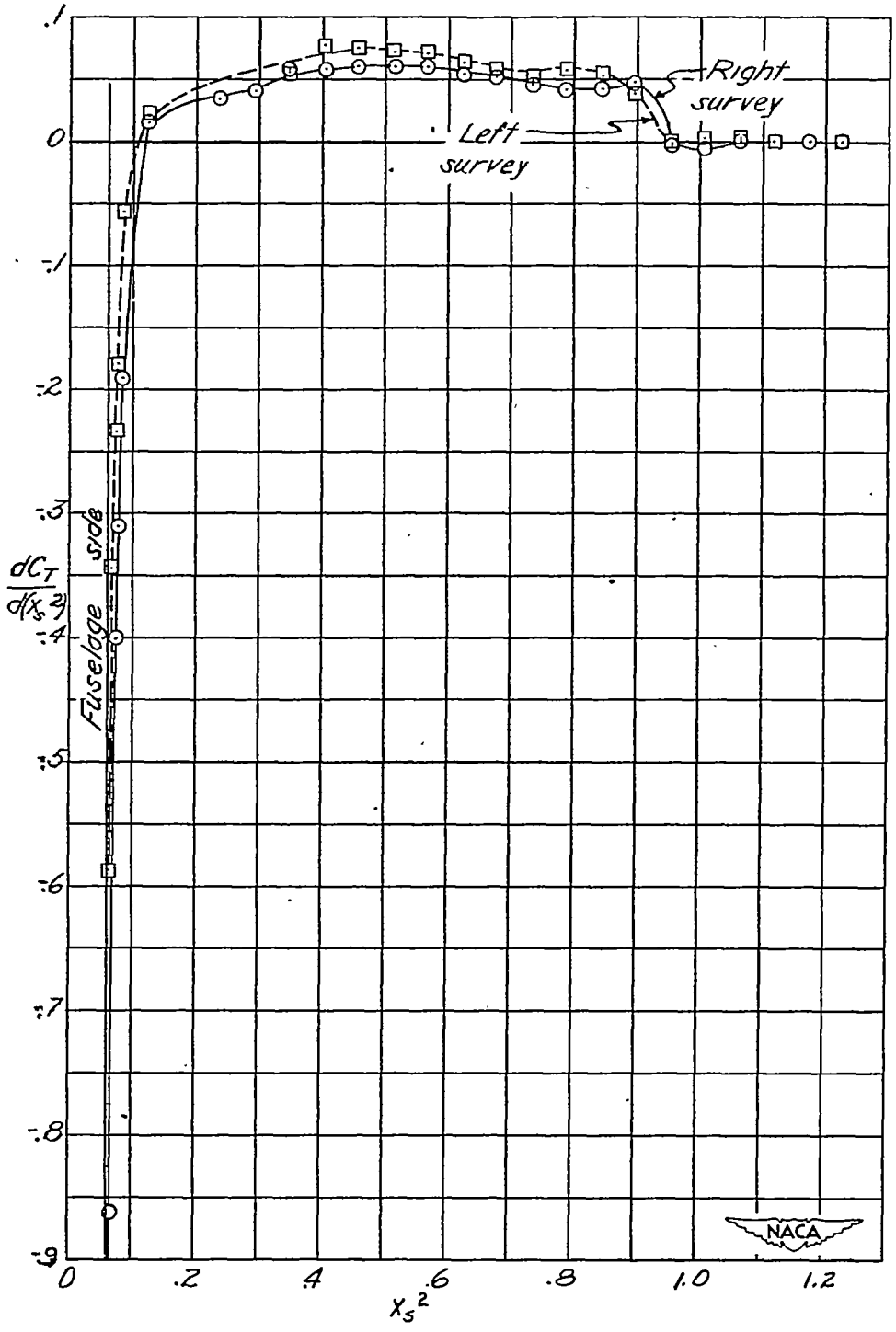
(b) Test conditions: η = 91.4 percent; J = 2.13; C_P = 0.147; C_T = 0.063; M = 0.444; M_t = 0.791.

Figure 17.— Continued.



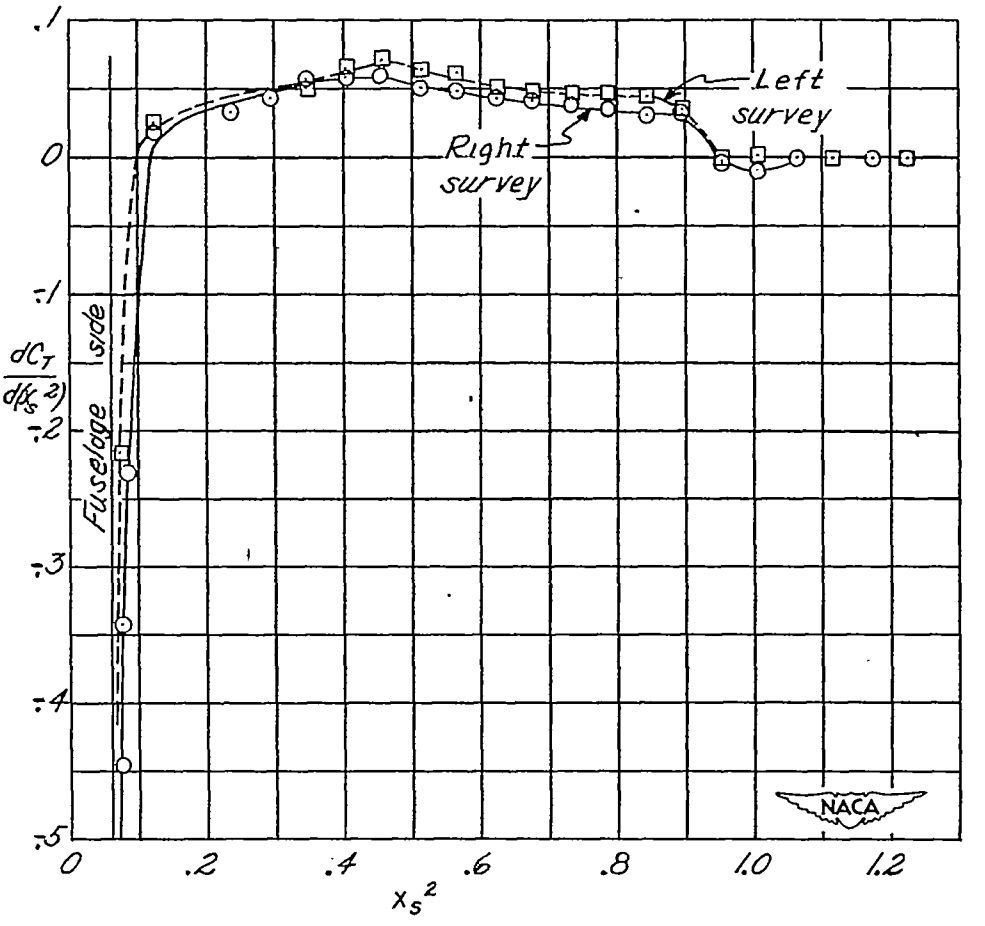
(c) Test conditions: η = 87.7 percent; J = 2.55; C_P = 0.142; C_T = 0.049; M = 0.534; M_t = 0.848.

Figure 17.— Continued.



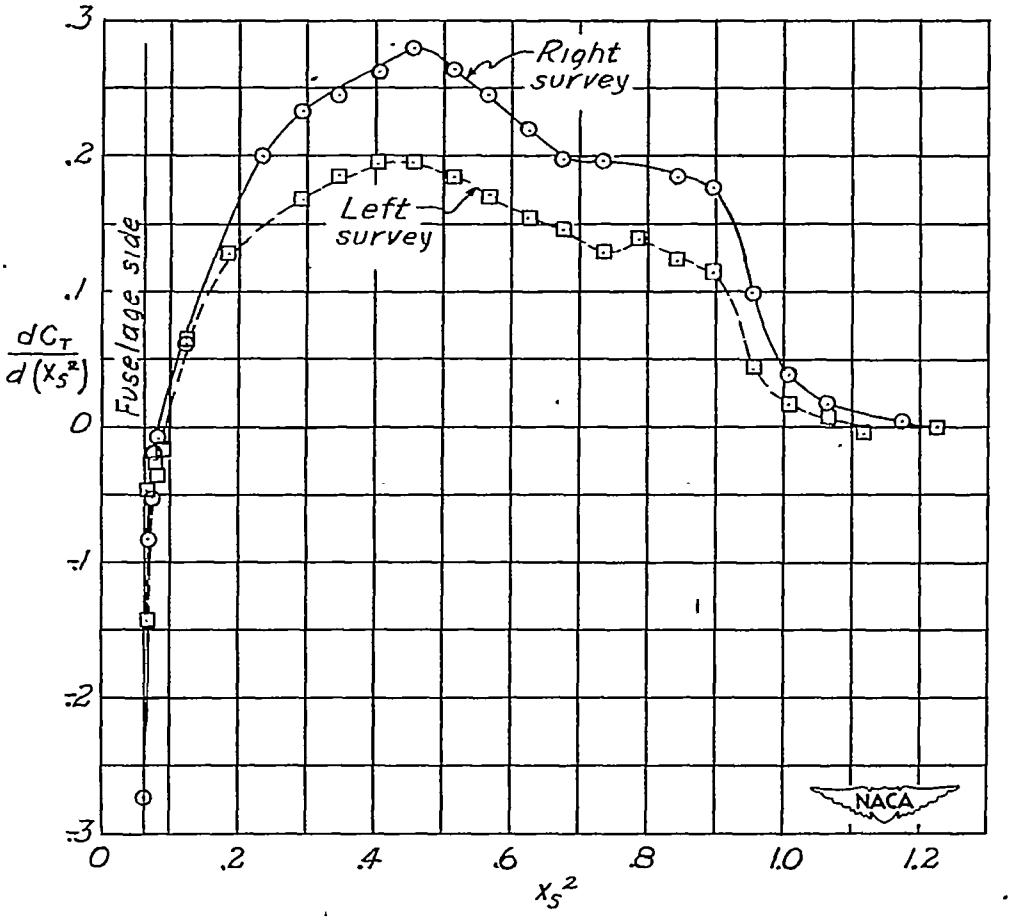
(d) Test conditions: η = 68.7 percent; J = 3.27; C_P = 0.153; C_T = 0.032; M = 0.677; M_t = 0.938.

Figure 17.— Continued.



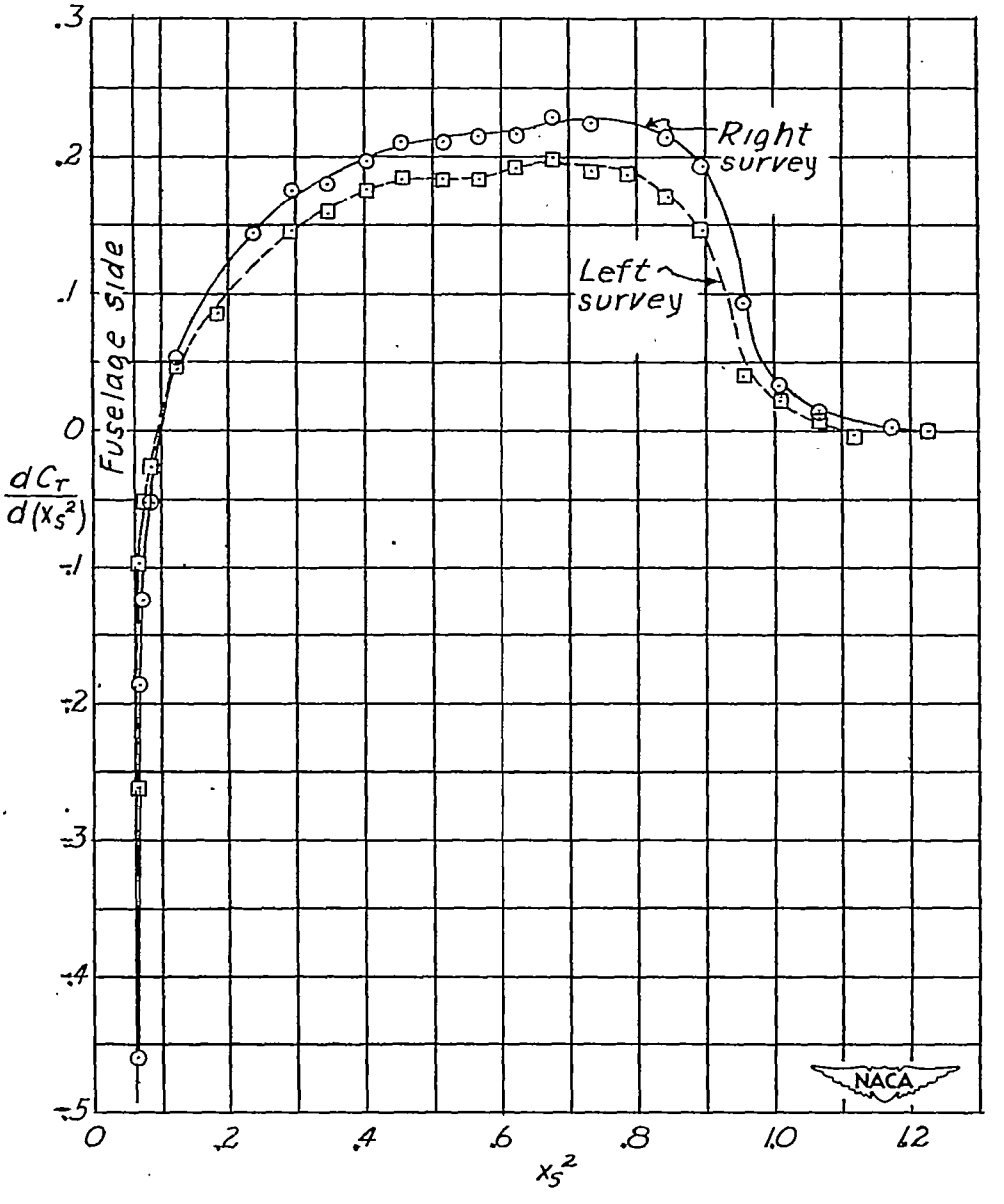
(e) Test conditions: η = 63.8 percent; J = 3.44; C_P = 0.148; C_T = 0.028; M = 0.706; M_t = 0.957.

Figure 17.— Concluded.



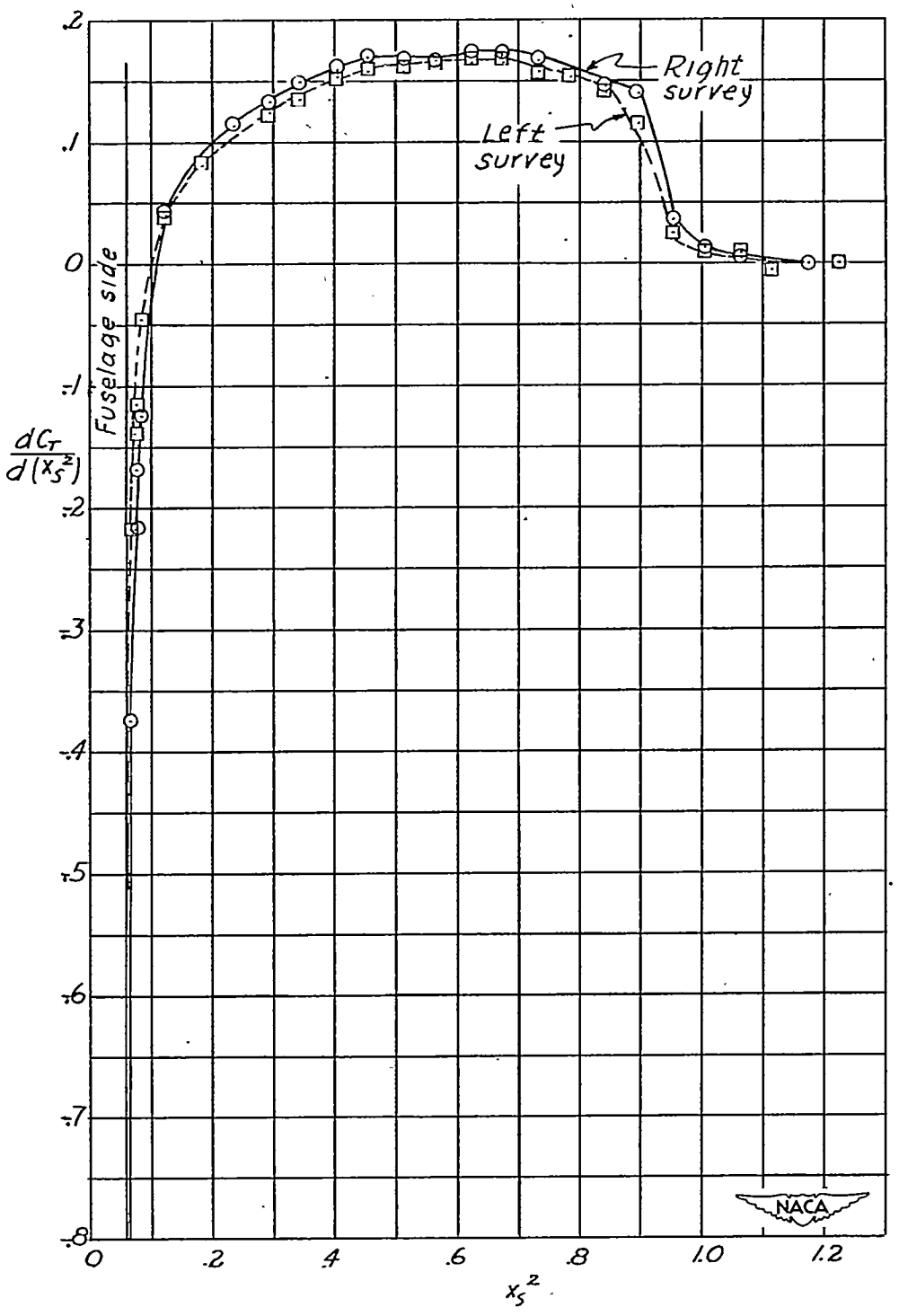
(a) Test conditions: η = 70.0 percent; J = 1.46; C_P = 0.315; C_T = 0.151; M = 0.304; M_t = 0.722.

Figure 18.- Thrust gradient curves of tested propeller at high speed. Power coefficient per blade of 0.17 at engine speed of 2600 rpm.



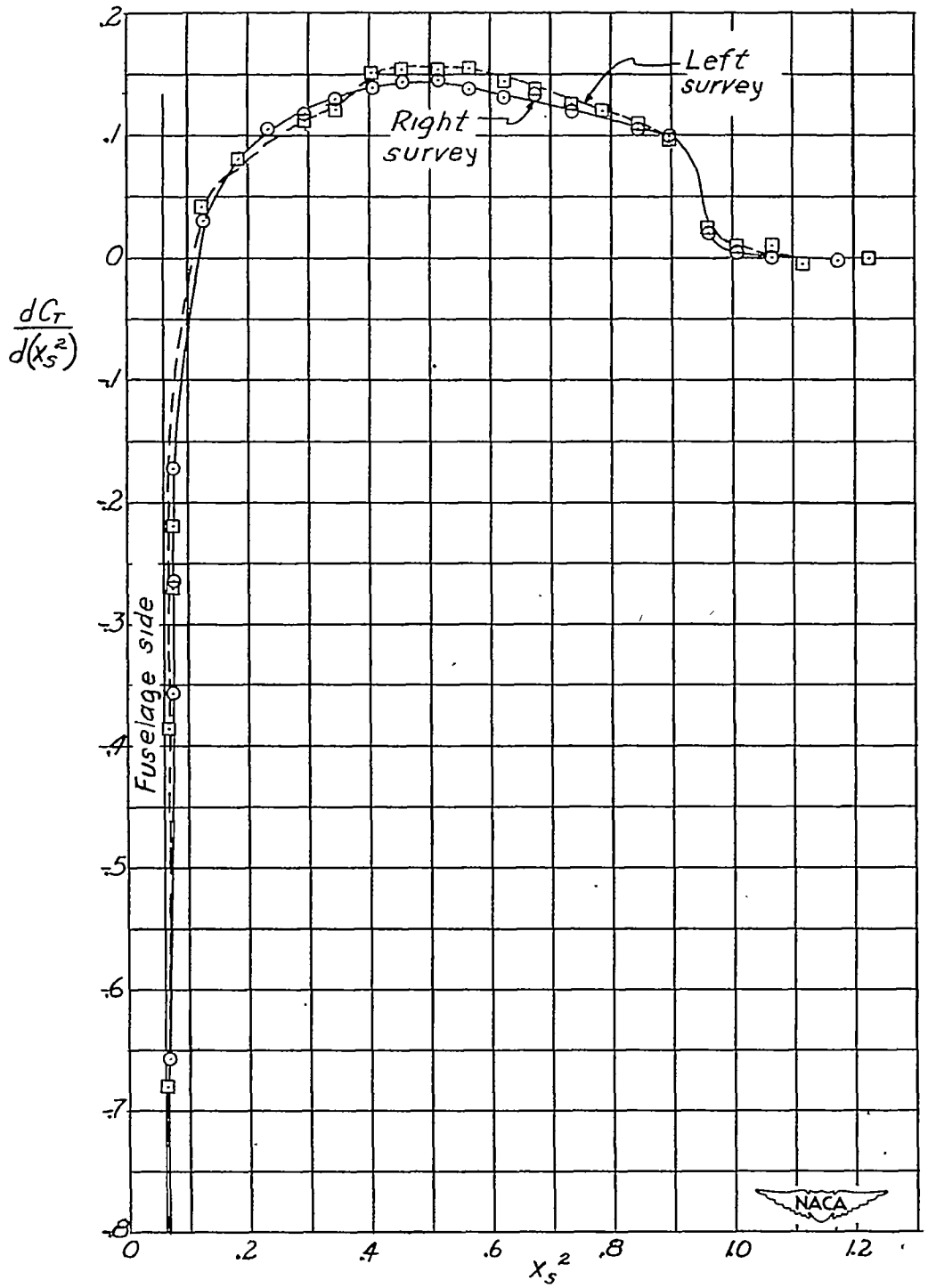
(b) Test conditions: η = 83.9 percent; J = 1.90; C_P = 0.319; C_T 0.141; M = 0.396; M_t = 0.765.

Figure 18.– Continued.



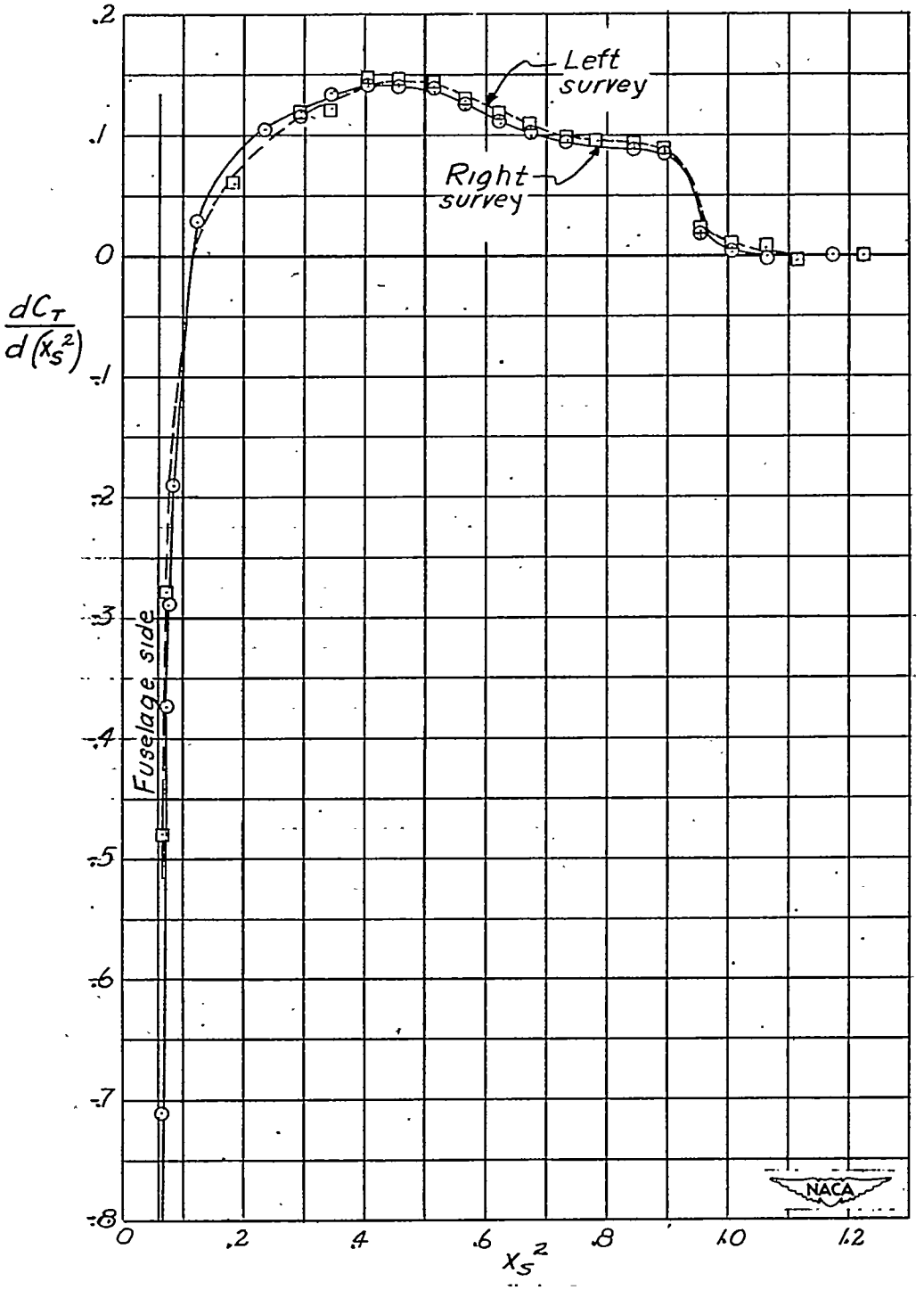
(c) Test conditions: η = 89.7 percent; J = 2.61; C_P = 0.322; C_T = 0.111; M = 0.545; M_t = 0.853.

Figure 18.– Continued.



(d) Test conditions: η = 89.0 percent; J = 3.14; C_P = 0.328; C_T = 0.093; M = 0.652; M_t = 0.923.

Figure 18.— Continued.



(e) Test Conditions: η = 81.5 percent; J = 3.42; C_P = 0.331; C_T = 0.079; M = 0.708; M_t = 0.961.

Figure 18.— Concluded.