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RESEARCH MEMORANDUM

THE EFFECT OF BLADE-SECTION THICKNESS RATIOS ON THE AERODYNAMIC CHARACTERISTICS OF RELATED FULL-SCALE PROPELLERS AT MACH NUMBERS UP TO 0.65

By

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The results of an investigation of two full-scale NACA propellers are presented for a range of blade angles from 20° to 55° at airspeeds up to 500 miles per hour. These results are compared with the results from previous investigations of five related NACA propellers to evaluate the effects of blade-section thickness ratios on propeller aerodynamic characteristics.

The envelope efficiencies of all the NACA propellers are high at the lower rotational speeds at which the adverse effects of compressibility are small. The highest efficiencies, about 93 percent at a helical-tip Mach number of 0.9 and 84 percent at a helical-tip Mach number of 1.1, reflect the importance of using thin, efficient airfoil sections throughout the blade. For propeller operation at constant rotational speed and power at helical-tip Mach numbers below 0.8 a reduction in blade-section thickness from 12 to 8 percent at the 0.7 radius, or approximately one-third all along the radius, results in gains in propeller efficiency up to 10 percent.

The maximum efficiency of a propeller operating at a helical-tip Mach number of 1.1 and air-stream Mach number of 0.625 may be increased approximately 20 percent by reducing the blade-section thickness from 12 to 5 percent at the 0.7 radius. At this same condition of operation for propellers having blade-section thicknesses between 12 and 8 percent at the 0.7 radius the maximum efficiency increases approximately 3 percent for each decrease in thickness of 1 percent at the 0.7 radius. For blade-section thicknesses between 8 and 5 percent at the 0.7 radius the rate of increase in propeller efficiency with reductions in blade-section thickness is smaller, but further reductions in thickness may still improve the maximum efficiency of propellers operating at high forward speeds with helical-tip Mach numbers as high as 1.1.

INTRODUCTION

A general investigation of the aerodynamic characteristics of a series of full-scale 10-foot-diameter propellers at airspeeds up to 500 miles per hour has been made in the Langley 16-foot high-speed tunnel. The purpose of this general investigation was to determine the combined influence of propeller-design parameters and air compressibility upon propeller performance. The blade designs embody variations in shank form, blade airfoil section, design lift coefficient or camber, blade width, and blade thickness ratio. Most of the blades have the high-critical-speed NACA 16-series airfoil sections (reference 1) and have been designed neglecting compressibility effects for a minimum induced-energy loss when operating as four-blade propellers at an advance ratio of 2.1 and a blade angle of 45° at the 0.7 radius.

The primary effects of blade-section camber on propeller performance have been presented in reference 2, and the data showing the characteristics of other related propellers in the series have been presented in references 3 to 9. This paper presents the aerodynamic characteristics of two propellers and extends the investigation of related propellers to include those having thickness ratios as low as 0.05 at the 0.7 radius. The purpose of the paper is to make a comparison of the performance data for these two propellers with the data contained in references 3, 5, 7, and 8 to afford an evaluation of the effects of blade-section thickness ratio on propeller aerodynamic characteristics.

The thickness ratio of propeller blade sections is of increasing importance in the design of propellers for high speeds because of the compromise which must be made between structural requirements and the requirements for thin high-critical-speed sections necessary to avoid excessive compressibility losses. Compressibility effects have long been known to cause radical changes in the characteristics of the sections along a propeller blade, and a lack of suitable airfoil section characteristics at the present time has made it necessary to evaluate by propeller tests the effect of blade-section thickness ratios upon propeller performance.

SYMBOLS

B number of blades

b blade width, feet

C_P propeller power coefficient $\left(\frac{P}{\rho n^3 D^5}\right)$

C_T propeller thrust coefficient $\left(\frac{T}{\rho n^2 D^4}\right)$

c_{l_d}	blade-section design lift coefficient
D	propeller diameter, feet
h	blade-section maximum thickness, feet
J	propeller advance ratio $\left(\frac{V}{nD}\right)$
M	air-stream Mach number
M_t	helical-tip Mach number $\left(M\sqrt{1 + \left(\frac{\pi}{J}\right)^2}\right)$
n	propeller rotational speed, rps
P	power absorbed by propeller, foot-pounds per second
T	propeller thrust, pounds
V	airspeed, feet per second
x	fraction of propeller-tip radius
β	blade angle at any radius, degrees
$\beta_{0.75R}$	blade angle at 0.75 tip radius, degrees
η	propeller efficiency $\left(J\frac{C_T}{C_P}\right)$
η_i	induced efficiency
ρ	mass density of air, slugs per cubic foot
σ	solidity $\left(B\frac{b}{D}/\pi x\right)$

APPARATUS

Propeller dynamometer.- Photographs of the 2000-horsepower dynamometer are shown in figures 1 and 2, and a diagram showing the important dimensions of the propeller dynamometer and its location with respect to the

Langley 16-foot-tunnel test section is shown in figure 3. A detailed description of all the test apparatus and the methods of measuring thrust and torque are presented in reference 3. The fairing profile was calculated from a distribution of sources and sinks to produce a body of revolution with uniform axial velocity in the plane of the propeller. This axial-velocity distribution has been checked experimentally and found to be uniform within 1 percent. The gap between the propeller blade and the spinner surface at the propeller blade-spinner juncture is very small (fig. 1) but is not sealed.

Propeller blades.- The two propellers for which data are presented in this paper are the NACA 10-(3)(062)-045A and NACA 10-(3)(05)-045. The NACA design numbers are descriptive of the shape, size, and aerodynamic characteristics of the blades used in this investigation. The digits of the first group of numbers represent the propeller diameter in feet, and the remaining digits indicate the design lift coefficient, thickness ratio, and solidity per blade at the 0.7 radius. The following table shows the blade design numbers of the various propellers discussed in this paper, and also shows the significance of the groups of digits in the number designation:

NACA design number	c_{l_d} at 0.7R	h/b at 0.7R	σ/B at 0.7R
10-(3)(08)-03	0.3	0.08	0.03
10-(3)(08)-03R	.3	.08	.03
10-(3)(12)-03	.3	.12	.03
10-(3)(05)-045	.3	.05	.045
10-(3)(062)-045	.3	.062	.045
10-(3)(062)-045A	.3	.062	.045
10-(3)(08)-045	.3	.08	.045

The suffix R indicates a blade having conventional round shank sections, and the suffix A indicates a blade with modified shank sections. The NACA 16-series blade sections were used for all the propellers listed in the table, and with the exception of the NACA 10-(3)(08)-03R blade, wide airfoil sections extend to the spinner. The spinner has a diameter 21.7 percent of the diameter of a 10-foot propeller.

Figure 4 shows the blade-form curves for the NACA propellers having a solidity of 0.03 per blade at the 0.7 radius, and figure 5 shows a comparison of the blade sections at two radii for the same group of propellers. The blade designs are closely related, but two of the propellers of this group differ not only in thickness but also in distribution of section design lift coefficient, blade width, and pitch distribution. These differences between the NACA 10-(3)(08)-03 and NACA 10-(3)(08)-03R blades are the result of an effort to maintain the minimum induced-energy-loss loading as far inboard as possible on the round-shank blade. The NACA 10-(3)(12)-03 blade has the same radial distribution of blade-section design lift coefficient, the same blade width, and approximately the same pitch distribution as the NACA 10-(3)(08)-03 blade, but its thickness is greater at all radii.

Figure 6 shows the blade-form curves and figure 7 shows the section comparisons for the group of propellers having a solidity of 0.045 per blade at the 0.7 radius. The propellers of this group have the same radial distribution of blade-section design lift coefficient, the same blade width, and approximately the same pitch distribution. The NACA 10-(3)(062)-045 design has the thickest shank sections of this group, although its outboard sections are considerably thinner than those of the NACA 10-(3)(08)-045 design. The NACA 10-(3)(062)-045A design was made by simply thinning the shank sections of the NACA 10-(3)(062)-045 blade until they had the same thickness as the NACA 10-(3)(08)-045 design at the spinner; the thickness of the sections between the spinner and the 0.7 radius was obtained by a faired line between these two radii. The NACA 10-(3)(05)-045 design was made by thinning the sections of the NACA 10-(3)(062)-045 blade until the sections at the spinner and tip had the same thickness as the NACA 10-(3)(062)-045A blade, but the sections between these two radii were made thinner.

TESTS AND REDUCTION OF DATA

Thrust, torque, and rotational speed were measured during tests at fixed blade angles of 20°, 25°, 30°, 35°, 40°, 45°, 50°, and 55° at the three-quarter (45-in.) radius. A constant rotational speed was used for most of the tests, and a range of advance ratio was covered by changing the tunnel airspeed, which could be varied from about 60 to 500 miles per hour. The range of blade angles covered at the various rotational speeds used in the tests of the NACA 10-(3)(062)-045A and NACA 10-(3)(05)-045 propellers is shown in table I. Similar information, together with figure numbers, is also shown in table I for the other propellers as taken from references 3, 5, 7, and 8. At the higher blade angles, the complete range of advance ratio could not be covered at the higher rotational speeds because of power limitations. In order to obtain propeller characteristics at maximum tunnel airspeeds, a blade angle (45°) was chosen for which the peak-efficiency operating condition could be attained when the tunnel airspeed was at or near the maximum and the dynamometer was operating at its maximum power and rotational speed. For these tests at a blade angle of 45°, the rotational speed was varied to obtain data from the peak-efficiency condition to the zero-torque operating condition.

The test data have been corrected for tunnel-wall interference and for forces acting on the spinner by the methods described in reference 3 and are presented in the form of the usual thrust and power coefficients and propeller efficiency. Propeller thrust, as used herein, is defined as the shaft tension caused by the spinner-to-tip part of the blade rotating in the air stream. Tests were frequently repeated during the test program, and, for purposes of comparison, the data are considered accurate to within 1 percent and the faired envelopes are believed to be accurate to within much closer limits.

RESULTS AND DISCUSSION

Faired curves of thrust coefficient, power coefficient, and propeller efficiency plotted against advance ratio are presented in figures 8 to 16 for the two-blade NACA 10-(3)(062)-045A propeller and in figures 17 to 25 for the two-blade NACA 10-(3)(05)-045 propeller. Test points are shown on the figures giving thrust and power coefficients. The variation of air-stream Mach number and helical-tip Mach number with advance ratio is shown in the figures giving propeller efficiency.

Effect of blade-section thickness ratio on envelope efficiency.- Figure 26 presents a comparison of the envelope efficiencies of NACA propellers 10-(3)(08)-03, 10-(3)(08)-03R, and 10-(3)(12)-03 (references 3, 5, and 8) at the various rotational speeds. The thinnest blade of this group (NACA 10-(3)(08)-03) maintains an envelope efficiency of over 0.90 throughout the range of advance ratio of the tests at rotational speeds of 1140, 1350, and 1600 rpm. At these rotational speeds and at the design value of advance ratio (2.1) the NACA 10-(3)(08)-03 propeller is from 2 to 3 percent more efficient than the round-shank propeller (NACA 10-(3)(08)-03R) and from $1\frac{1}{2}$ to $5\frac{1}{2}$ percent more efficient than the NACA 10-(3)(12)-03 propeller. At the higher rotational speeds (2000 and 2160 rpm) the envelope efficiencies of all three propellers are reduced. The propeller with the thinnest blade sections suffers the least reduction in envelope efficiency, and the propeller with the thickest outboard blade sections suffers the greatest loss in envelope efficiency. At 2160 rpm and an advance ratio of 0.90 the envelope efficiencies of the NACA 10-(3)(08)-03R and NACA 10-(3)(12)-03 propellers are lower by 4 and 12 percent, respectively, than the envelope efficiency of the NACA 10-(3)(08)-03 propeller. These differences in envelope efficiency at the higher rotational speeds may be explained by compressibility effects which generally lower the lift-drag ratios of thick blade sections at high section Mach numbers.

In figure 26(b) the envelope efficiencies of the NACA propellers in the 0.03-solidity group are compared with the induced, or optimum, efficiency of a two-blade propeller with the Betz minimum induced-energy-loss loading. This curve of optimum efficiency was calculated by a method neglecting all profile-drag losses (reference 10) for a two-blade propeller operating at the same values of power coefficient as were obtained with the NACA 10-(3)(08)-03 propeller. Although the power coefficients for maximum efficiency are slightly different for the three propellers in this group, the values of induced efficiency may be considered accurate to within about 1 percent for all three propellers. At the design value of advance ratio (2.1) the induced losses amount to about 4 percent, and the profile-drag losses amount to 3 percent for the NACA 10-(3)(08)-03 propeller. At this same design value of advance ratio the profile-drag losses of the NACA 10-(3)(08)-03R and NACA 10-(3)(12)-03 propellers are about twice as great as those of the propeller having the thinner blade sections. The higher efficiency of the NACA 10-(3)(08)-03 propeller reflects the importance of using thin, efficient airfoil sections throughout the blade.

A comparison of the envelope efficiencies of the NACA propellers in the 0.045-solidity group is shown in figure 27 for various rotational speeds. Again the thinnest blade (NACA 10-(3)(05)-045) of the group has the highest efficiency, and the envelope efficiencies of all the propellers are reduced at the higher rotational speeds. There are only small differences in the envelope efficiencies of the NACA 10-(3)(05)-045 and NACA 10-(3)(062)-045A propellers, although the blade sections of the latter propeller are thicker at all radii except at the shank and at the tip. The fact that the thinner blade sections of the NACA 10-(3)(05)-045 propeller do not improve its efficiency much above that of the NACA 10-(3)(062)-045A propeller may possibly be explained by only slight improvements in the lift-drag ratios of the thinner blade sections. Figure 14 of reference 11 shows that there is little difference in the lift-drag ratios of 6- and 9-percent-thick sections (16-3xx airfoils) at lift coefficients up to 0.4. Since a large portion of the radial load is perhaps carried by the blade sections of the thinner NACA propellers having a thickness of 9 percent or less, a reduction in thickness from 6.2 to 5 percent at the 0.7 radius might be expected to cause only small changes in the propeller efficiency. This is perhaps true for the conditions of operation under which the tests were made; however, it should be pointed out that the differences in efficiency between the two propellers may be greater at air-stream Mach numbers higher than those used in these tests. If higher air-stream Mach numbers and lower rotational speeds had been used to attain the helical-tip Mach numbers shown in the figures, then greater portions of the blades would be subjected to the effects of compressibility. Since the airfoil data in reference 11 show that, in general, the thinner sections have the higher lift-drag ratios at the higher Mach numbers, then a reasonable assumption would be that the propeller having the thinner blade sections along the radius should have less efficiency losses due to compressibility. The envelope efficiencies of the NACA 10-(3)(062)-045 and NACA 10-(3)(08)-045 propellers, which had the thickest blade sections, are from $1\frac{1}{2}$ to 4 percent lower than the envelope efficiencies of the thinnest propeller in the 0.045-solidity group.

The optimum, or induced, efficiency has been calculated using the same values of power coefficients as were obtained for each of the NACA propellers in the 0.045-solidity group, and the curve showing induced efficiency in figure 27(b) may be considered accurate to within about 1 percent for all four propellers. At the design value of advance ratio (2.1) the curves in figure 27(b) show that the induced losses amount to about 5 percent, and the profile-drag losses amount to only 2 percent for the NACA propeller having the thinnest blade sections. The NACA 10-(3)(08)-045 propeller, which has the thickest outboard blade sections in this group, suffers the greatest profile-drag loss (about 4 percent).

The envelope efficiencies of all the NACA propellers in both solidity groups are quite high, and the differences in efficiency between the various propellers of each group are small and difficult to analyze for some conditions of operation. Where the differences in efficiency are small the relative differences in thrust and power coefficients are also small, and it is difficult to draw any general conclusion as to whether a loss in efficiency is caused by a loss of thrust, or an increase of power, or both.

Effect of thickness ratio on constant-power propeller operation.- Airplane propellers often operate over an extensive range of advance ratio at constant rotational speed and torque. Since blade-section thickness ratio affects the power-absorption qualities of a propeller to some extent, the data for the NACA propellers have been compared in figure 28 for operation at a constant power coefficient of 0.15 and a rotational speed of 1140 rpm. This condition of operation may be considered representative for two-blade, 10-foot-diameter propellers and provides a reasonable basis of comparison. It is interesting to note in figure 28(a) that the drop in efficiency occurs at a lower value of advance ratio but is more gradual for the round-shank propeller than for the NACA 10-(3)(12)-03 propeller, which has thinner shanks but thicker outboard blade sections than the round-shank propeller. At advance ratios above 3.2 it appears that the thicker outboard sections of the NACA 10-(3)(12)-03 propeller may cause greater efficiency losses than the thick shank sections of the NACA 10-(3)(08)-03R propeller. However, the gain in efficiency of about 10 percent at an advance ratio of 3.2 ($M = 0.54$), which may be realized by using the thinner blade sections of the NACA 10-(3)(08)-03 propeller, should be emphasized. A reduction in blade-section thickness from 12 to 8 percent at the 0.7 radius, or approximately one-third all along the radius, resulted in gains in efficiency up to 10 percent. A reduction in blade-section thickness of only the inboard blade sections from 30 to 13 percent at the 0.3 radius also resulted in gains in propeller efficiency up to 10 percent.

Figure 28(b) compares the efficiencies for constant power operation of the propellers in the 0.045-solidity group. The differences in efficiency of the propellers in this group do not amount to more than 4 percent, and their efficiencies appear to be about equal at the lowest values of advance ratio and also at the highest values of advance ratio. The single exception is the propeller which has the thickest shank sections (NACA 10-(3)(062)-045); at the highest value of advance ratio (3.5) the efficiency of this propeller is about 2 percent less than the efficiency of the other three propellers. The curves in figure 28(b) show that a reduction in blade-section thickness of only the outboard blade sections (from 8 to 5 percent at the 0.7 radius) resulted in gains in propeller efficiency up to 4 percent. These improvements in efficiency appear to be limited to the range of advance ratio for which the propeller is designed. It should be pointed out, however, that the helical-tip Mach number of the NACA propellers did not exceed 0.8 for the conditions of operation shown in figure 28.

Figures 29 and 30 have been prepared to emphasize the importance of blade-section thickness in the design of propellers to operate at airspeeds where the tip Mach numbers are below the critical value. Figure 29 shows the effect of airspeed on the difference in efficiency between the NACA 10-(3)(08)-03 and NACA 10-(3)(12)-03 two-blade propellers when operating at a constant power coefficient of 0.15 and a constant rotational speed of 1140 rpm. The thinner blade sections of the NACA 10-(3)(08)-03 propeller effect an increase in efficiency of 10 percent with an increase in airspeed from 260 to 420 miles per hour. The corresponding change in helical-tip Mach number is from 0.63 to 0.76 as shown in figure 29. Figure 30 shows the effect of airspeed on the difference in efficiency between the NACA 10-(3)(05)-045 and NACA 10-(3)(08)-045 two-blade propellers when operating at a constant power coefficient of 0.15 and a constant rotational speed of 1140 rpm. The thinner outboard blade sections of the NACA 10-(3)(05)-045 propeller effect an increase in efficiency of 4 percent with an increase in airspeed up to 220 miles per hour, but from 220 to 460 miles per hour the beneficial effects of the thinner blade sections are gradually lost. Apparently the thicker outboard blade sections of the NACA 10-(3)(08)-045 propeller can carry their loads just as efficiently as the thinner sections of the NACA 10-(3)(05)-045 propeller at an airspeed of 460 miles per hour. The helical-tip Mach number at this airspeed is only 0.8, and it is possible that beneficial effects of the thinner blade sections may appear for different radial distributions of section Mach number. It should be realized that none of the NACA propellers was designed to operate at advance ratios as high as 3.2, otherwise higher efficiencies might be expected at the higher values of advance ratio because of a different pitch distribution. Since the superiority of the thinner outboard blade sections appears principally in the range of advance ratio for which the propeller was designed, substantial gains in efficiency through the use of thinner outboard blade sections may not be realized unless care is used in selecting the radial pitch distribution.

Effect of thickness ratio and compressibility on propeller characteristics.- The effect of compressibility on the maximum efficiency of NACA propellers having different blade-section thicknesses is shown in figure 31 for a blade angle at the 0.75 radius of 45°. Figure 31(a) shows that the NACA 10-(3)(12)-03 propeller, which has the thickest outboard blade sections in the 0.03-solidity group, suffers the greatest efficiency losses at the higher tip Mach numbers. These losses begin for this propeller at a helical-tip Mach number of about 0.825, and the loss amounts to 26 percent at a helical-tip Mach number of 1.1. The loss in efficiency due to compressibility is more gradual for the NACA 10-(3)(08)-03R propeller, and the serious losses do not begin until a helical-tip Mach number of about 0.875 is reached. For this propeller the loss in efficiency due to compressibility amounts to about 19 percent at a helical-tip Mach number of 1.1. The maximum efficiency of the NACA 10-(3)(08)-03 propeller, which has the thinnest blade sections in the 0.03-solidity group, is about 2 percent higher than the maximum efficiency of the other two propellers in the range of helical-tip Mach numbers below the critical value. The critical value of tip Mach number is perhaps slightly higher for the NACA 10-(3)(08)-03 propeller than for the NACA 10-(3)(08)-03R propeller, and the loss in maximum efficiency due to compressibility amounts to about 16 percent at a helical-tip Mach number of 1.1.

Figure 31(a) shows that a reduction in blade-section thickness from 12 to 8 percent at the 0.7 radius, or approximately one-third all along the radius, resulted in a gain in propeller efficiency of about 12 percent at a helical-tip Mach number of 1.1. At this same helical-tip Mach number a reduction in blade-section thickness of only the inboard blade-sections (from 30 to 13 percent at the 0.3 radius) resulted in a gain in propeller efficiency of about 5 percent.

Figure 31(b) shows the effect of compressibility on the maximum efficiency of the NACA propellers in the 0.045-solidity group. Again, the propeller having the thickest outboard blade sections (NACA 10-(3)(08)-045) suffers the greatest efficiency losses at the higher tip Mach numbers. From a helical-tip Mach number of 0.90 to 1.1 the efficiency loss due to compressibility for this propeller amounts to 18 percent. Over this same range of helical-tip Mach number the propeller having the thinnest outboard blade sections (NACA 10-(3)(05)-045) has a loss in efficiency due to compressibility of only 9 percent. The NACA 10-(3)(062)-045 propeller, which has the thickest shank sections, shows a loss in efficiency due to compressibility of 13 percent at a helical-tip Mach number of 1.1. These losses at the higher tip Mach numbers are more gradual for the NACA 10-(3)(062)-045 propeller than for the NACA 10-(3)(08)-045 propeller, which has thinner blade sections at the shank but thicker outboard blade sections. The critical values of helical-tip Mach numbers are approximately the same for all the propellers in the 0.045-solidity group, and the differences in maximum efficiency are small at tip Mach numbers below the critical value. The maximum efficiency of the NACA 10-(3)(062)-045A propeller is the same as for the thinner NACA 10-(3)(05)-045 propeller except at the lower values of helical-tip Mach number, where the thinner blade perhaps has a slight advantage.

The curves in figure 31(b) show that a reduction in blade-section thickness of only the outboard blade sections (from 8 to 5 percent at the 0.7 radius) resulted in a gain in propeller efficiency of about 12 percent at a helical-tip Mach number of 1.1. At this same helical-tip Mach number a reduction in blade-section thickness of only the inboard blade sections (from 16.6 to 13 percent at the 0.3 radius) resulted in a gain in propeller efficiency of about 6 percent. A small reduction in thickness (from 6.2 to 5 percent at the 0.7 radius) of the blade sections between the shank and the tip had little effect on the maximum propeller efficiency for the conditions of operation tested.

An examination of the thrust and power coefficients of the propellers operating when the effects of compressibility are present may provide a better understanding of the results. In figure 32 the thrust and power coefficients for maximum efficiency are shown plotted against helical-tip Mach number for the test propellers at a blade angle of 45° at the 0.75 radius. It should be realized that the scarcity of data prevents a definite establishment of the critical Mach numbers, but the curves in figure 32 are shown to illustrate the trends indicated by the data. The curves are somewhat similar to plots of airfoil lift coefficient against Mach number for constant angles of attack and show that increases in thrust and power coefficient occur before the critical Mach number is reached. The critical Mach number is higher for the propellers having the thinner blade sections. After the critical Mach number is reached, there is a marked decrease in both thrust and power coefficients up to a helical-tip Mach number of approximately 1.0. At this helical-tip Mach number near 1.0 the power coefficients begin to increase again, and the thrust coefficients either level off or, in the case of the thinner blades, begin to increase again. These changes in thrust and power coefficients which occur with changes in helical-tip Mach number are, with one exception, less abrupt for the propellers having the thicker blade sections. The single exception is the NACA 10-(3)(08)-045 propeller which has relatively thin shank sections but thick outboard blade sections. The curves in figures 31 and 32 show that the radial distribution of blade-section thickness ratios has a pronounced effect on the characteristics of propellers operating at helical-tip Mach numbers above the critical value.

Any efficiency comparisons of the propellers in the 0.03-solidity group with those in the 0.045-solidity group to study the effects of thickness ratio will include the effects of solidity; however, these effects are small (of the order of 2 percent), and some generalization may be permitted despite the variation in solidity. The NACA propellers discussed in this paper are closely related, and it may be assumed that the radial distribution of camber, solidity, and blade-section thickness is a reasonable optimum for the better propellers. With the generalization in mind, the data for the NACA propellers may serve to indicate the compressibility losses to be expected for propellers having various blade-section thickness ratios.

The curves in figure 33 show the variation of maximum propeller efficiency with thickness ratio at the 0.7 radius for constant values of helical-tip Mach Number. At a helical-tip Mach number of 0.9 and air-stream Mach number of 0.520 the maximum efficiency of a propeller may be increased approximately 7 percent by reducing the blade-section thickness from 12 to 5 percent at the 0.7 radius. For this Mach number gradient along the blade the rate of change of maximum propeller efficiency with blade-section thickness is small for thicknesses up to 12 percent at the 0.7 radius, and figure 33 indicates that reductions in blade-section thickness below 5 percent at the 0.7 radius will probably increase the maximum efficiency very little. However, at a helical-tip Mach number of 1.1 and air-stream Mach number of 0.625 the maximum efficiency of a propeller may be increased approximately 20 percent by reducing the blade-section thickness from 12 to 5 percent at the 0.7 radius. For this higher Mach number gradient along the blade the rate of change of maximum propeller efficiency with blade-section thickness is greater, and for thicknesses between 12 and 8 percent at the 0.7 radius the maximum efficiency increases approximately 3 percent for each decrease in thickness of 1 percent at the 0.7 radius. For thicknesses between 8 and 5 percent at the 0.7 radius the rate of increase in propeller efficiency with reductions in blade-section thickness is smaller. Figure 33 indicates that further reductions in thickness may still improve the maximum efficiency of propellers operating at helical-tip Mach numbers as high as 1.1, particularly for conditions of operation where the air-stream Mach number is high so that large portions of the blades are subjected to the effects of air compressibility.

CONCLUSIONS

An investigation of a series of 10-foot-diameter two-blade NACA propellers differing in blade-section thickness has been completed for a range of blade angles from 20° to 55° at airspeeds up to 500 miles per hour. The results of these investigations have been compared to afford an evaluation of the effects of blade-section thickness ratios on propeller aerodynamic characteristics, and the following conclusions may be drawn:

1. The envelope efficiencies of all the NACA propellers are high at the lower Mach numbers where the adverse effects of compressibility are small. The higher envelope efficiencies, however, are attained by the propellers having the thinner blade sections. The highest efficiencies (about 93 percent at a helical-tip Mach number of 0.9 and 84 percent at a helical-tip Mach number of 1.1) reflect the importance of using thin, efficient airfoil sections throughout the blade.

2. For propeller operation at constant rotational speed (1140 rpm) and power ($C_P = 0.15$) at helical-tip Mach numbers below 0.8,

(a) A reduction in blade-section thickness from 12 to 8 percent at the 0.7 radius, or approximately one-third all along the radius, results in gains in propeller efficiency up to 10 percent.

(b) A reduction in blade-section thickness of only the inboard blade sections (from 30 to 13 percent at the 0.3 radius) results in gains in propeller efficiency up to 10 percent.

(c) A reduction in blade-section thickness of only the outboard blade sections (from 8 to 5 percent at the 0.7 radius) results in gains in efficiency up to 4 percent.

3. For operation at a blade angle of 45° at the 0.75 radius and a helical-tip Mach number of 1.1 the loss in maximum propeller efficiency due to compressibility amounts to 26 percent for the NACA propeller having a blade-section thickness of 12 percent at the 0.7 radius. The corresponding loss in maximum propeller efficiency amounts to only 9 percent for the NACA propeller having a blade-section thickness of 5 percent at the 0.7 radius.

4. At a helical-tip Mach number of 0.9 and air-stream Mach number of 0.520 the rate of change of maximum propeller efficiency with blade-section thickness is small for thicknesses up to 12 percent at the 0.7 radius, and reductions in blade-section thickness below 5 percent at the 0.7 radius will probably increase the maximum efficiency very little.

5. At a helical-tip Mach number of 1.1 and air-stream Mach number of 0.625 the maximum efficiency of a propeller may be increased approximately 20 percent by reducing the blade-section thickness from 12 to 5 percent at the 0.7 radius. For blade-section thicknesses between 12 and 8 percent at the 0.7 radius the maximum efficiency increases approximately 3 percent for each decrease in thickness of 1 percent at the 0.7 radius. For blade-section thicknesses between 8 and 5 percent at the 0.7 radius the rate of increase in propeller efficiency with reductions in blade-section thickness is smaller, but further reductions in thickness may still improve the maximum efficiency of propellers operating at high forward speeds with helical-tip Mach numbers as high as 1.1.

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TABLE I

RANGE OF BLADE ANGLE AND ROTATIONAL SPEED

FOR NACA PROPELLER TESTS

Figure	Rotational speed (rpm)	Blade angle at 0.75 radius, $\beta_{0.75R}$ (deg)							
NACA 10-(3)(062)-045A propeller									
8	1140	20	25	30	35	40	45	50	55
9	1350	20	25	30	35	40	45	50	
10	1500						45		
11	1600	20	25	30	35	40	45		
12	2000	20	25	30	35				
13	2160	20	25	30					
14, 15, 16	Varied						45		
NACA 10-(3)(05)-045 propeller									
17	1140	20	25	30	35	40	45	50	55
18	1350	20	25	30	35	40	45	50	
19	1500						45		
20	1600	20	25	30	35	40	45		
21	2000	20	25	30	35				
22	2160	20	25	30					
23, 24, 25	Varied						45		
NACA 10-(3)(062)-045 propeller (reference 7)									
4	1140		25	30	35	40	45	50	55
5	1350	20	25	30	35	40	45	50	
6	1500						45		
7	1600	20	25	30	35	40	45		
8	2000	20	25	30	35				
9	2160	20	25	30					
10	Varied						45		
NACA 10-(3)(08)-045 propeller (reference 7)									
11	1140		25	30	35	40	45	50	55
12	1350	20	25	30	35	40	45	50	
13	1500						45		
14	1600	20	25	30	35	40	45		
15	2000	20	25	30	35				
16	2160	20	25	30					
17	Varied						45		

NACA

TABLE I

RANGE OF BLADE ANGLE AND ROTATIONAL SPEED

FOR NACA PROPELLER TESTS — Concluded

Figure	Rotational speed (rpm)	Blade angle at 0.75 radius, $\beta_{0.75R}$ (deg)							
NACA 10-(3)(08)-03 propeller (reference 3)									
19	1140			30	35	40	45	50	55
20	1350	20	25	30	35	40	45	50	
21	1500						45		
22	1600	20	25	30	35	40	45		
23	2000	20	25	30	35				
24	2160	20	25	30					
25	Varied						45		
NACA 10-(3)(08)-03R propeller (reference 5)									
3	1140				35	40	45	50	55
4	1350	20	25	30	35	40	45	50	
8	1500						45		
5	1600	20	25	30	35	40	45		
6	2000	20	25	30	35				
7	2160	20	25	30					
9, 10	Varied						45	50	
NACA 10-(3)(12)-03 propeller (reference 8)									
2	1140		25	30	35	40	45	50	55
3	1350	20	25	30	35	40	45	50	
4	1500						45		
5	1600	20	25	30	35	40	45		
6	2000	20	25	30	35				
7	2160	20	25	30					
8	Varied						45		

NACA

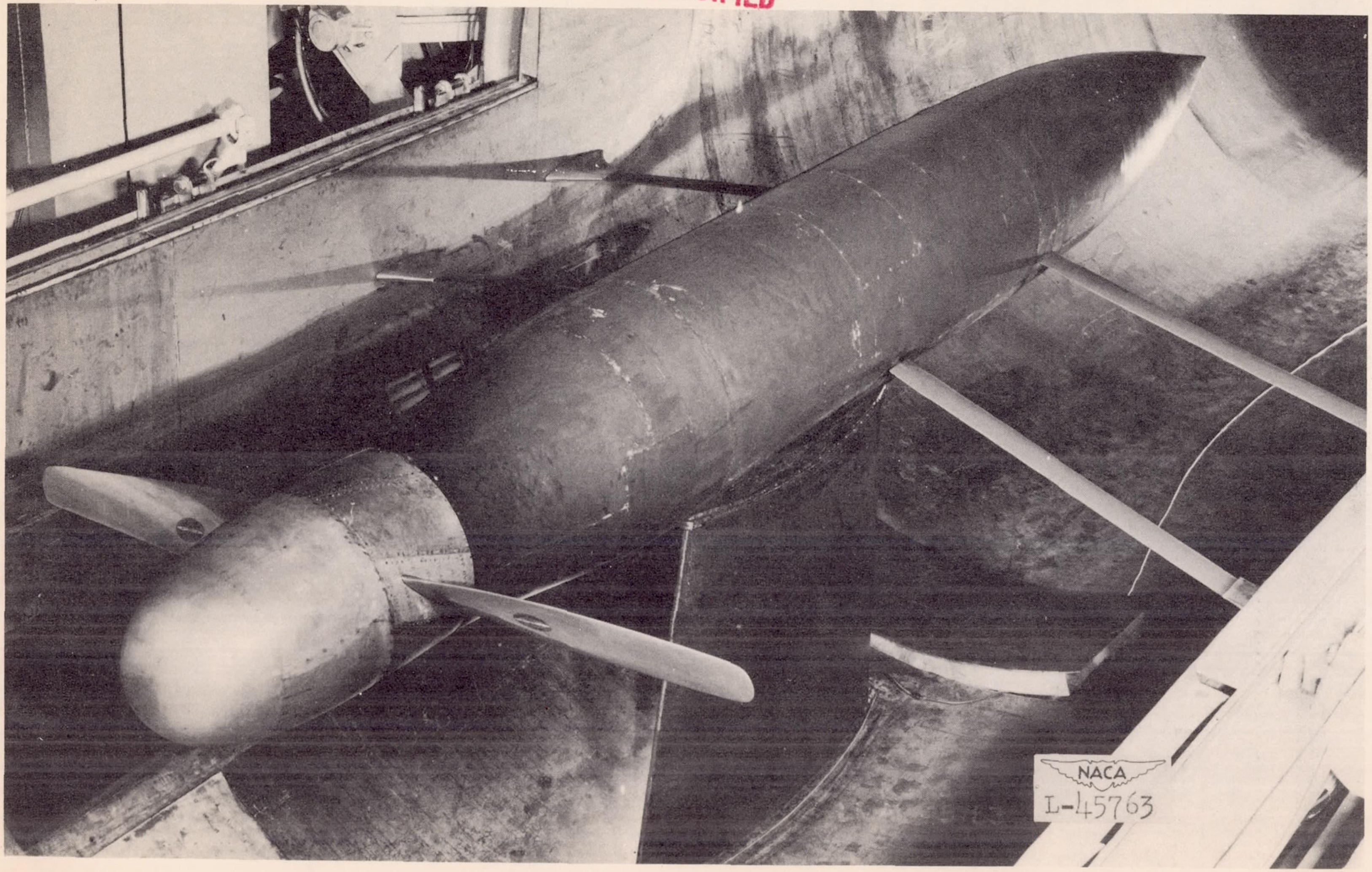

Figure 1.- Propeller dynamometer in test section with tunnel open.

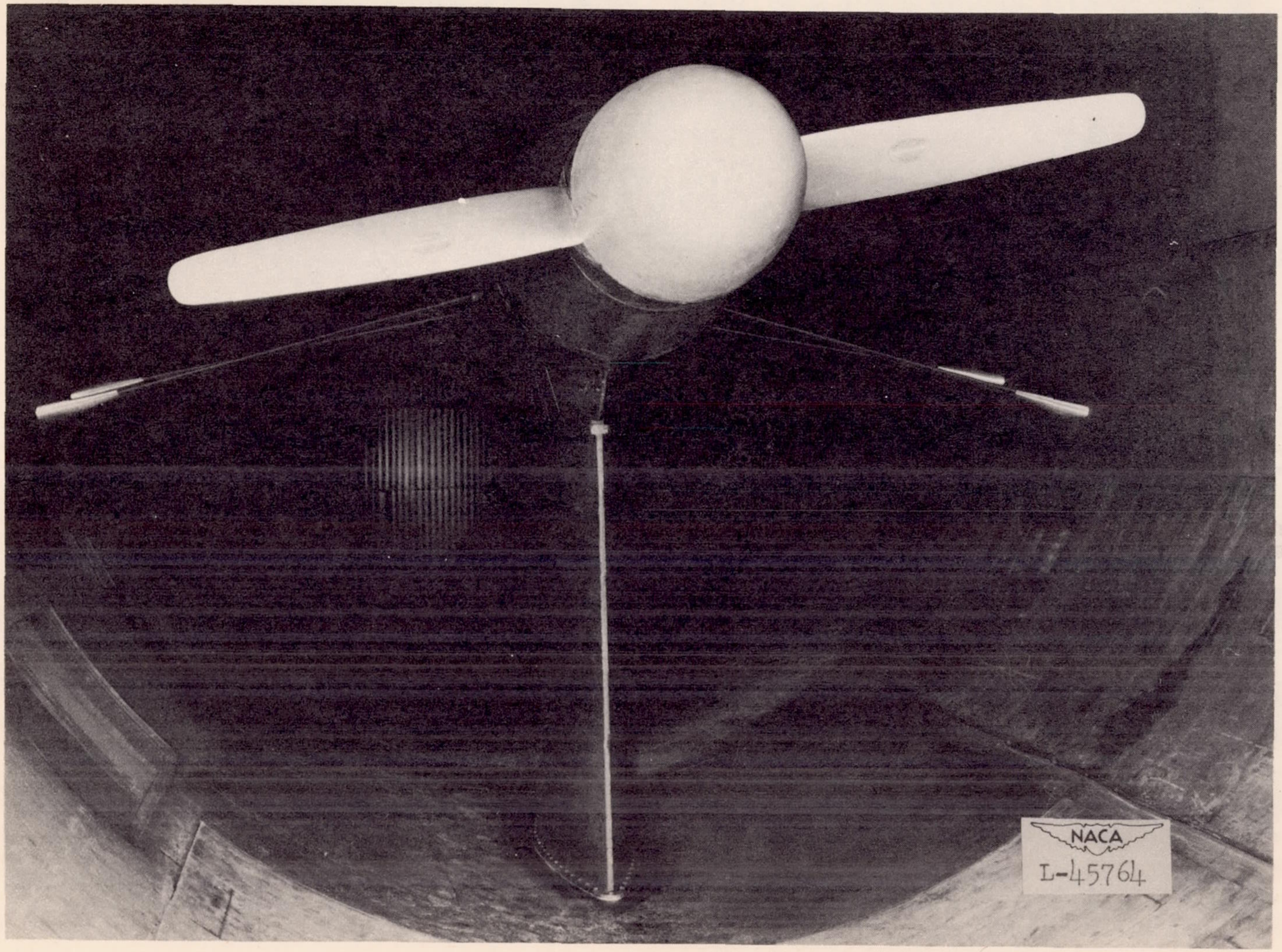

Figure 2.— Propeller dynamometer in test section with tunnel closed.

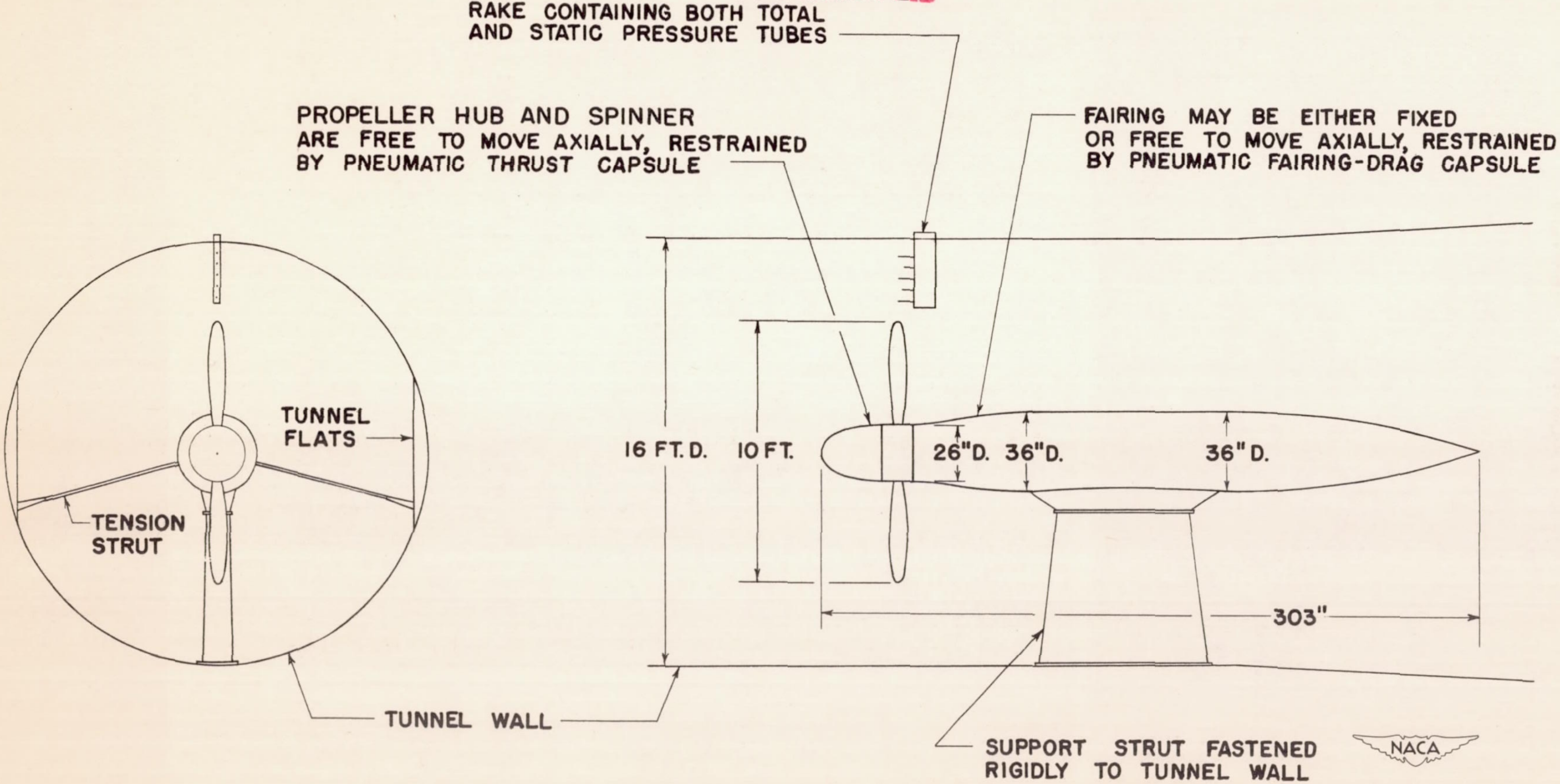

Figure 3.- Configuration of 2000-horsepower dynamometer for tests of propellers in the Langley 16-foot high-speed tunnel.

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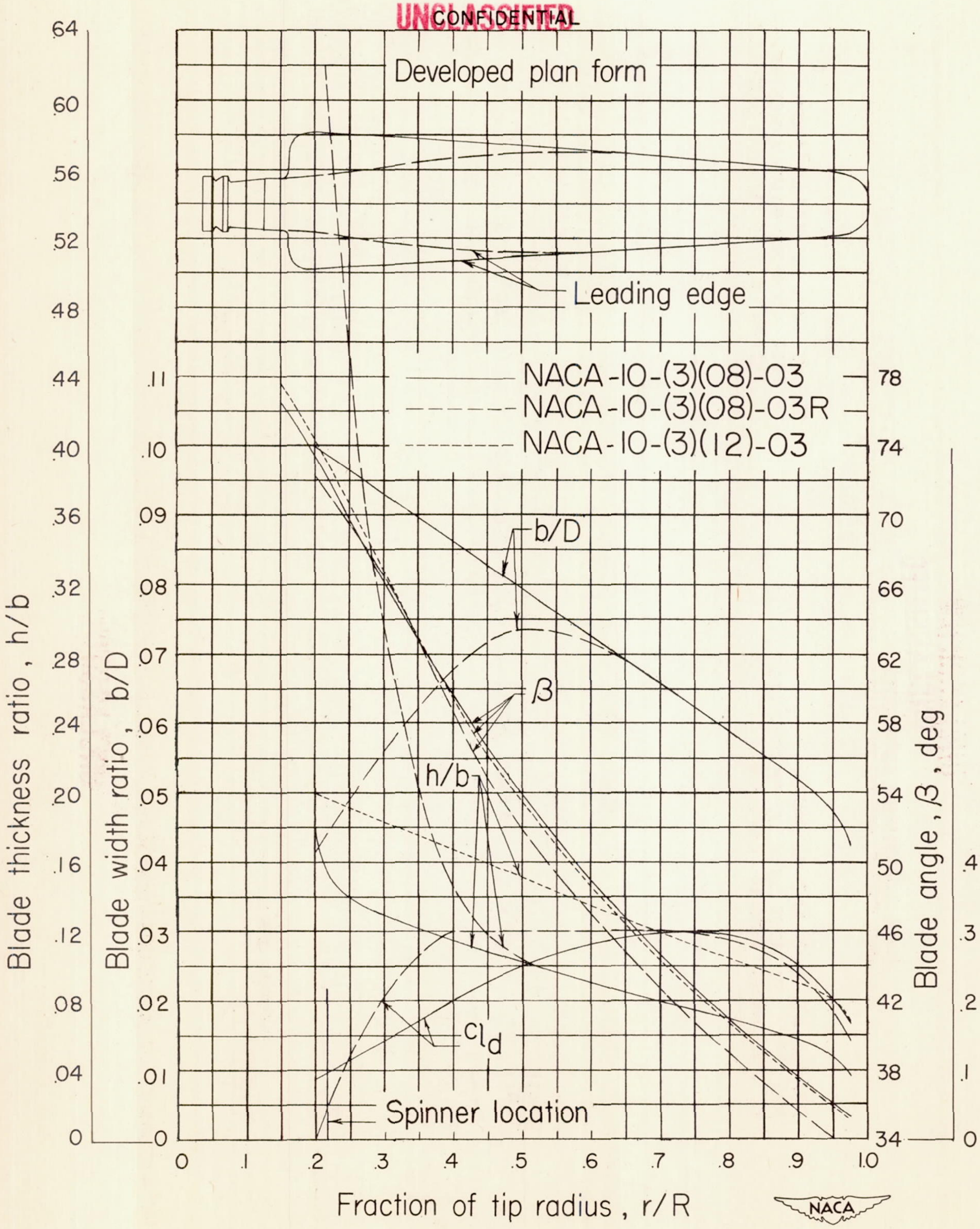

Figure 4.- Blade-form curves for NACA propellers having a solidity of 0.03 per blade at the 0.7 radius.

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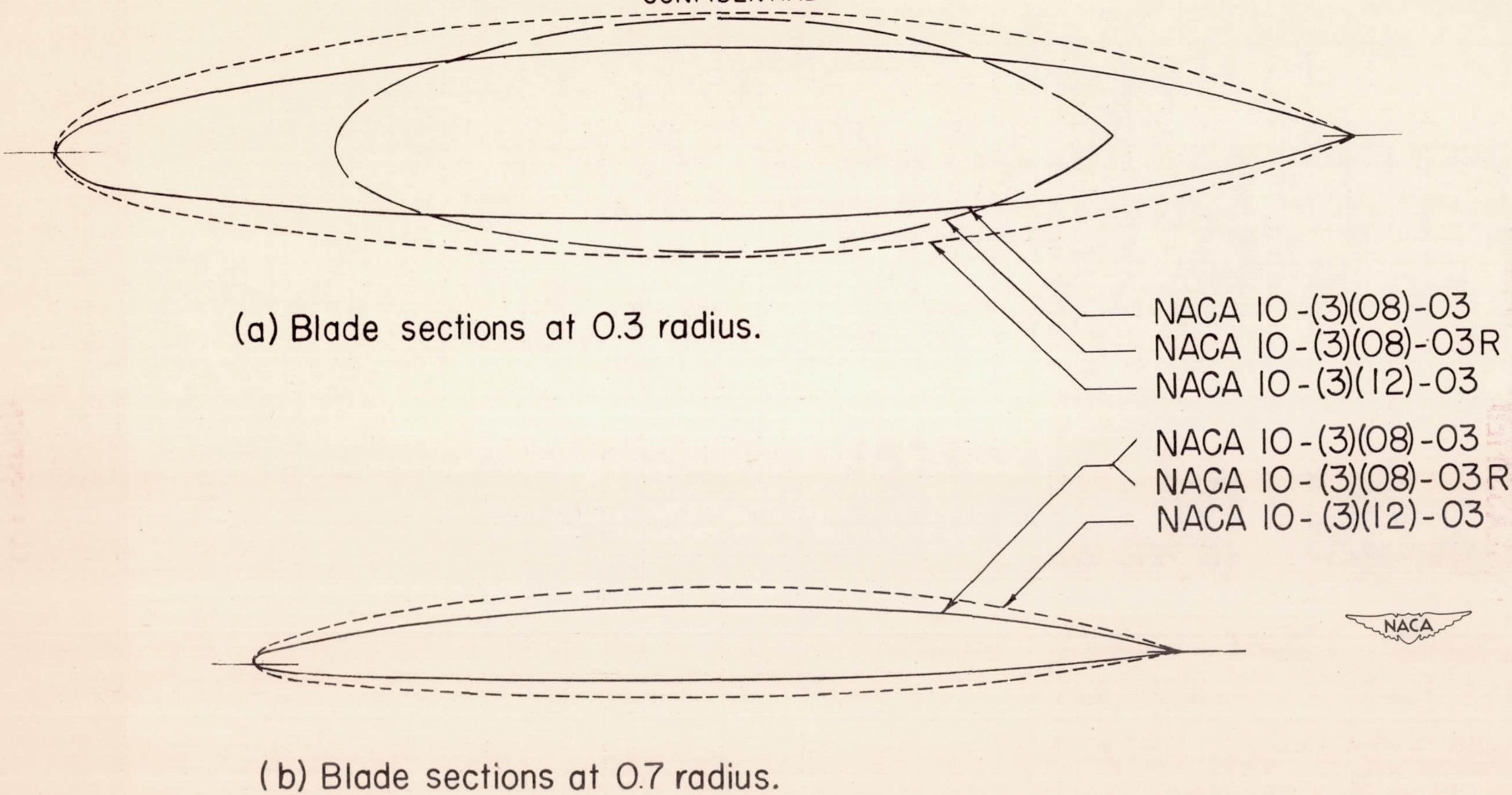


Figure 5.– Comparison of blade sections at two radii for NACA propellers having a solidity of 0.03 per blade at the 0.7 radius.

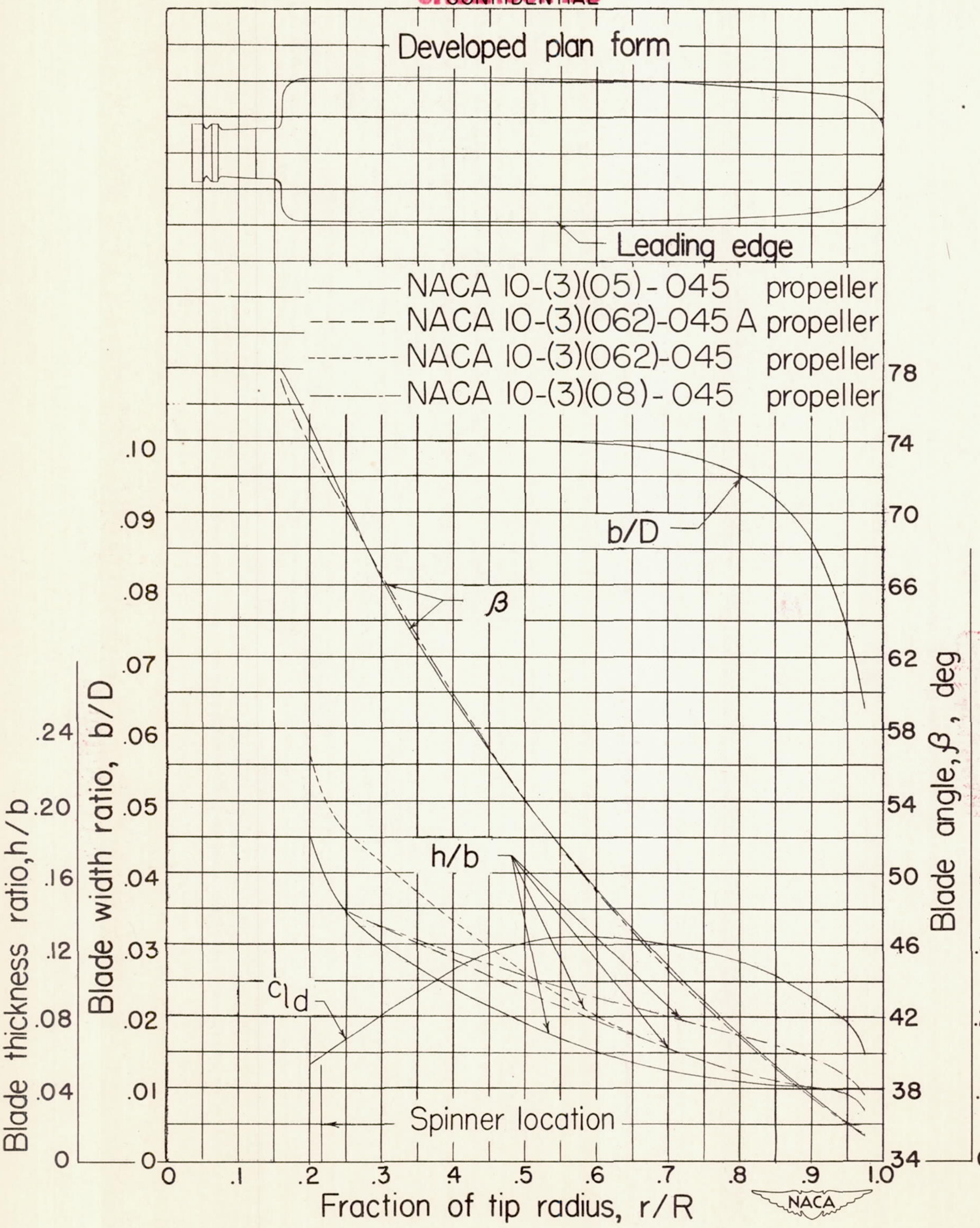
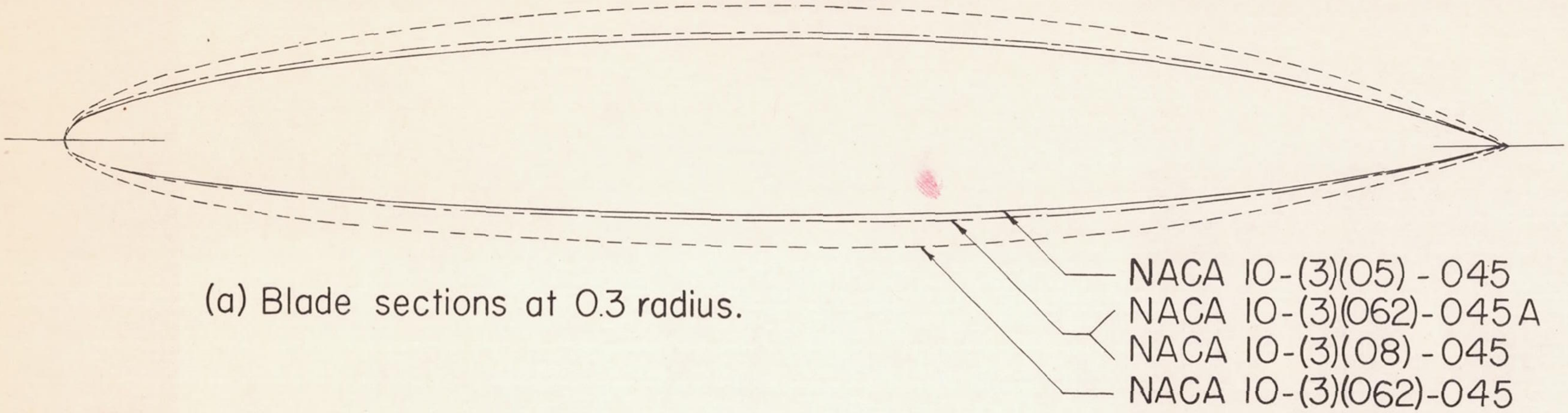
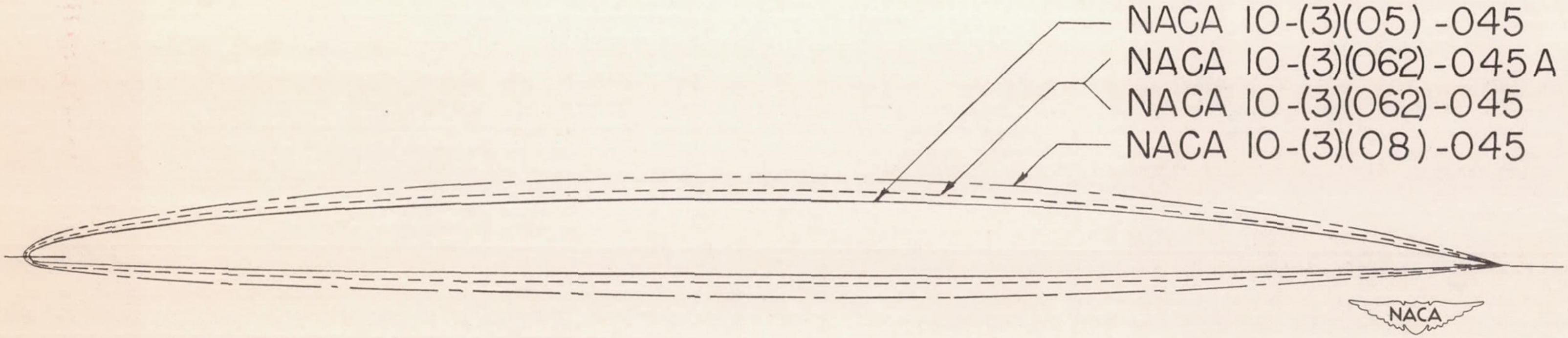


Figure 6.- Blade-form curves for NACA propellers having a solidity of 0.045 per blade at the 0.7 radius.

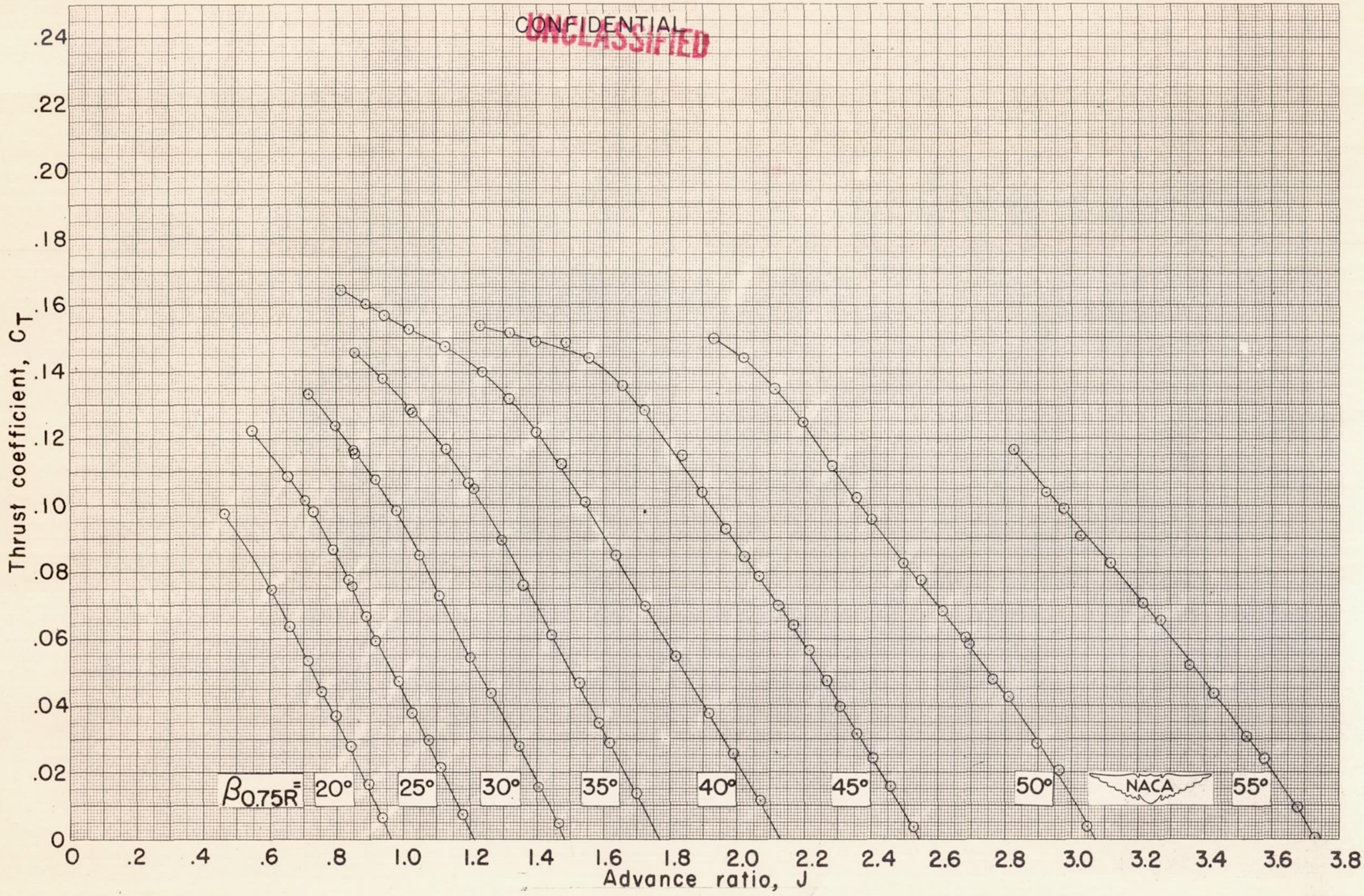


(a) Blade sections at 0.3 radius.



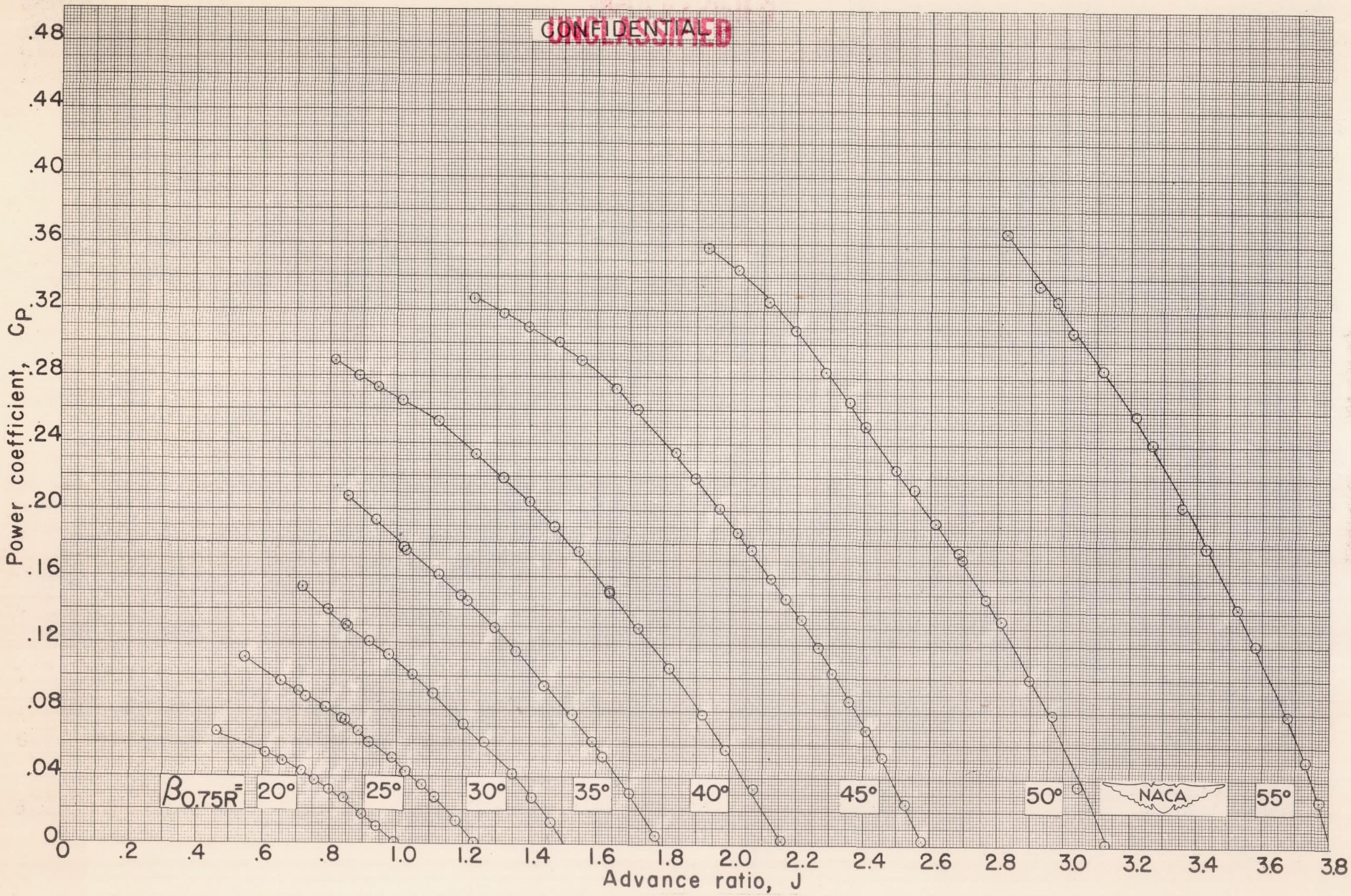
(b) Blade sections at 0.7 radius.

Figure 7.- Comparison of blade sections at two radii for NACA propellers having a solidity of 0.045 per blade at the 0.7 radius.



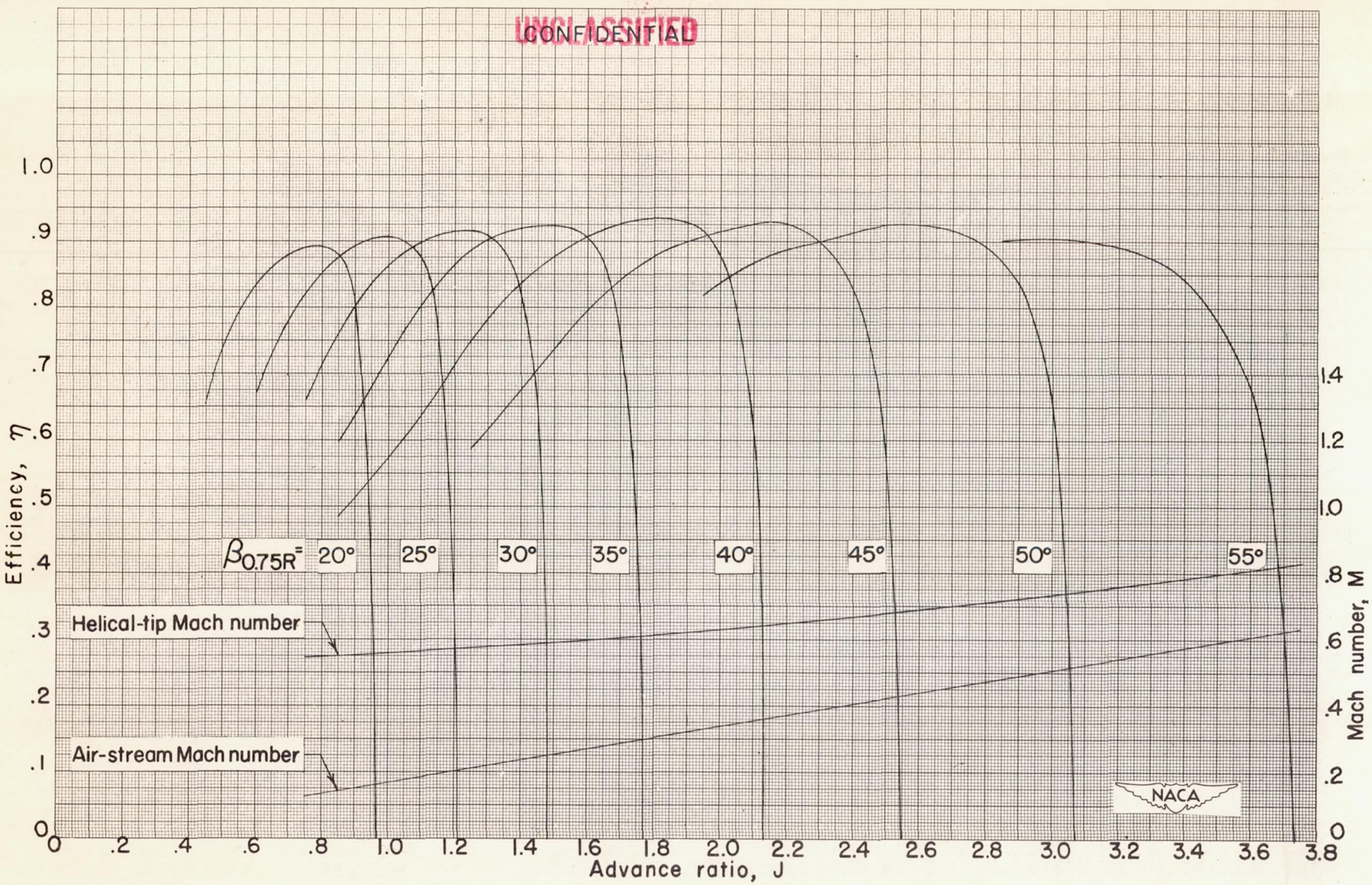
(a) Thrust coefficient.

Figure 8.- Characteristics of NACA 10-(3)(062)-045A propeller. Rotational speed, 1140 rpm.



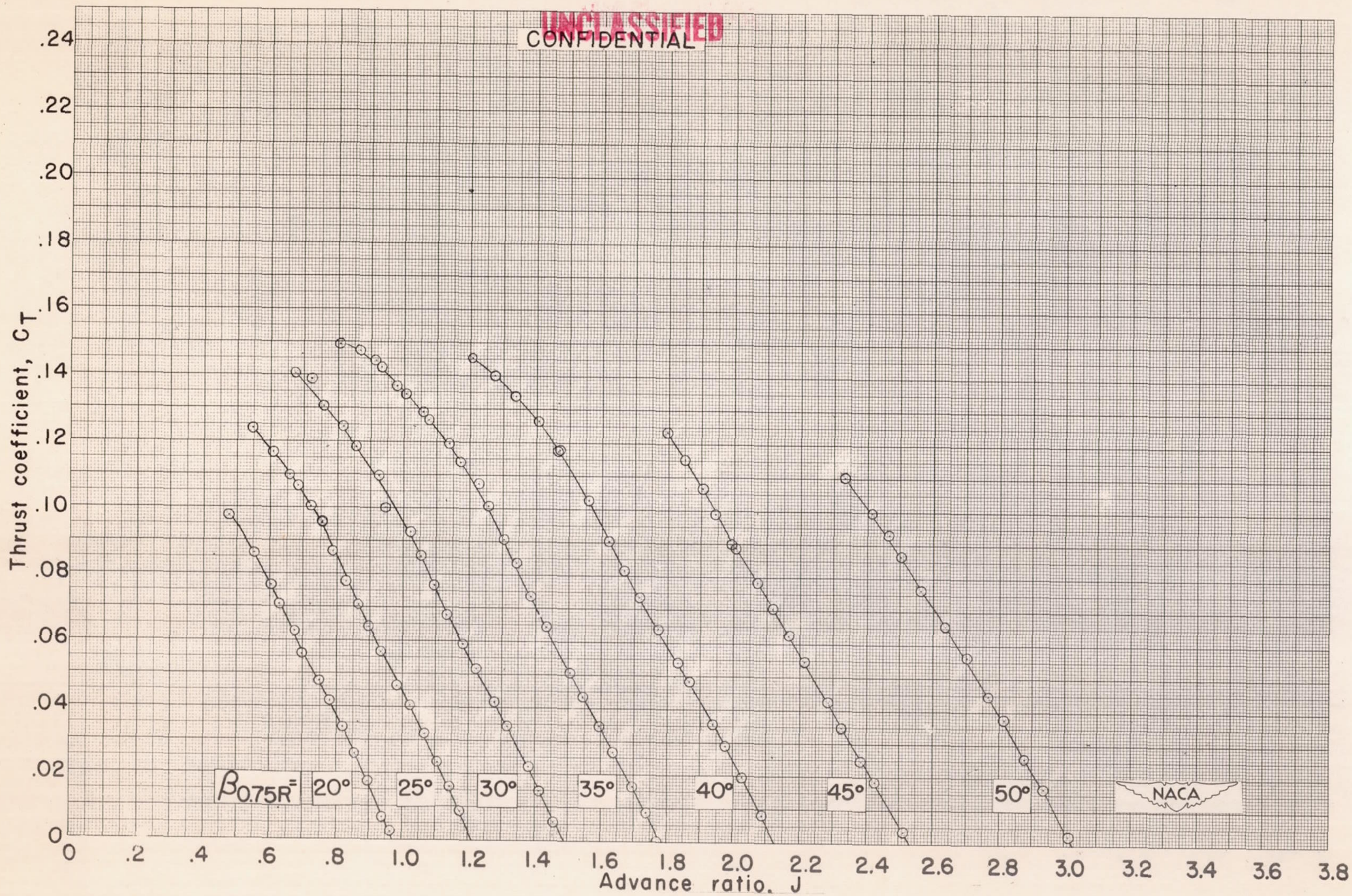
(b) Power coefficient.

Figure 8.— Continued. Rotational speed, 1140 rpm.



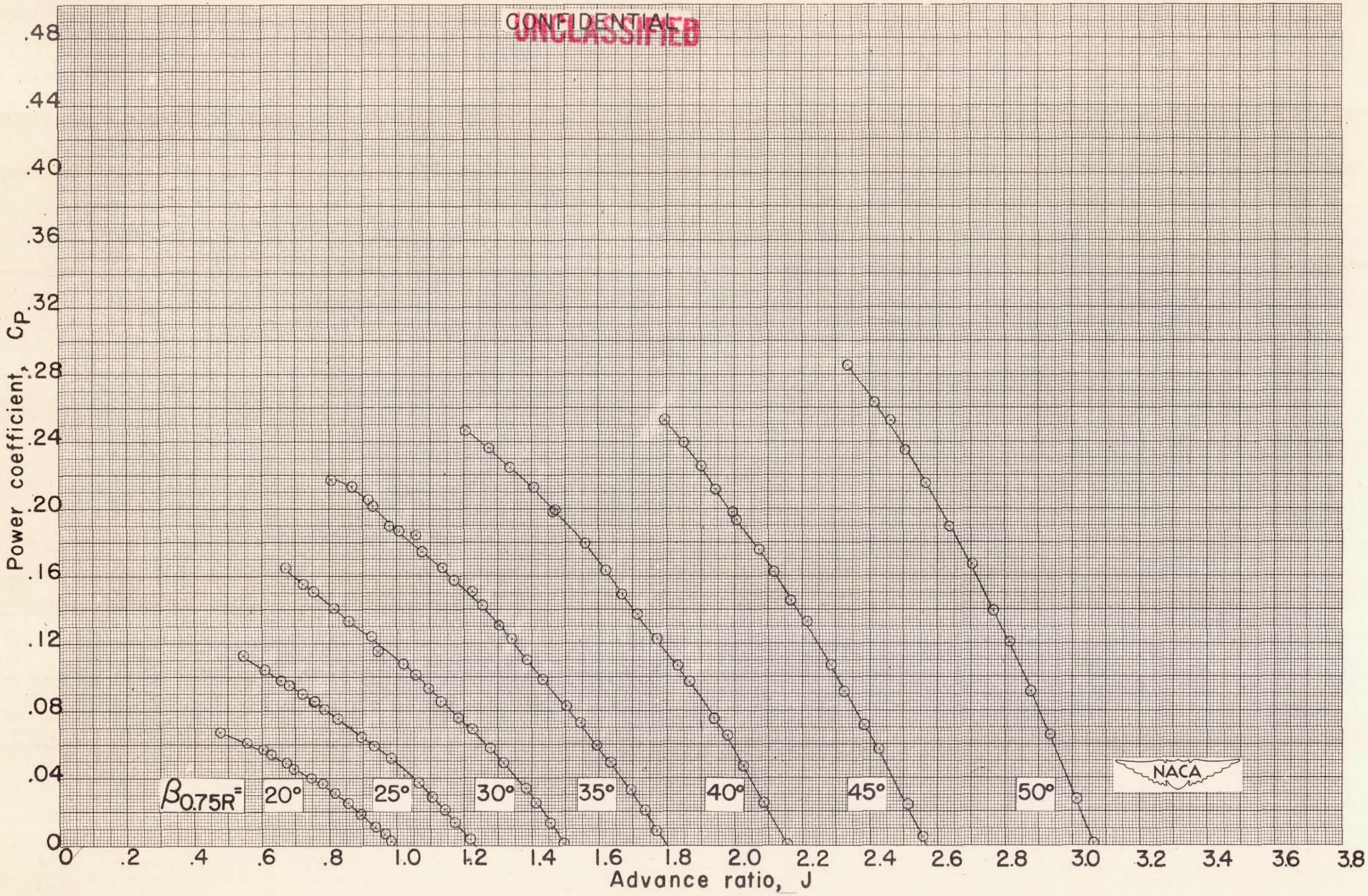
(c) Efficiency.

Figure 8.– Concluded. Rotational speed, 1140 rpm.



(a) Thrust coefficient.

Figure 9.– Characteristics of NACA 10–(3)(062)–045A propeller. Rotational speed, 1350 rpm.



(b) Power coefficient.

Figure 9.- Continued. Rotational speed, 1350 rpm.

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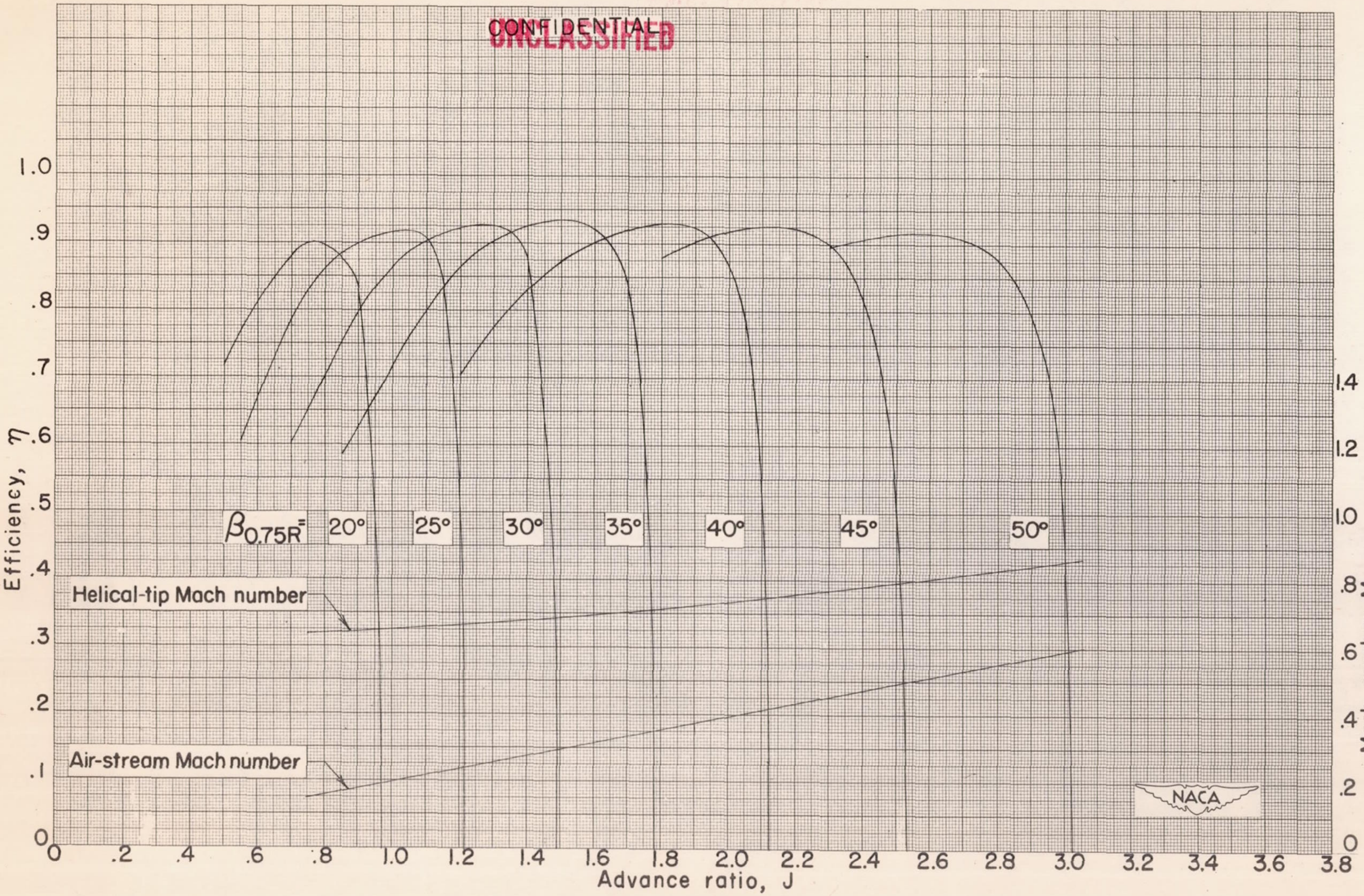

(c) Efficiency.

Figure 9.- Concluded. Rotational speed, 1350 rpm.

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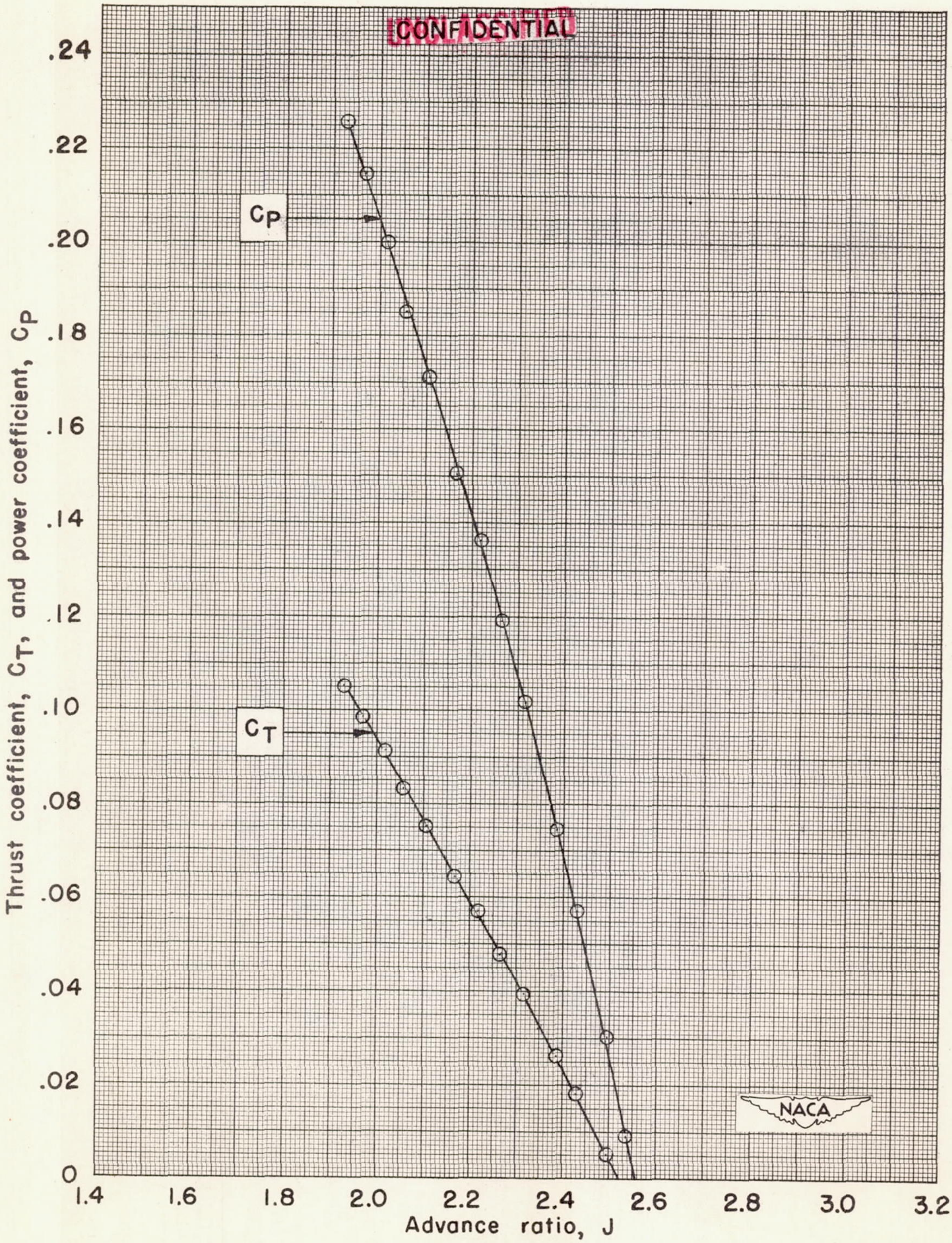
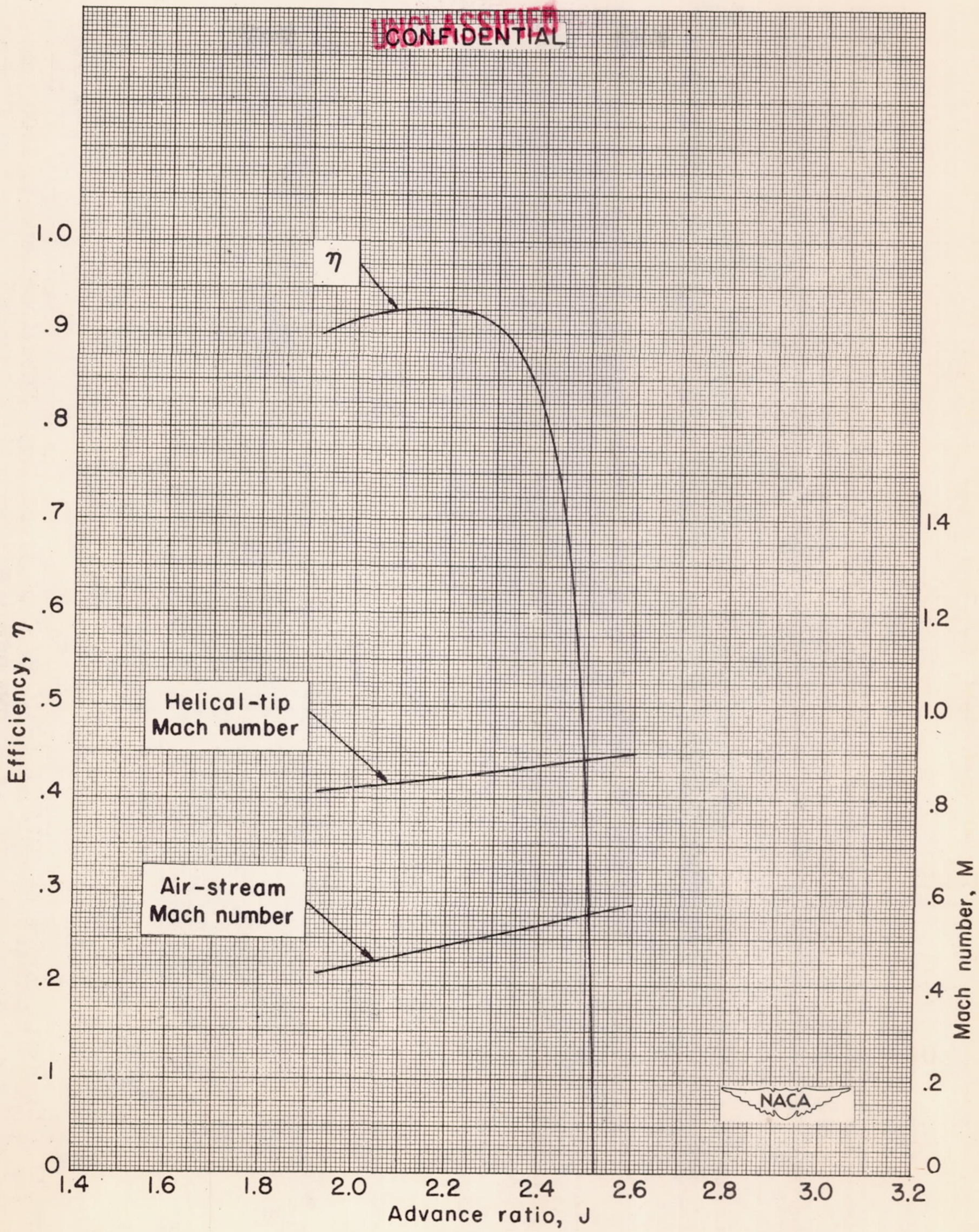


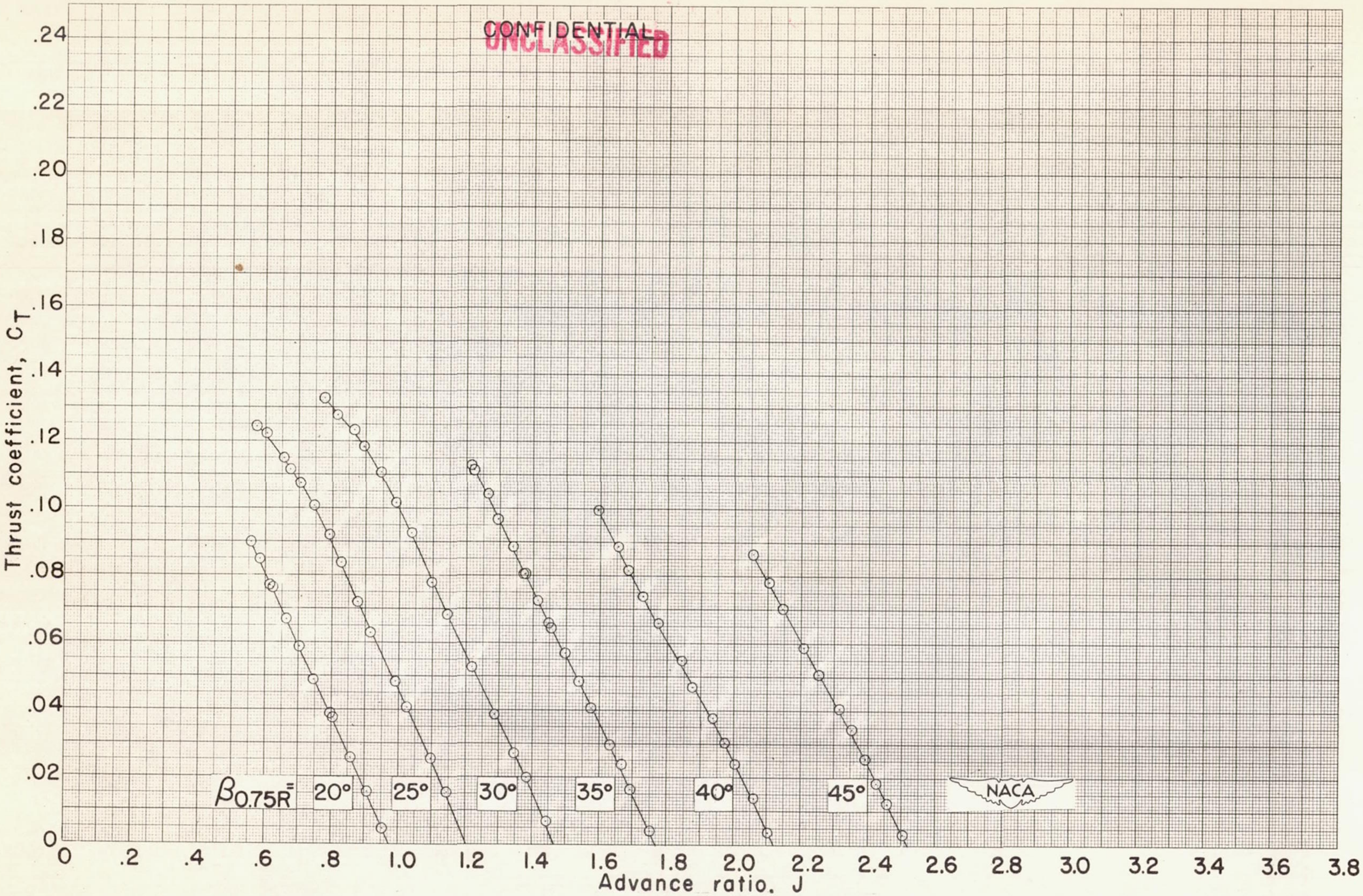
(a) Thrust and power coefficients.

Figure 10.– Characteristics of NACA 10–(3)(062)–045A propeller. Rotational speed, 1500 rpm; $\beta_{0.75R} = 45^{\circ}$.



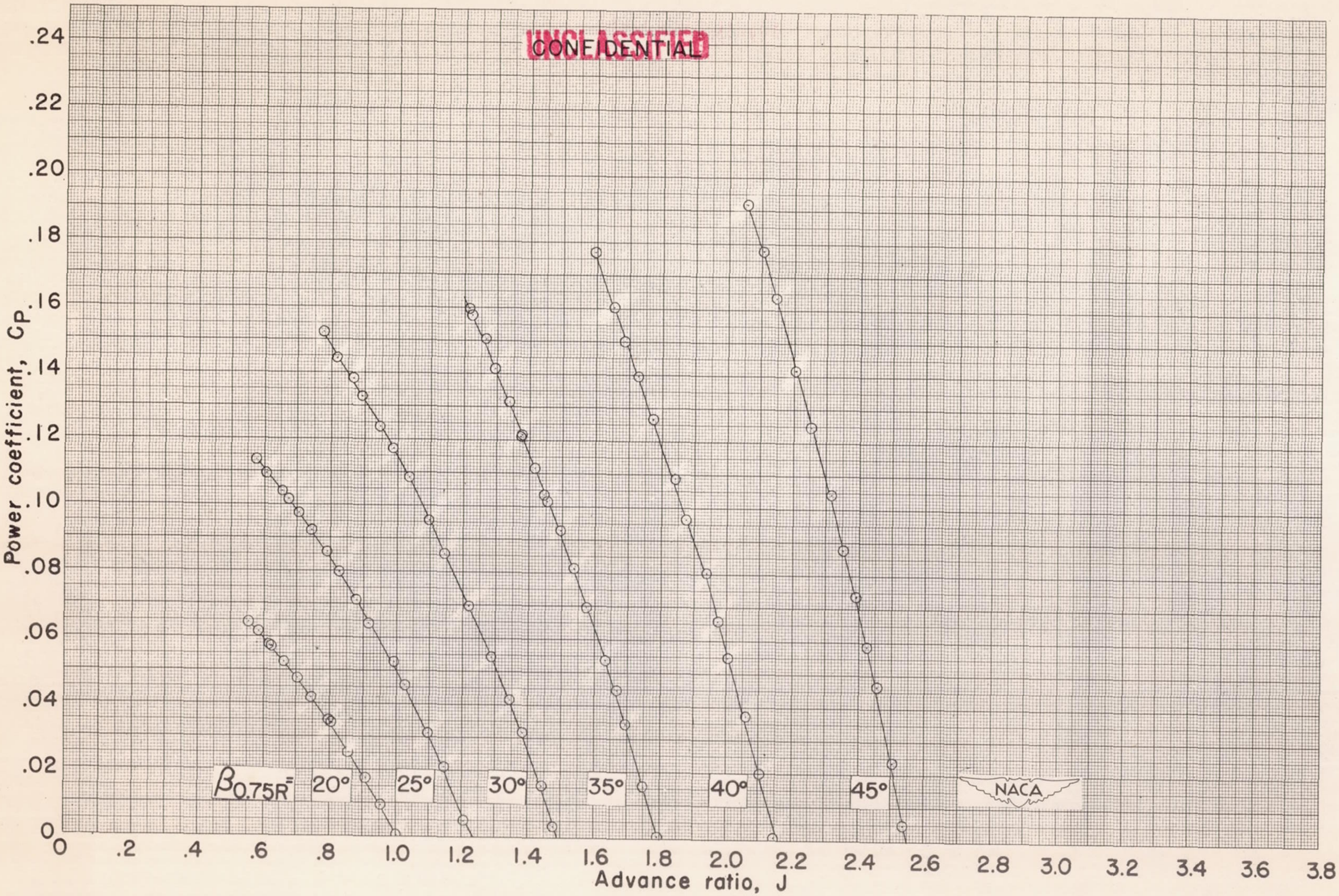
(b) Efficiency.

Figure 10.– Concluded. Rotational speed, 1500 rpm.



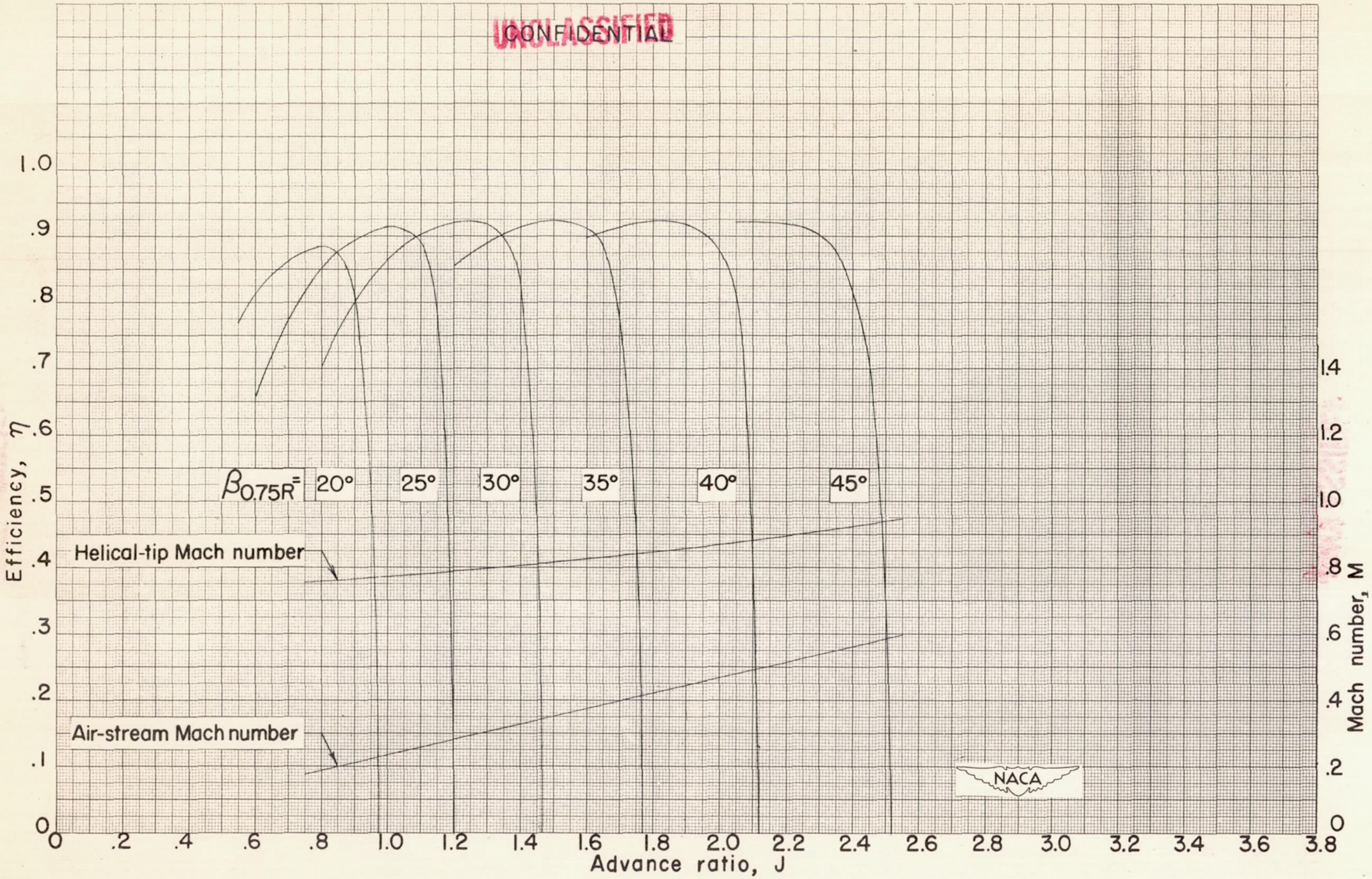
(a) Thrust coefficient.

Figure 11.– Characteristics of NACA 10–(3)(062)–045A propeller. Rotational speed, 1600 rpm.



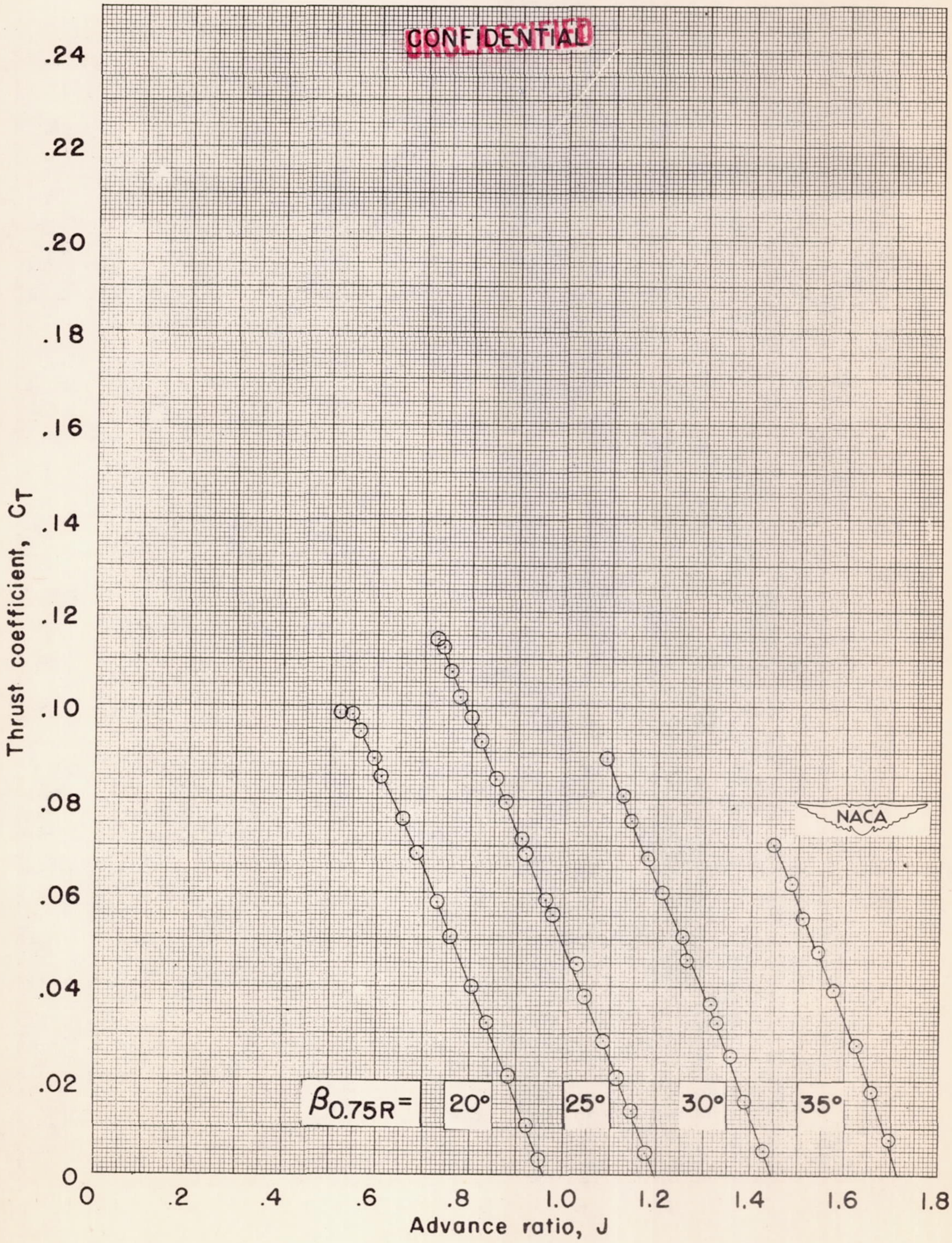
(b) Power coefficient.

Figure 11.- Continued. Rotational speed, 1600 rpm.



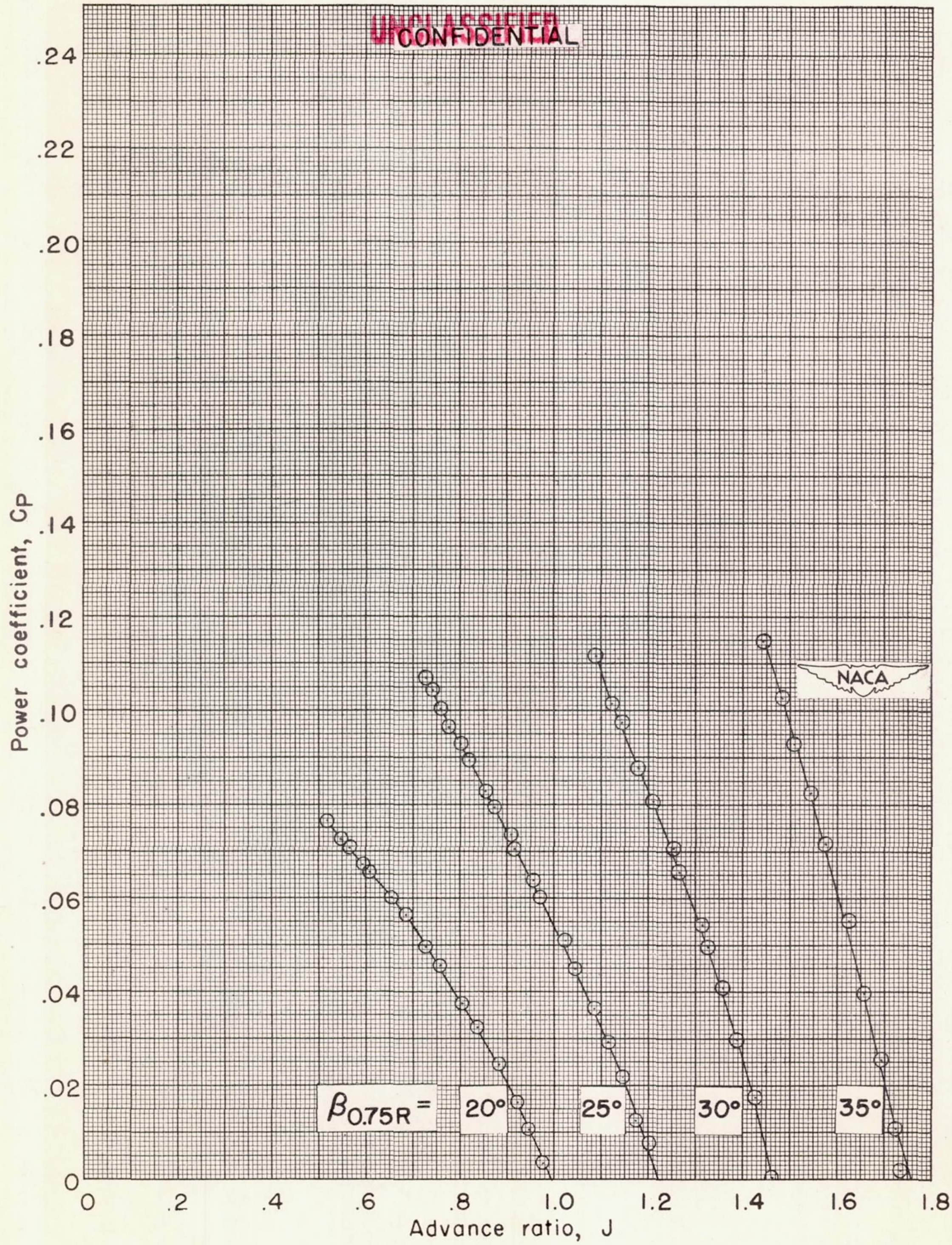
(c) Efficiency.

Figure 11.– Concluded. Rotational speed, 1600 rpm.



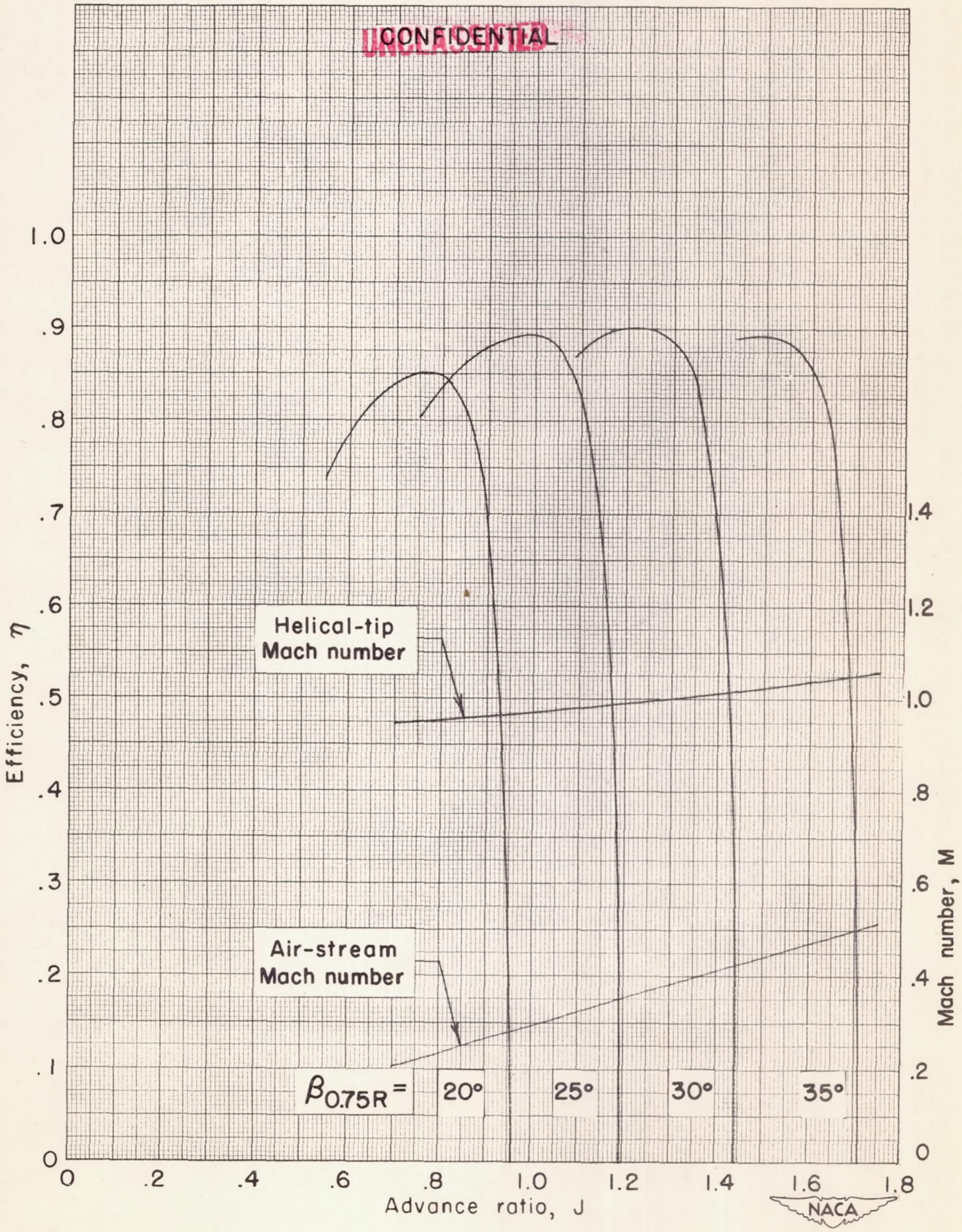
(a) Thrust coefficient.

Figure 12.- Characteristics of NACA 10-(3)(062)-045A propeller. Rotational speed, 2000 rpm.



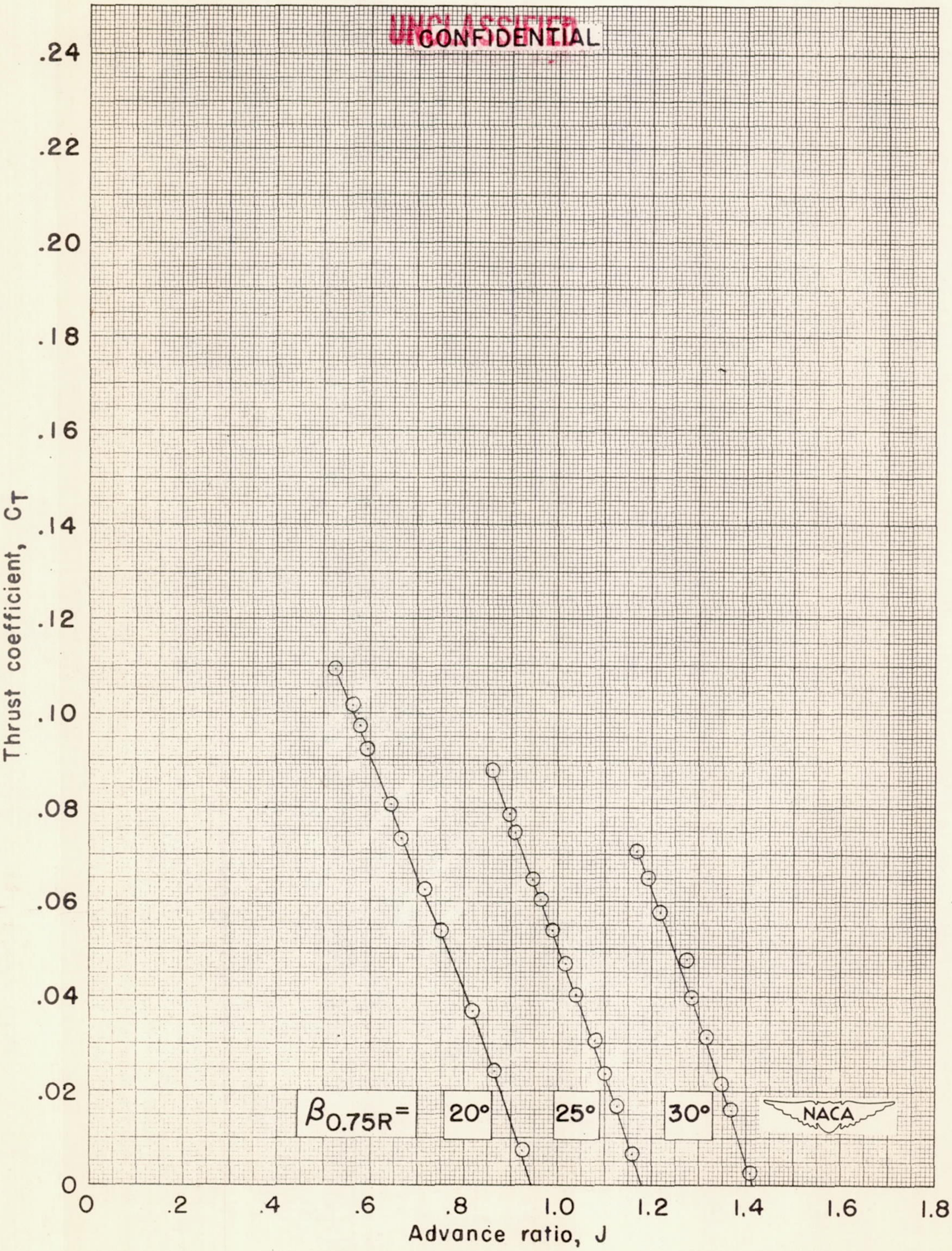
(b) Power coefficient.

Figure 12.– Continued. Rotational speed, 2000 rpm.



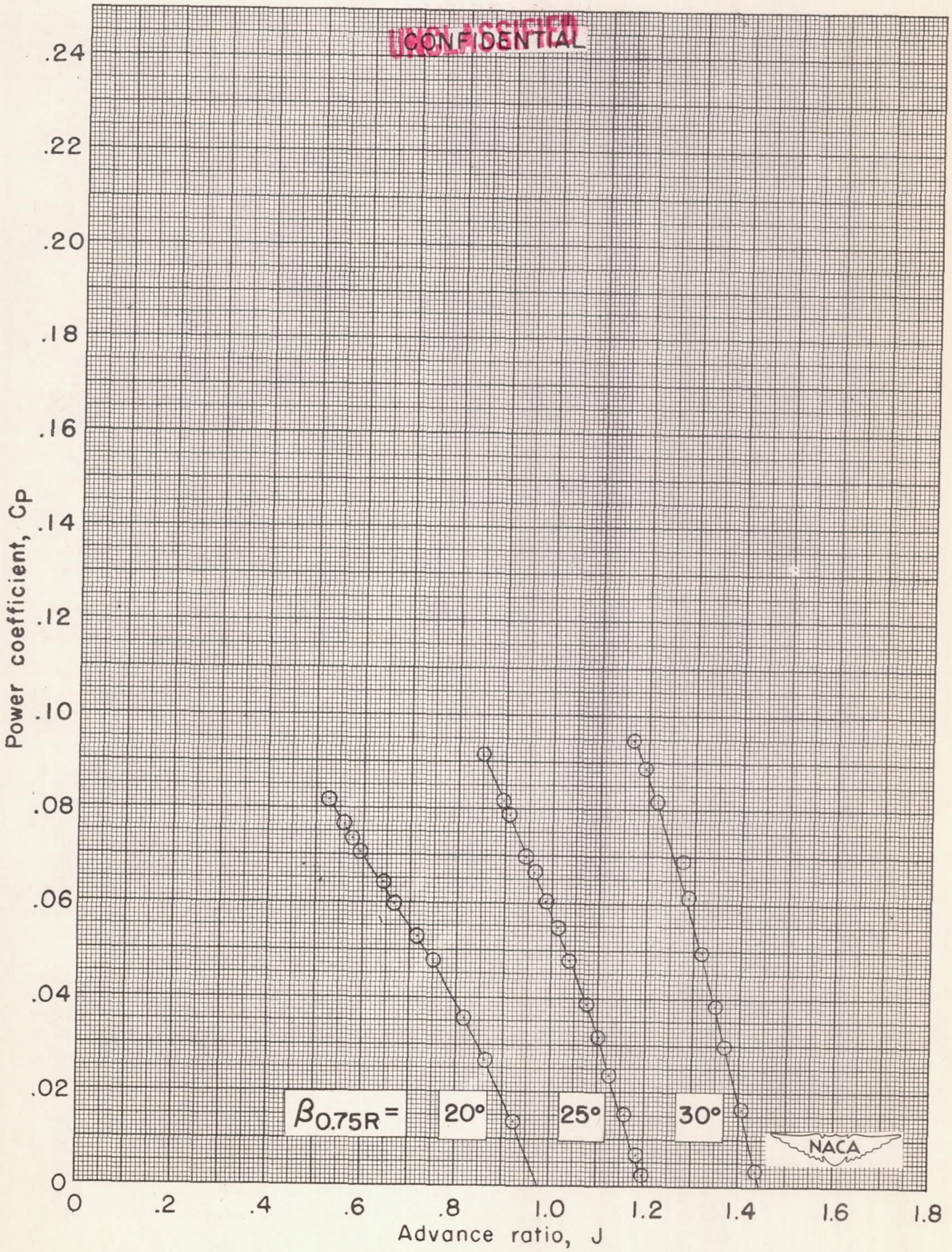
(c) Efficiency.

Figure 12.– Concluded. Rotational speed, 2000 rpm.



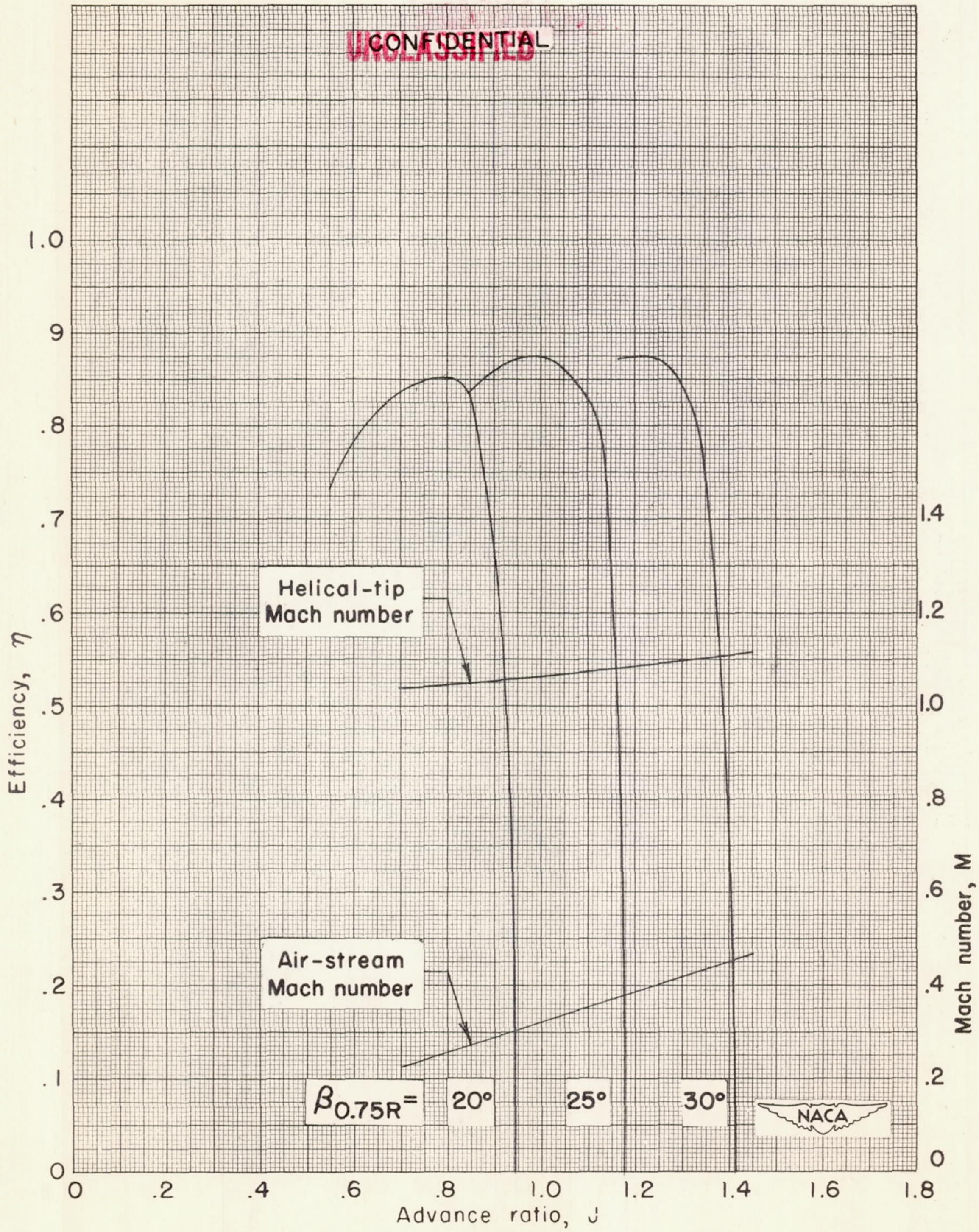
(a) Thrust coefficient.

Figure 13.– Characteristics of NACA 10–(3)(062)–045A propeller. Rotational speed, 2160 rpm.



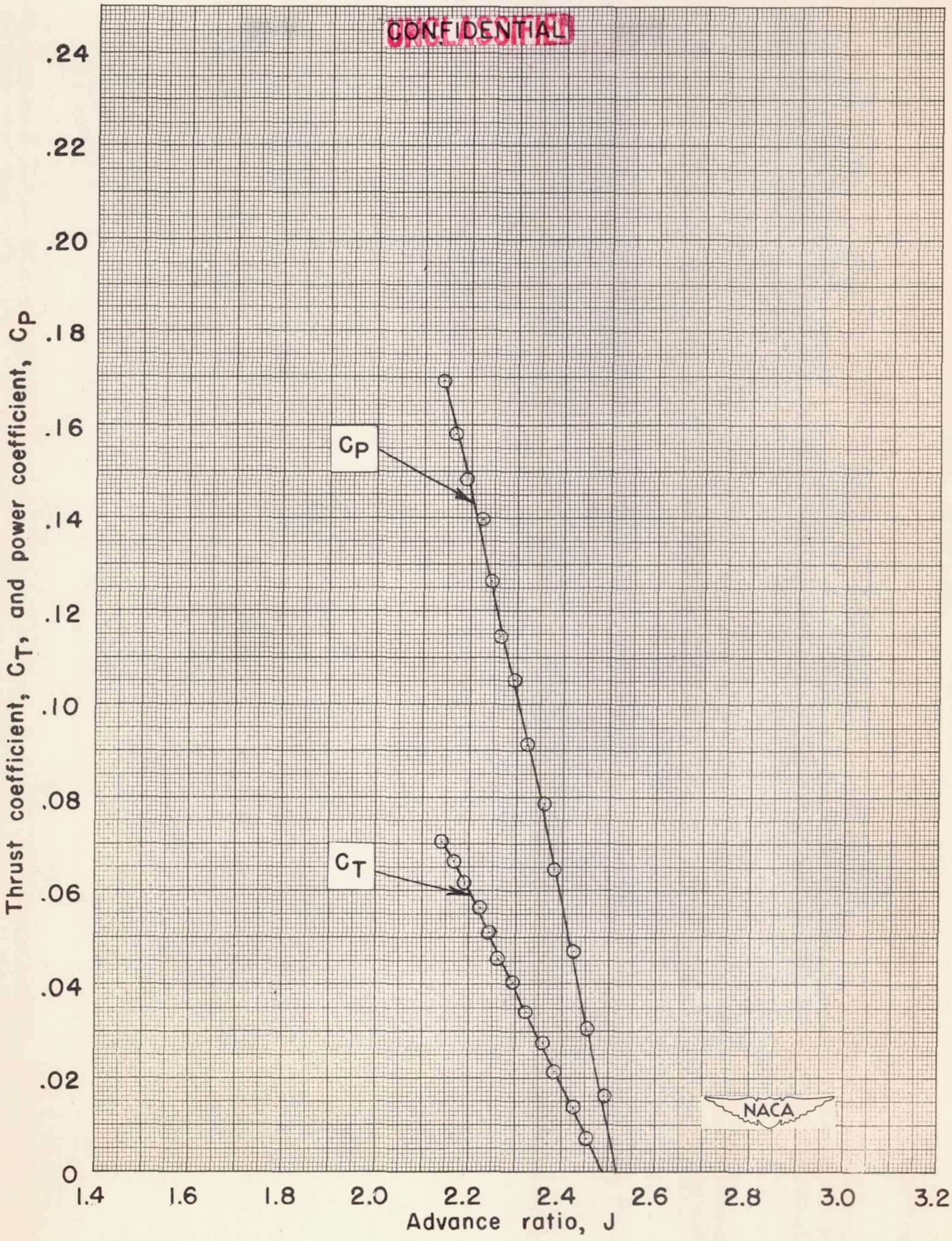
(b) Power coefficient.

Figure 13.– Continued. Rotational speed, 2160 rpm.



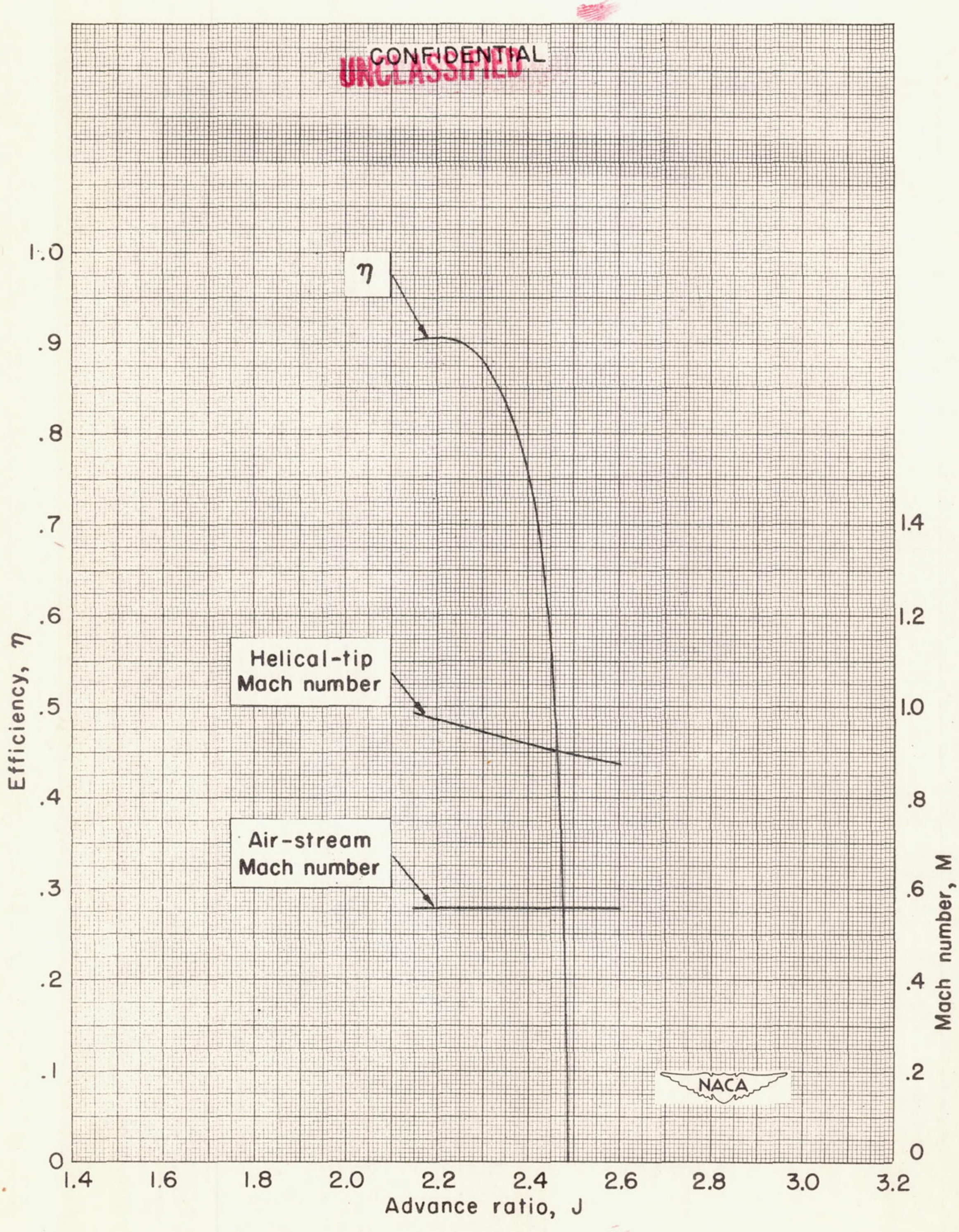
(c) Efficiency.

Figure 13.— Concluded. Rotational speed, 2160 rpm.



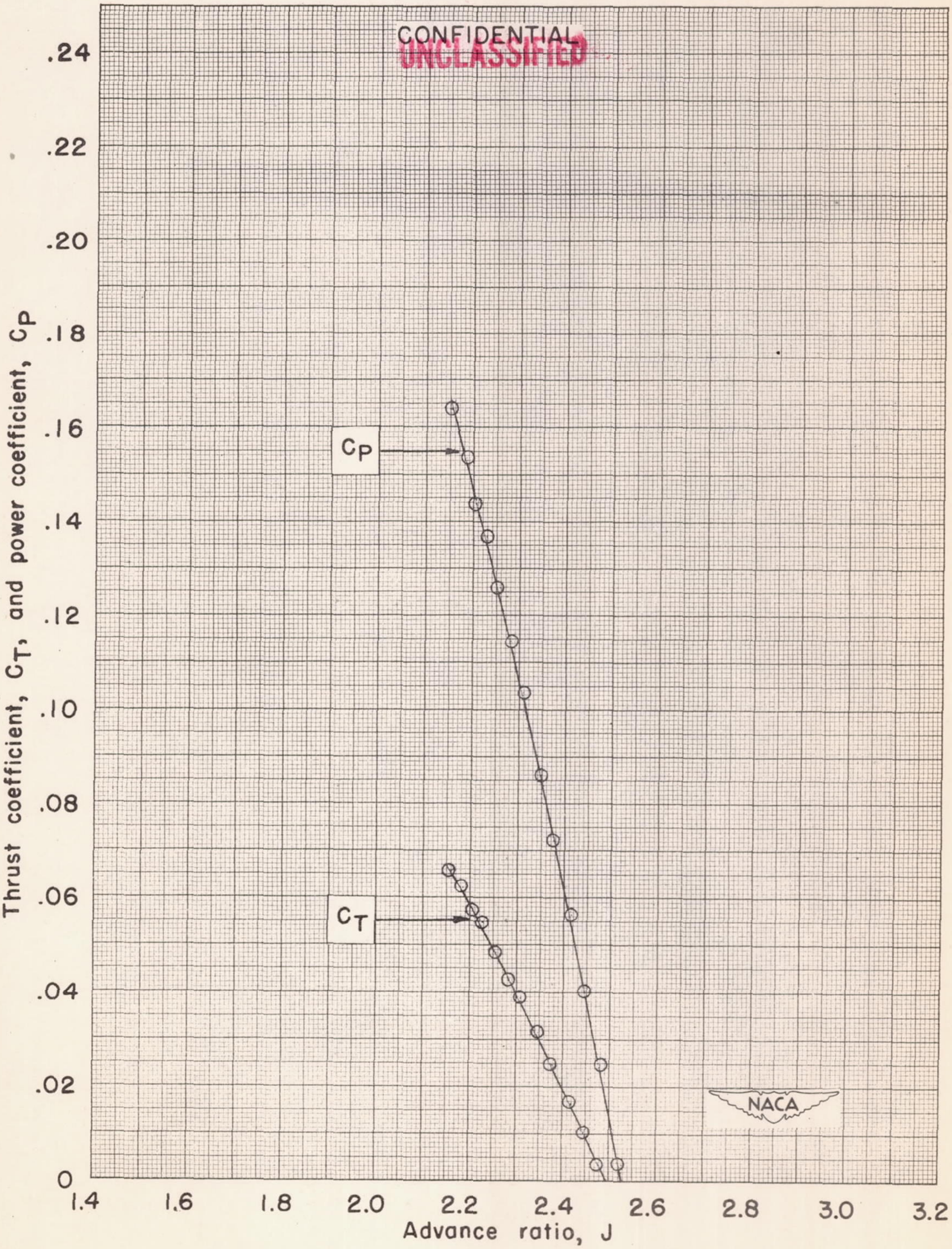
(a) Thrust and power coefficients.

Figure 14.- Characteristics of NACA 10-(3)(062)-045A propeller at high forward speeds. Air-stream Mach number at maximum efficiency, 0.558; $\beta_{0.75R} = 45^{\circ}$.



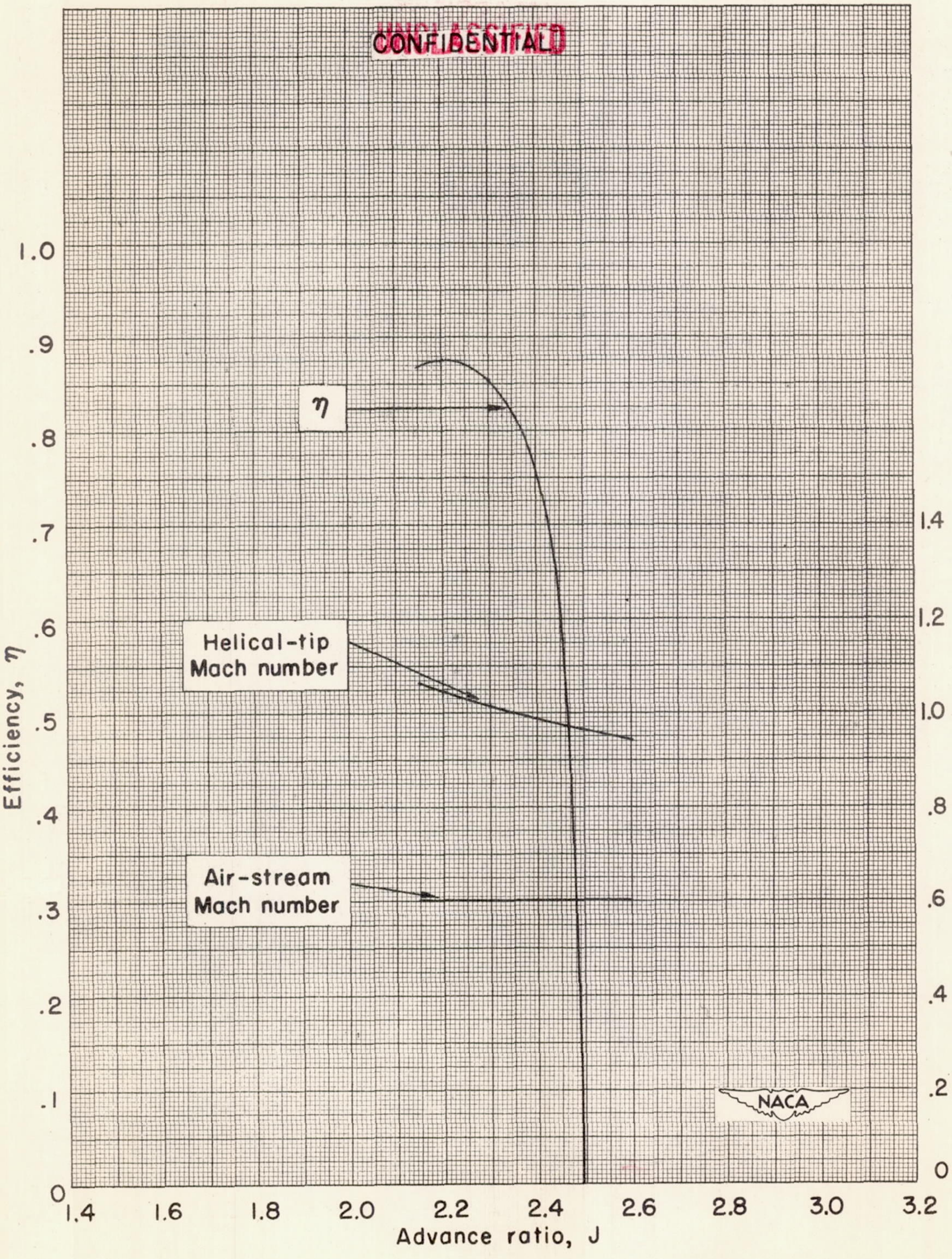
(b) Efficiency.

Figure 14.– Concluded. Air-stream Mach number at maximum efficiency, 0.558.



(a) Thrust and power coefficients.

Figure 15.– Characteristics of NACA 10–(3)(062)–045A propeller at high forward speeds. Air–stream Mach number at maximum efficiency, 0.601 $\beta_{0.75R} = 45^{\circ}$.



(b) Efficiency.

Figure 15.– Concluded. Air-stream Mach number at maximum efficiency, 0.601.

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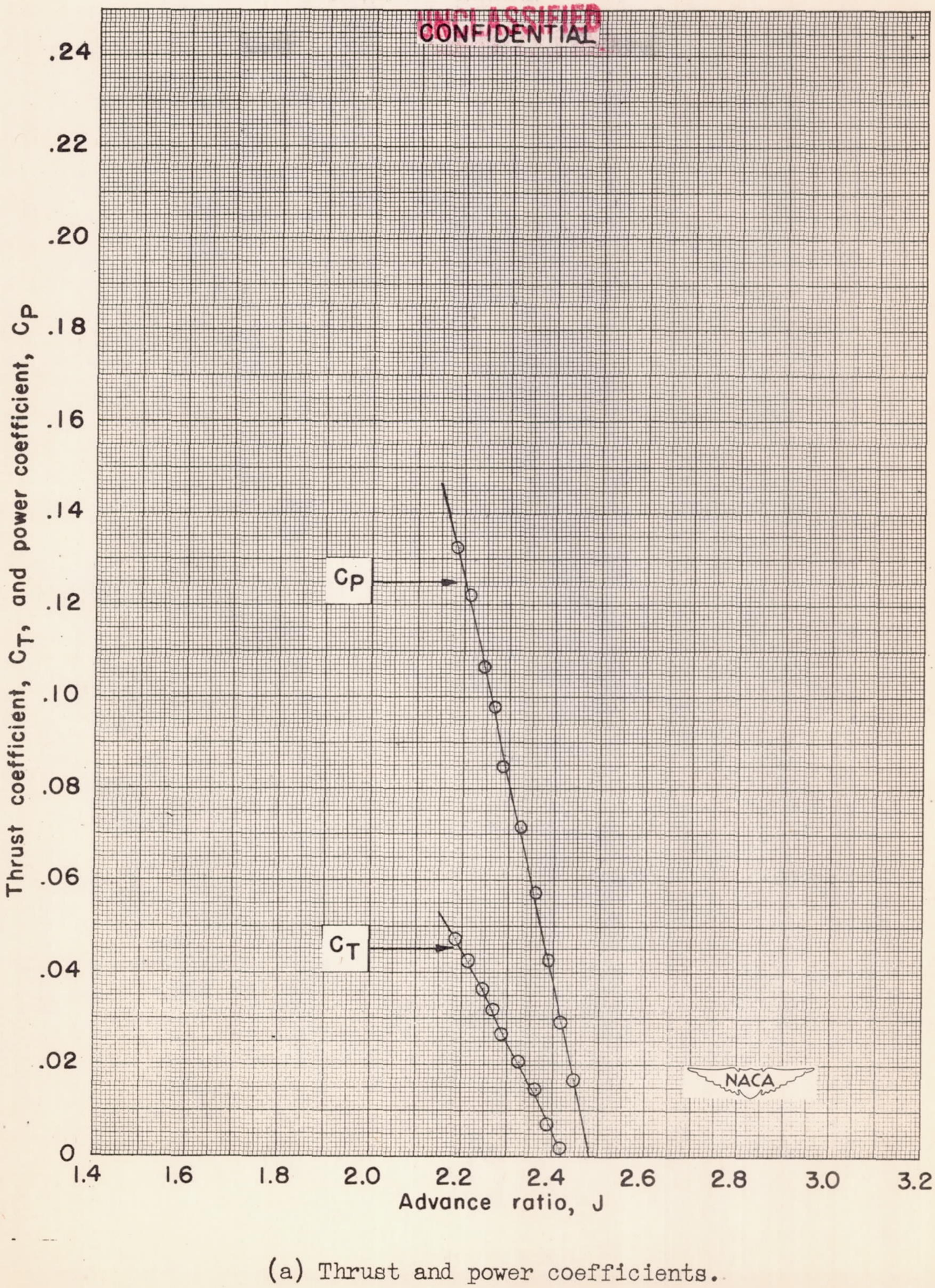

(a) Thrust and power coefficients.

Figure 16.– Characteristics of NACA 10–(3)(062)–045A propeller at high forward speeds. Air-stream Mach number at maximum efficiency, 0.657; $\beta_{0.75R} = 45^{\circ}$.

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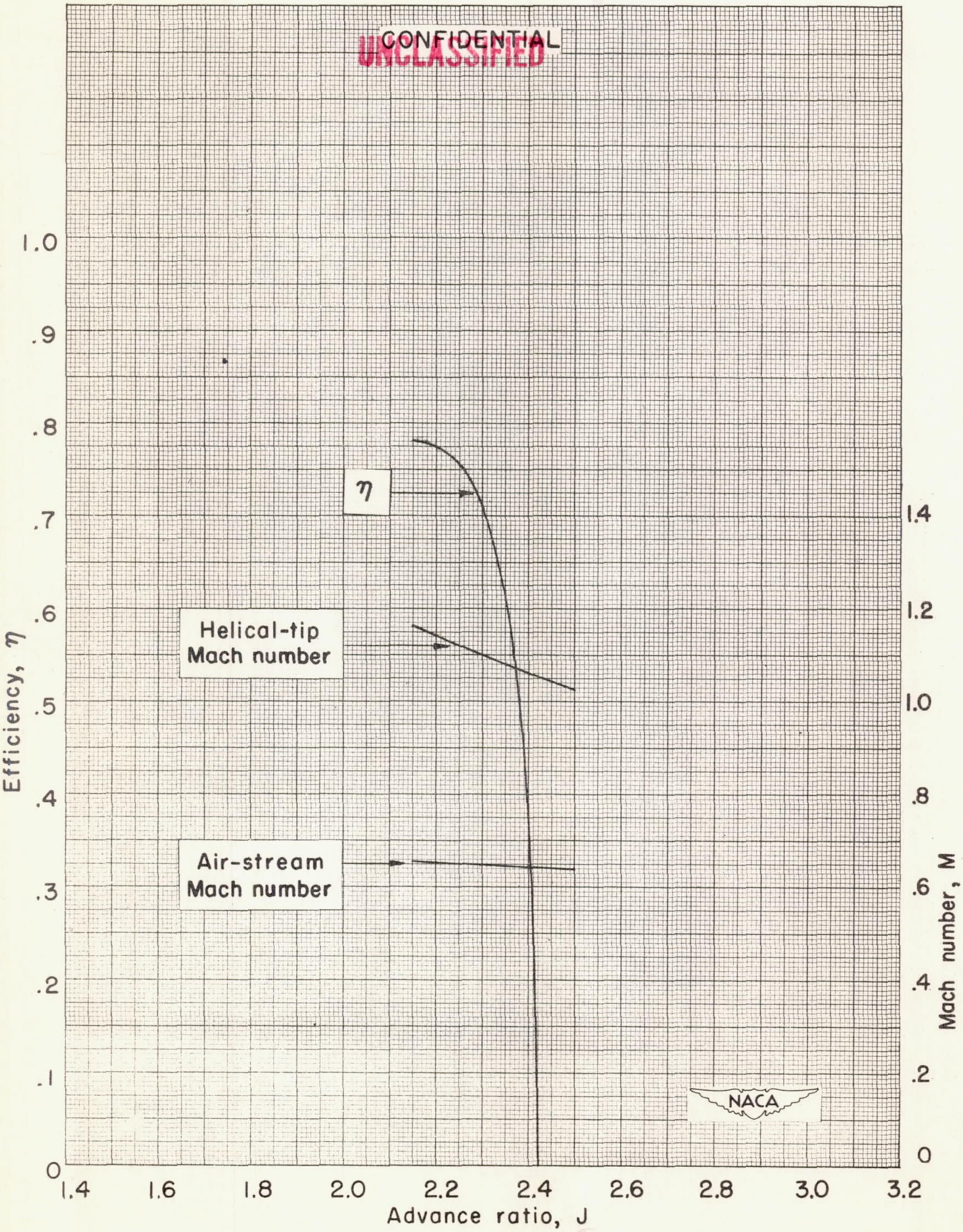
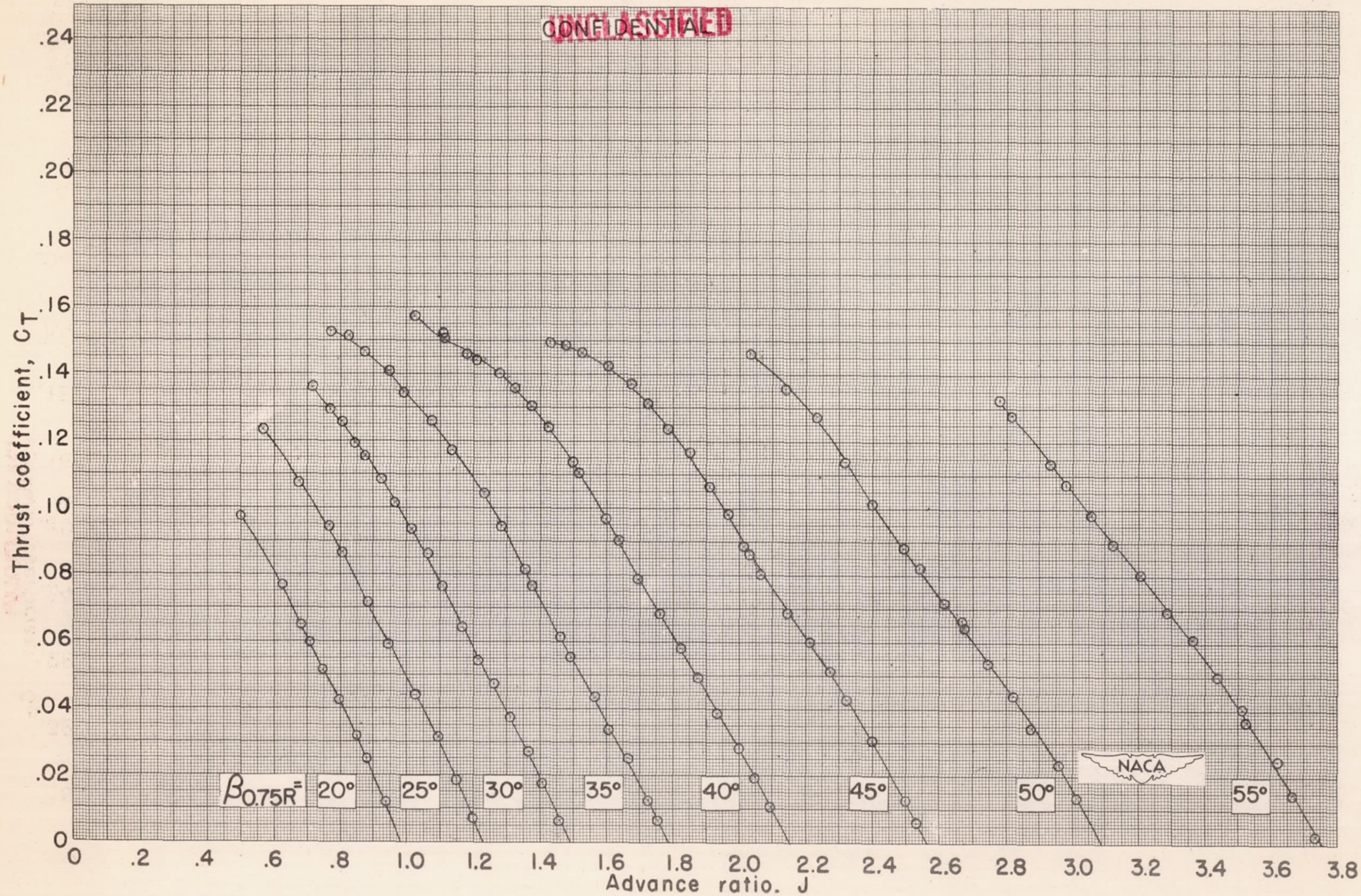


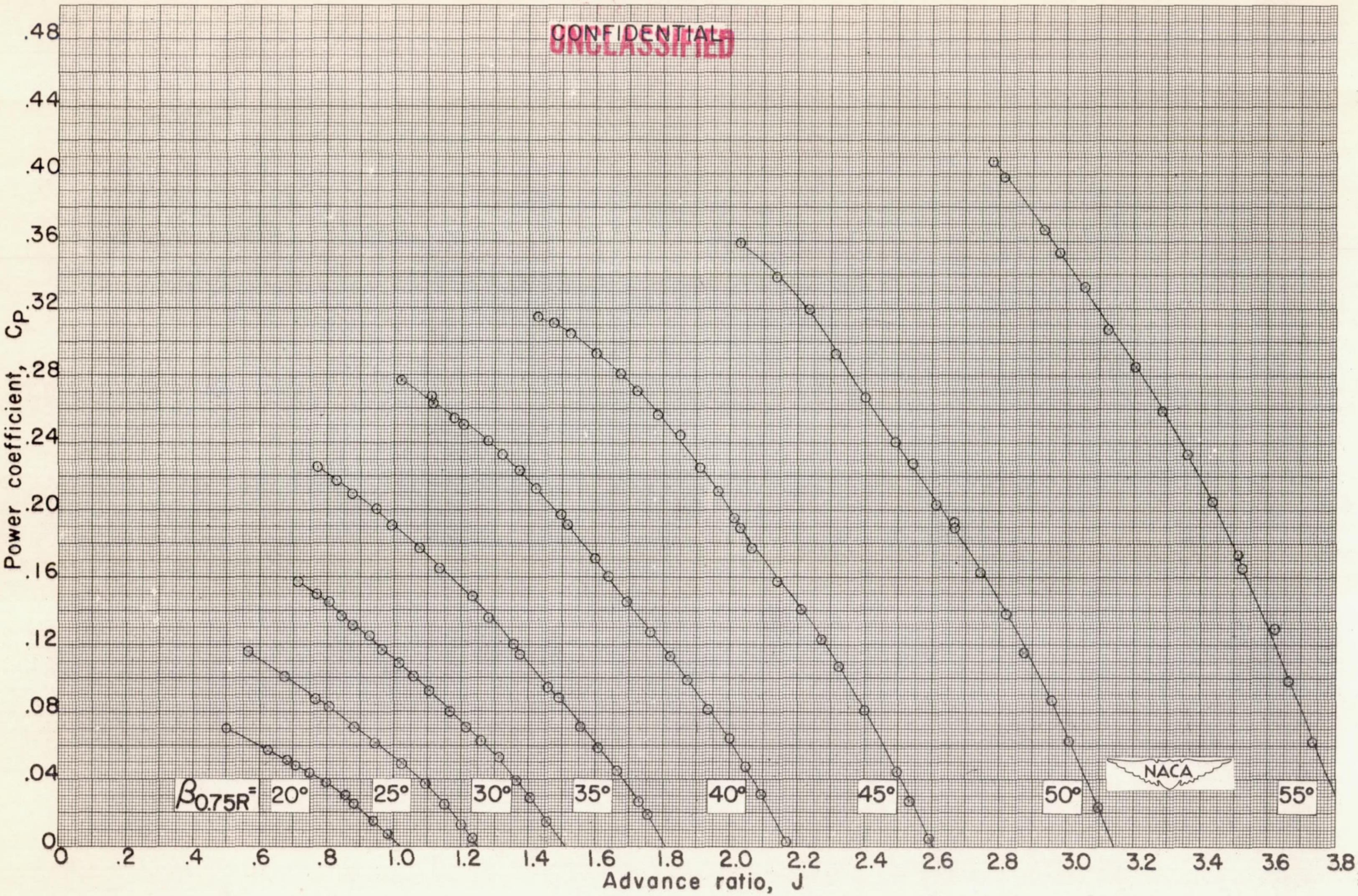
(b) Efficiency.

Figure 16.- Concluded. Air-stream Mach number at maximum efficiency, 0.657.



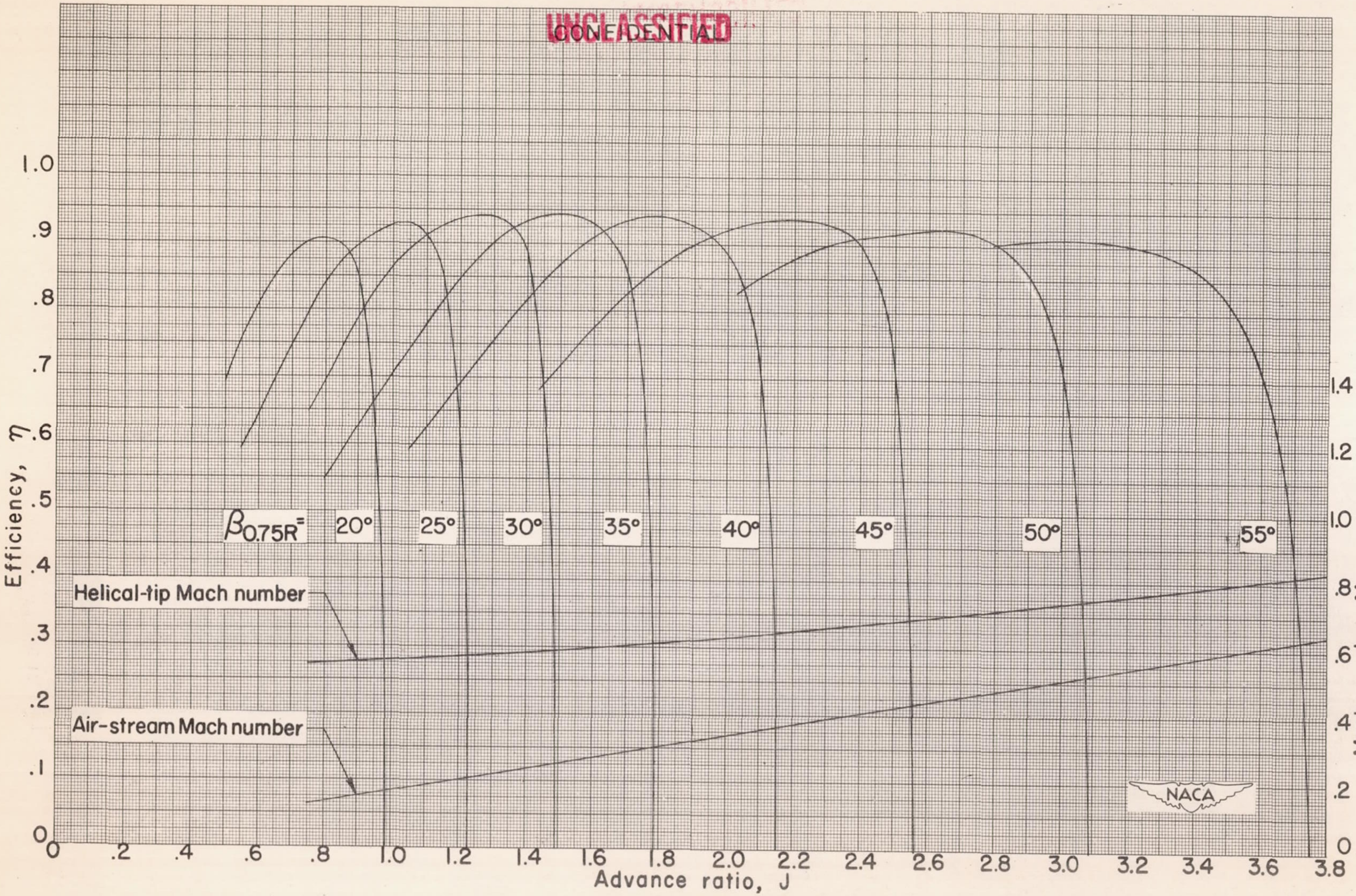
(a) Thrust coefficient.

Figure 17.- Characteristics of NACA 10-(3)(05)-045 propeller. Rotational speed, 1140 rpm.



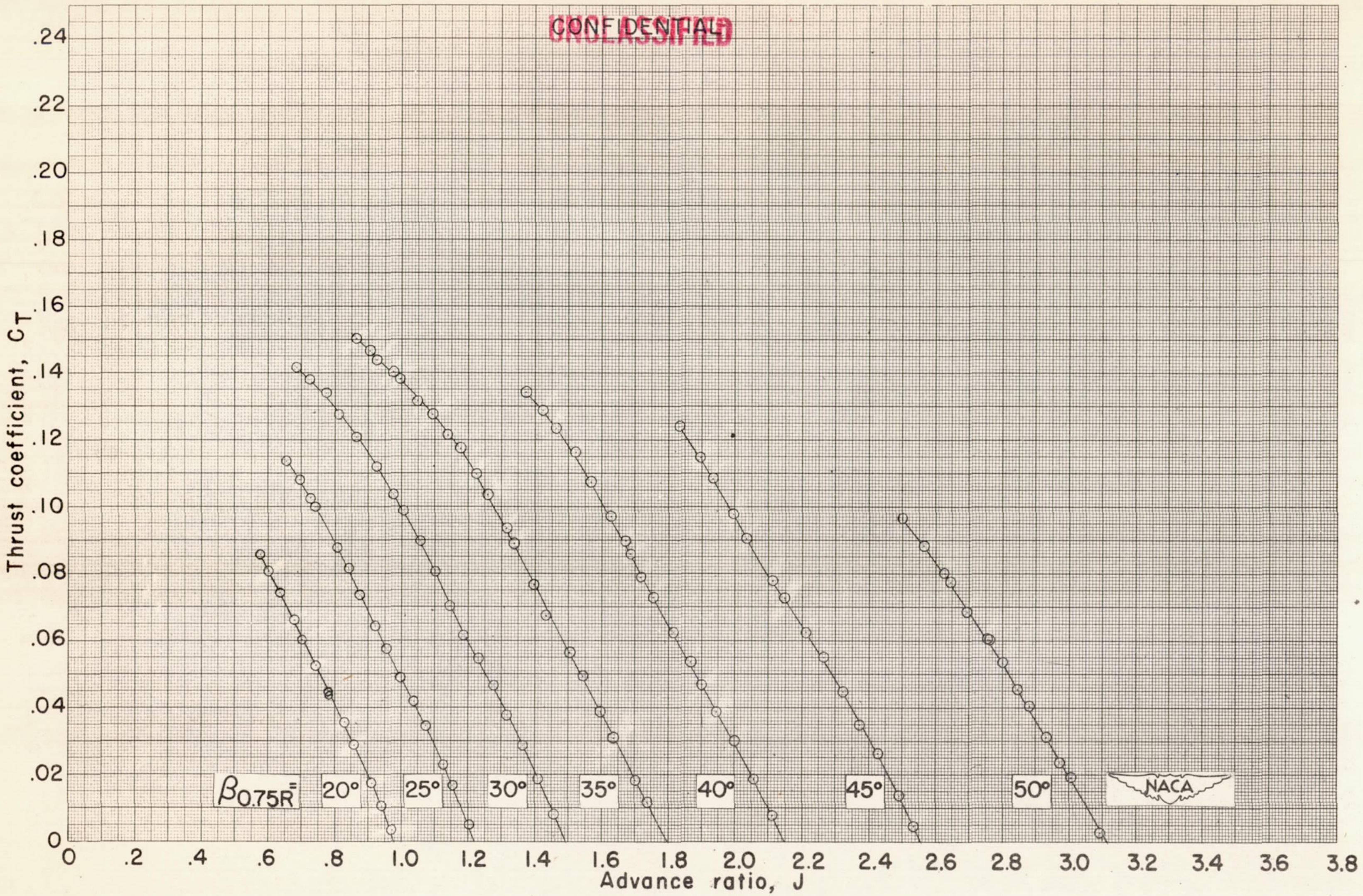
(b) Power coefficient.

Figure 17.- Continued. Rotational speed, 1140 rpm.



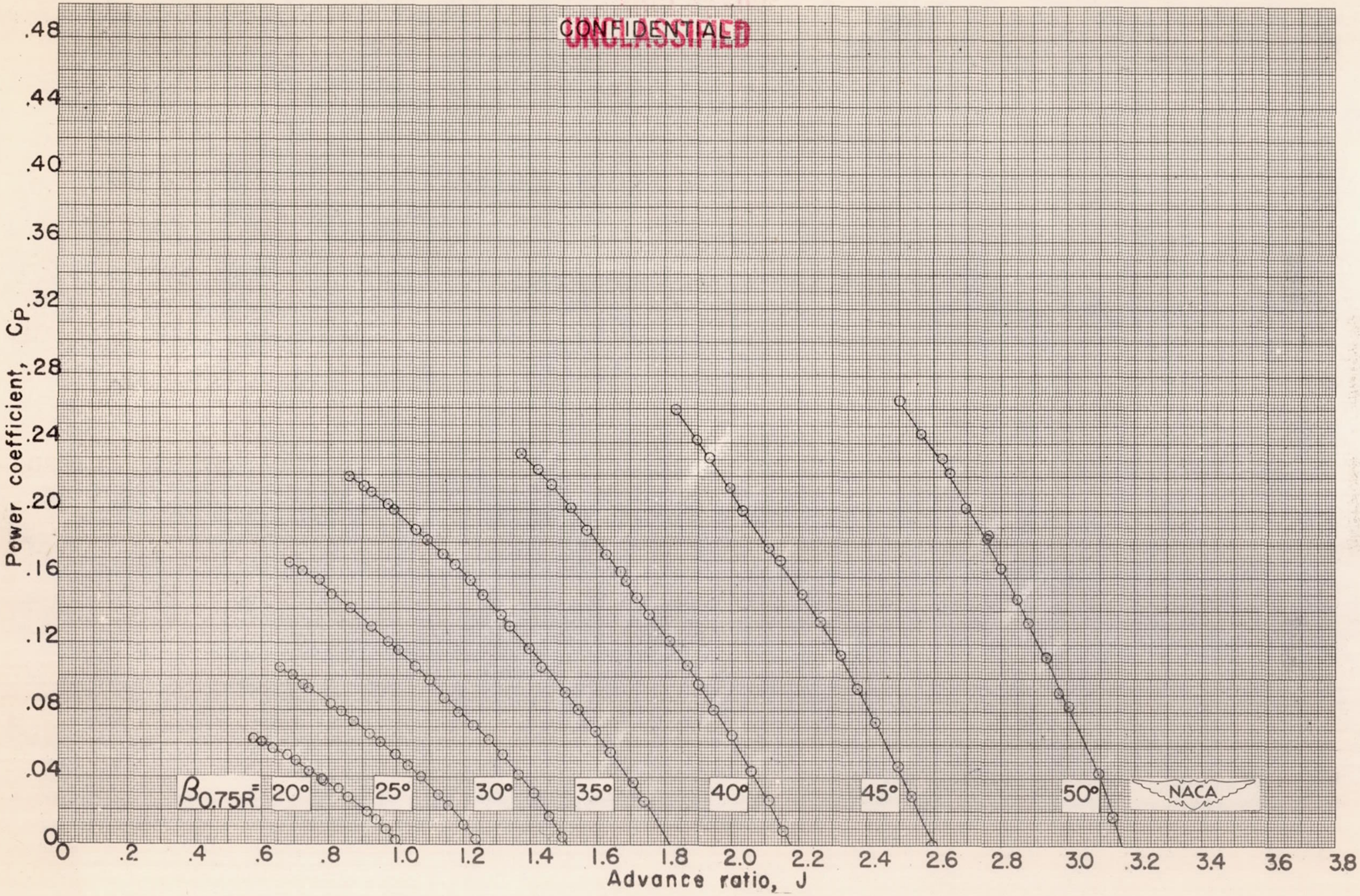
(c) Efficiency.

Figure 17.– Concluded. Rotational speed, 1140 rpm.



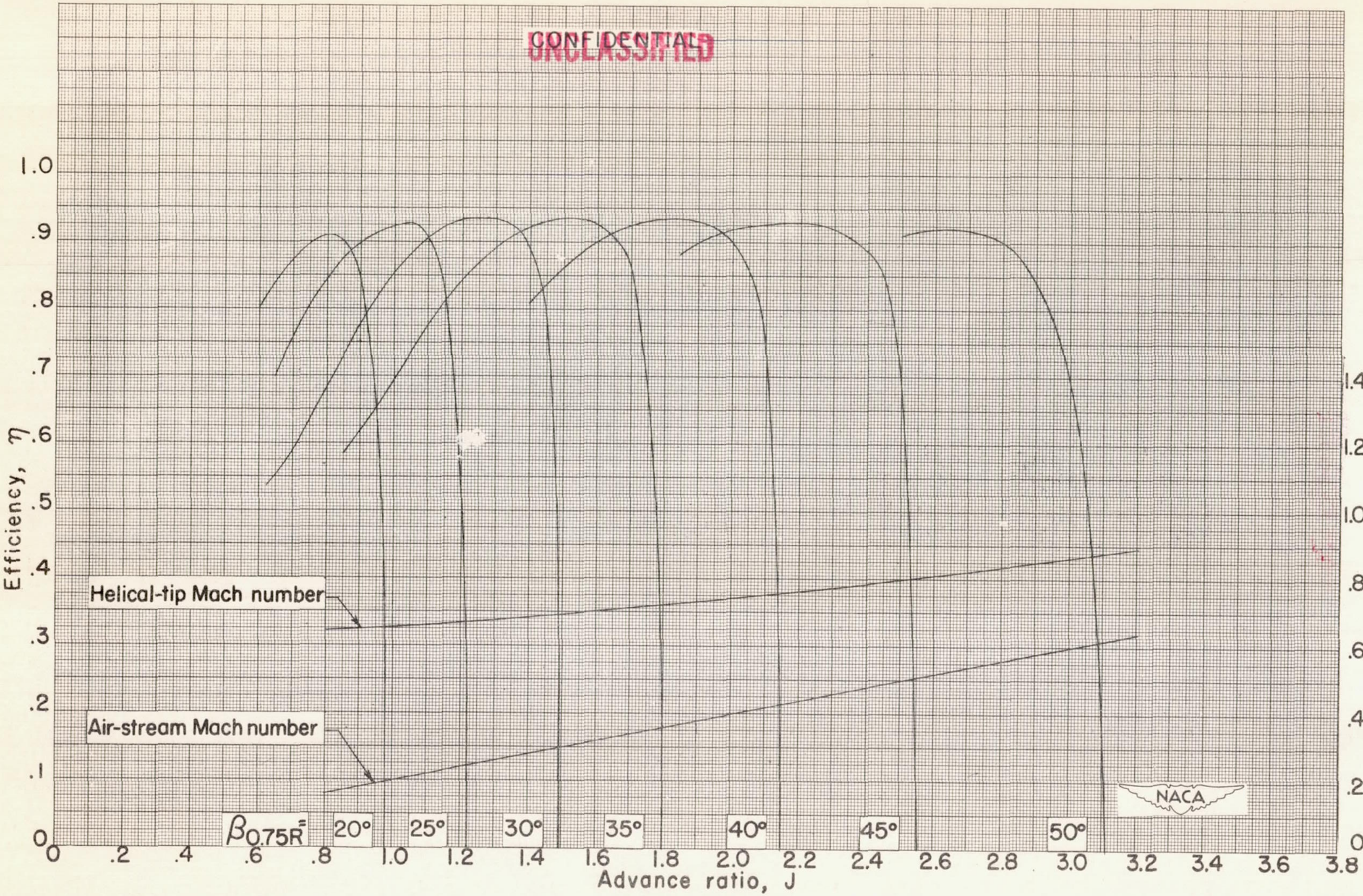
(a) Thrust coefficient.

Figure 18.– Characteristics of NACA 10–(3)(05)–045 propeller. Rotational speed, 1350 rpm.



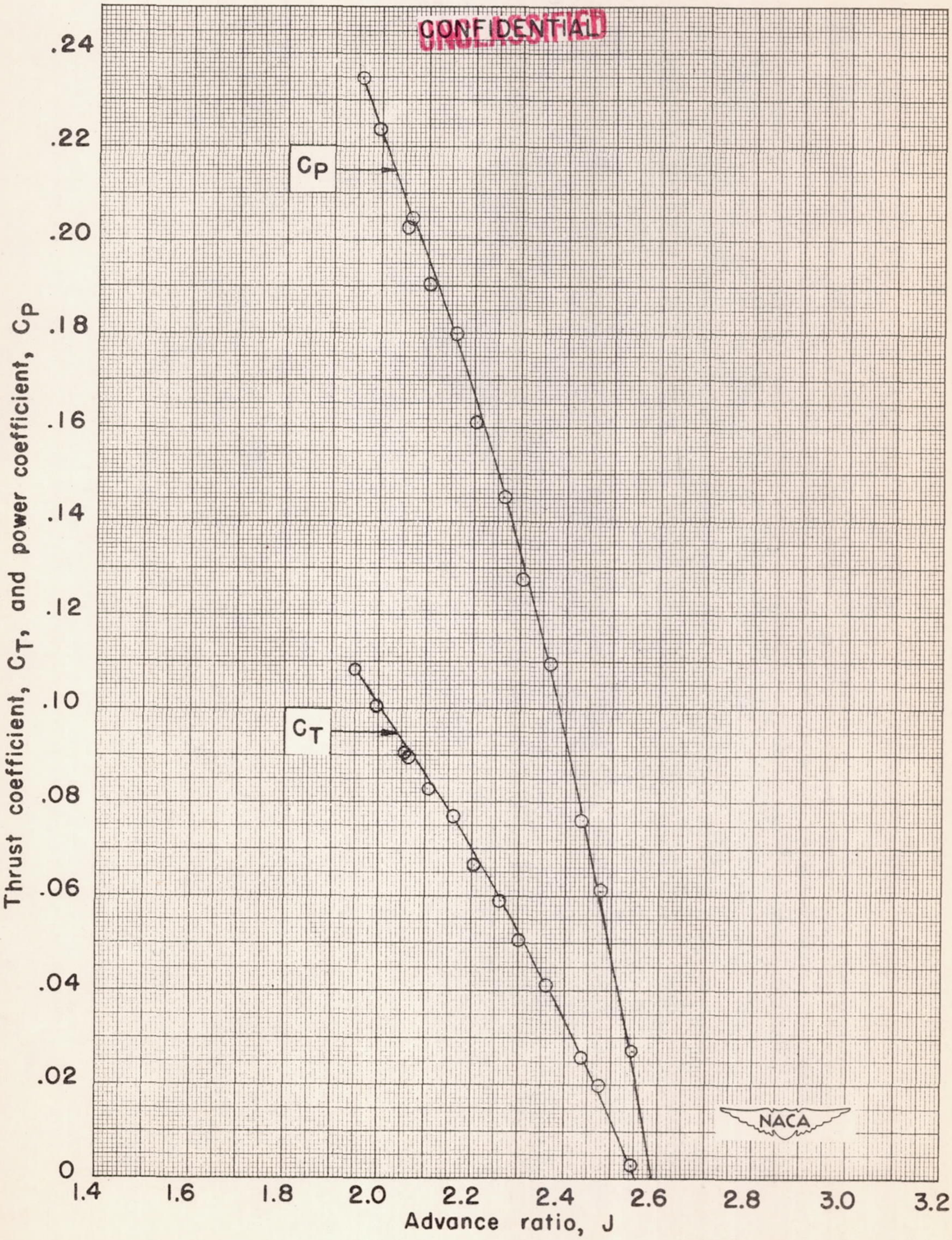
(b) Power coefficient.

Figure 18.- Continued. Rotational speed, 1350 rpm.



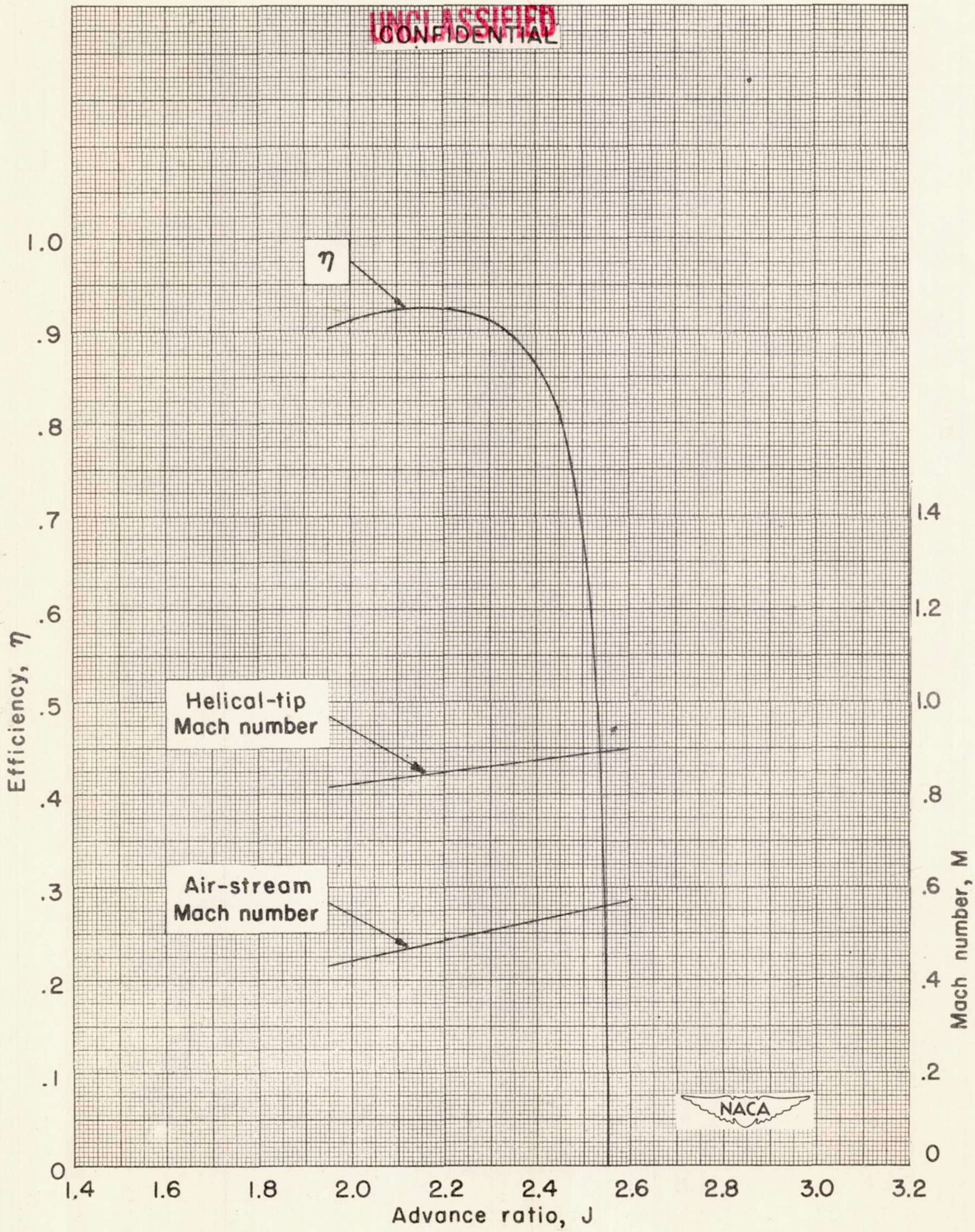
(c) Efficiency.

Figure 18.– Concluded. Rotational speed, 1350 rpm.



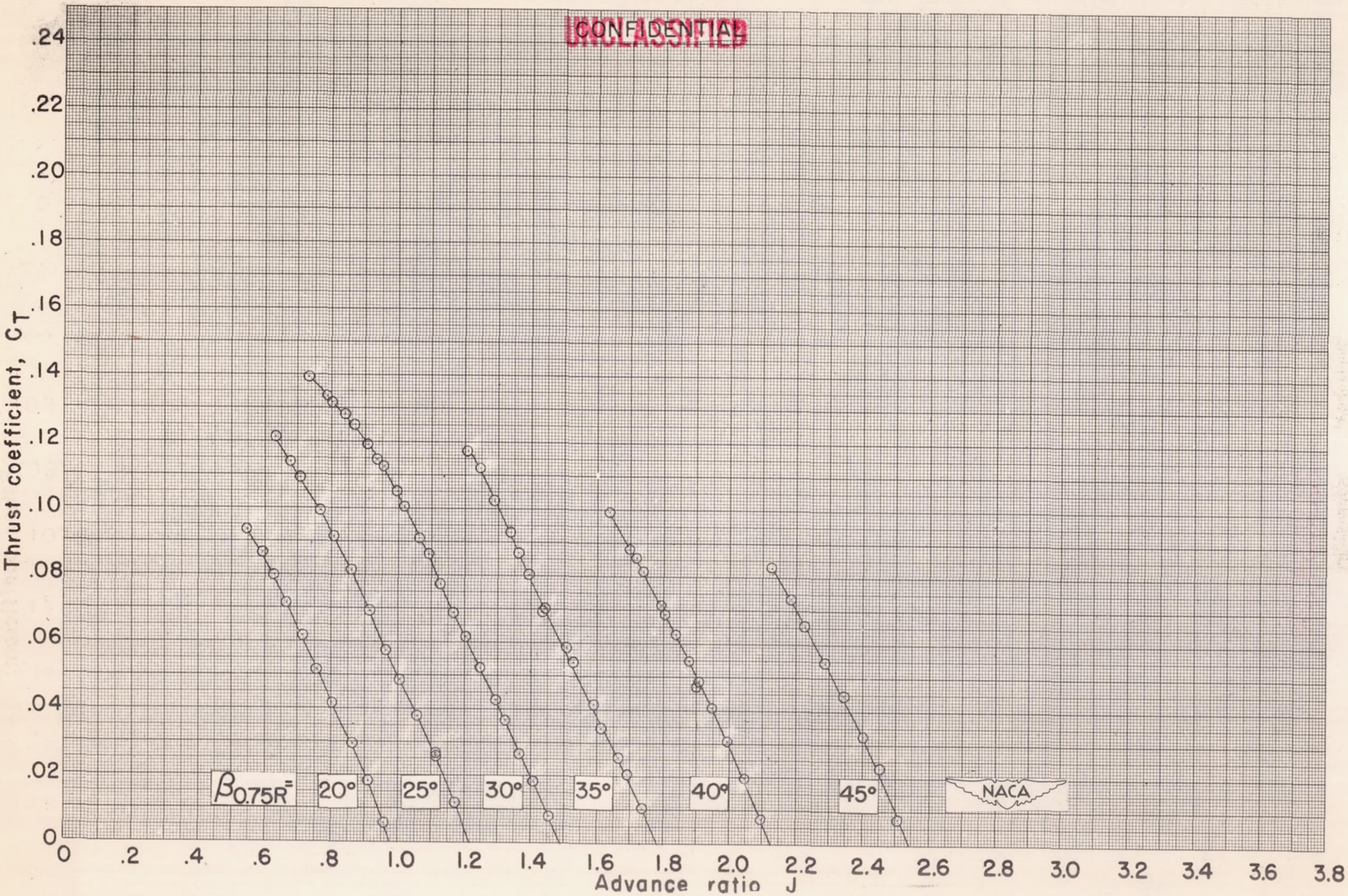
(a) Thrust and power coefficients.

Figure 19.- Characteristics of NACA 10-(3)(05)-045 propeller. Rotational speed, 1500 rpm; $\beta_{0.75R} = 45^{\circ}$.



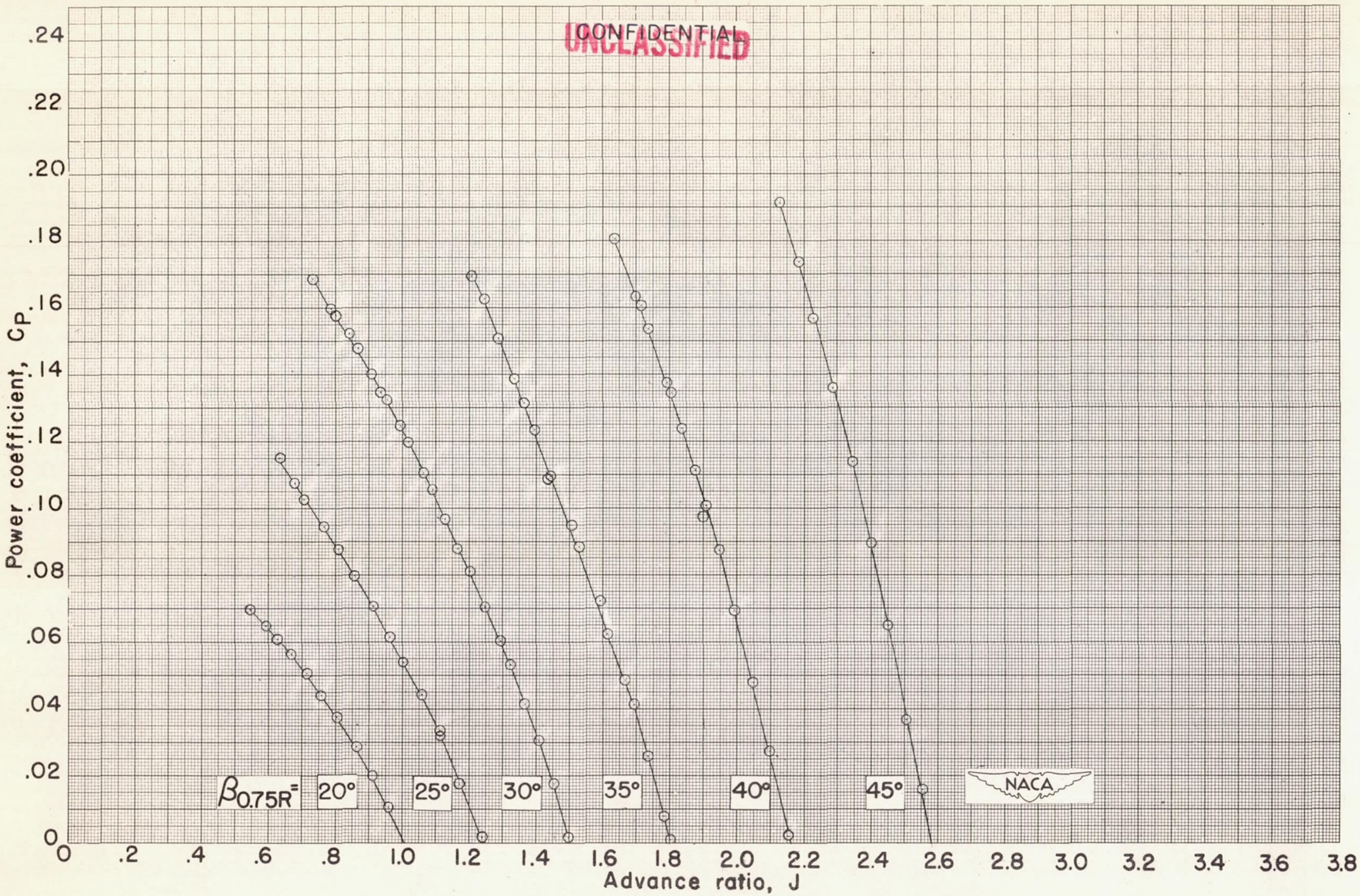
(b) Efficiency.

Figure 19.– Concluded. Rotational speed, 1500 rpm.



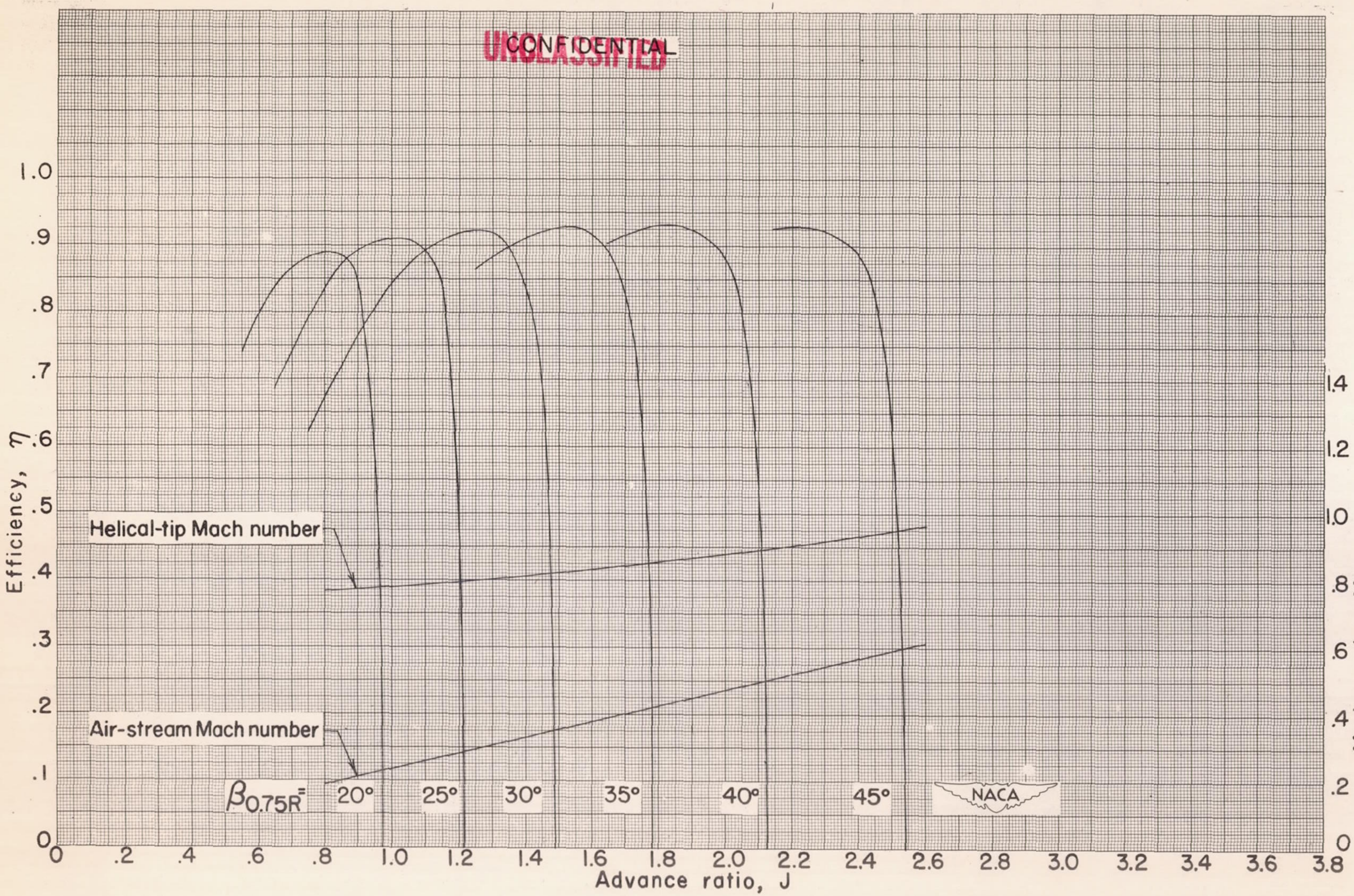
(a) Thrust coefficient.

Figure 20.- Characteristics of NACA 10-(3)(05)-045 propeller. Rotational speed, 1600 rpm.



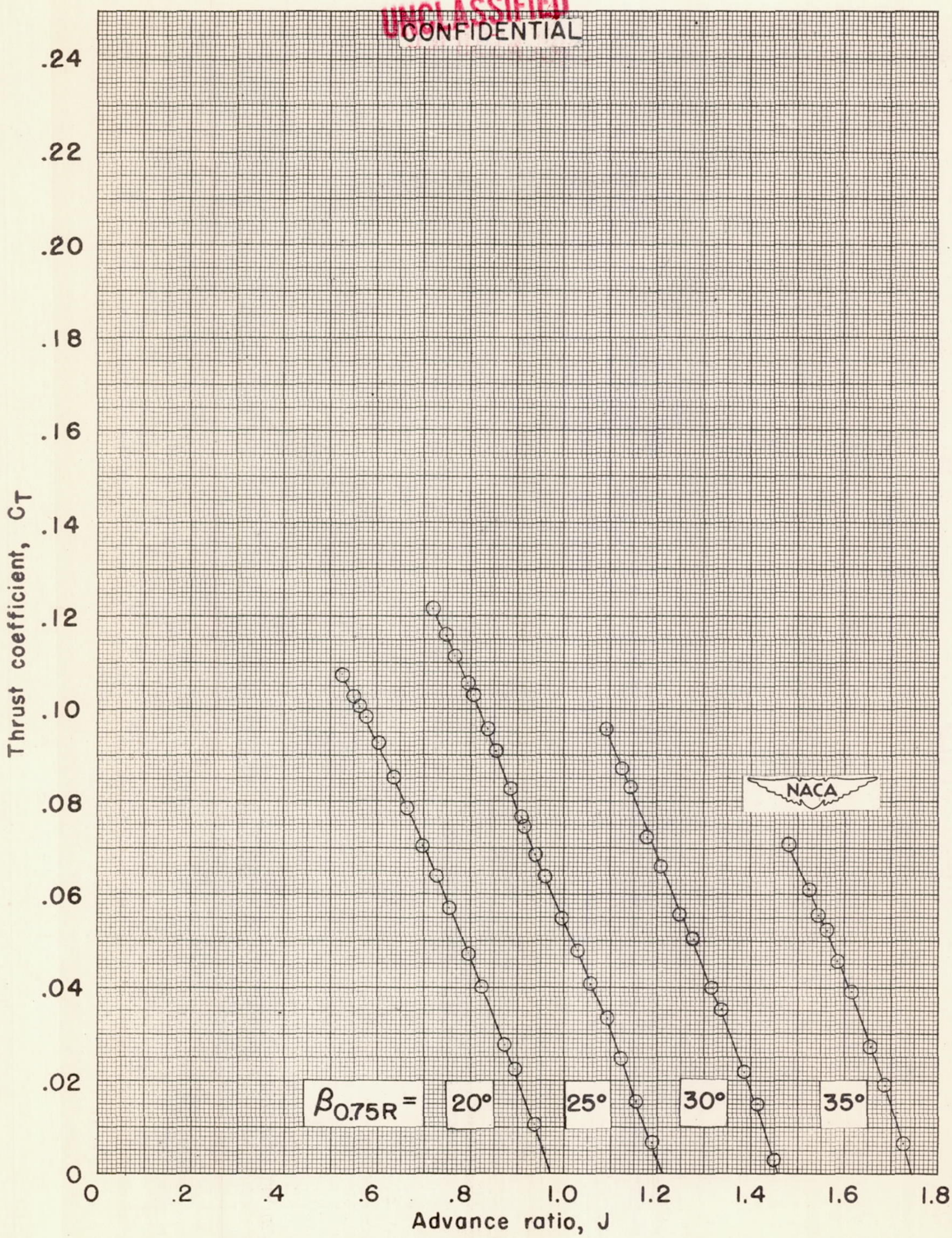
(b) Power coefficient.

Figure 20.– Continued. Rotational speed, 1600 rpm.



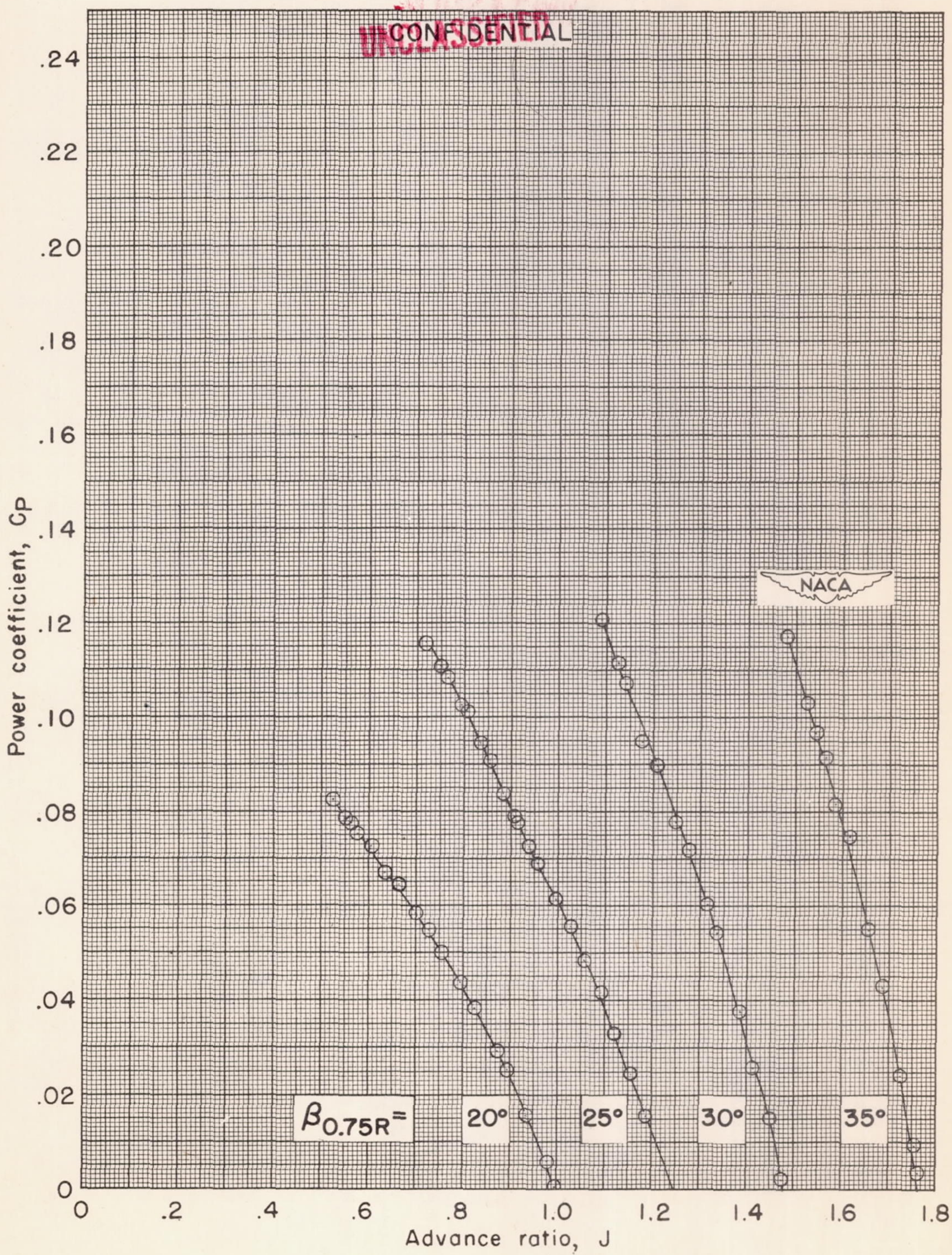
(c) Efficiency.

Figure 20.- Concluded. Rotational speed, 1600 rpm.



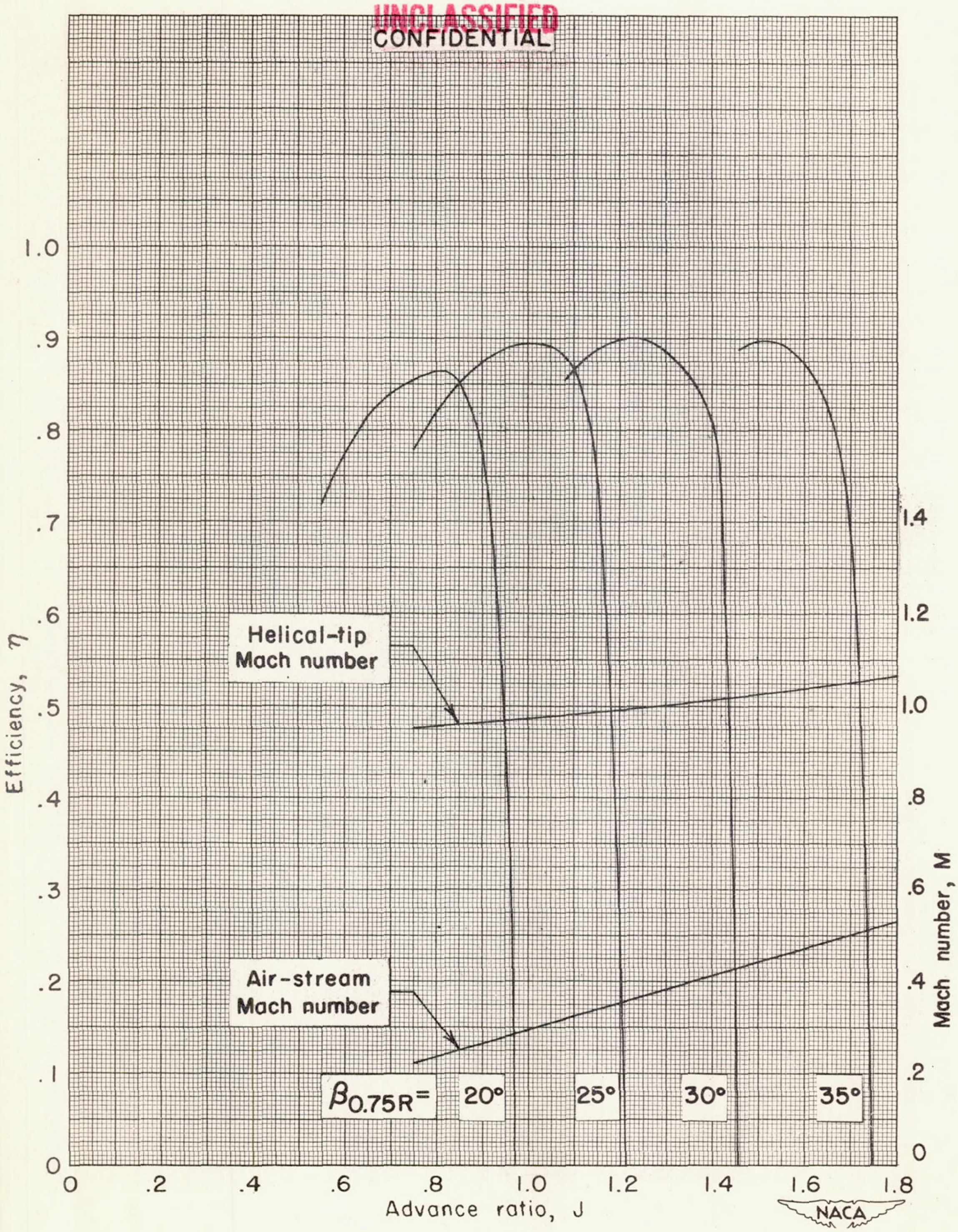
(a) Thrust coefficient.

Figure 21.– Characteristics of NACA 10–(3)(05)–045 propeller. Rotational speed, 2000 rpm.



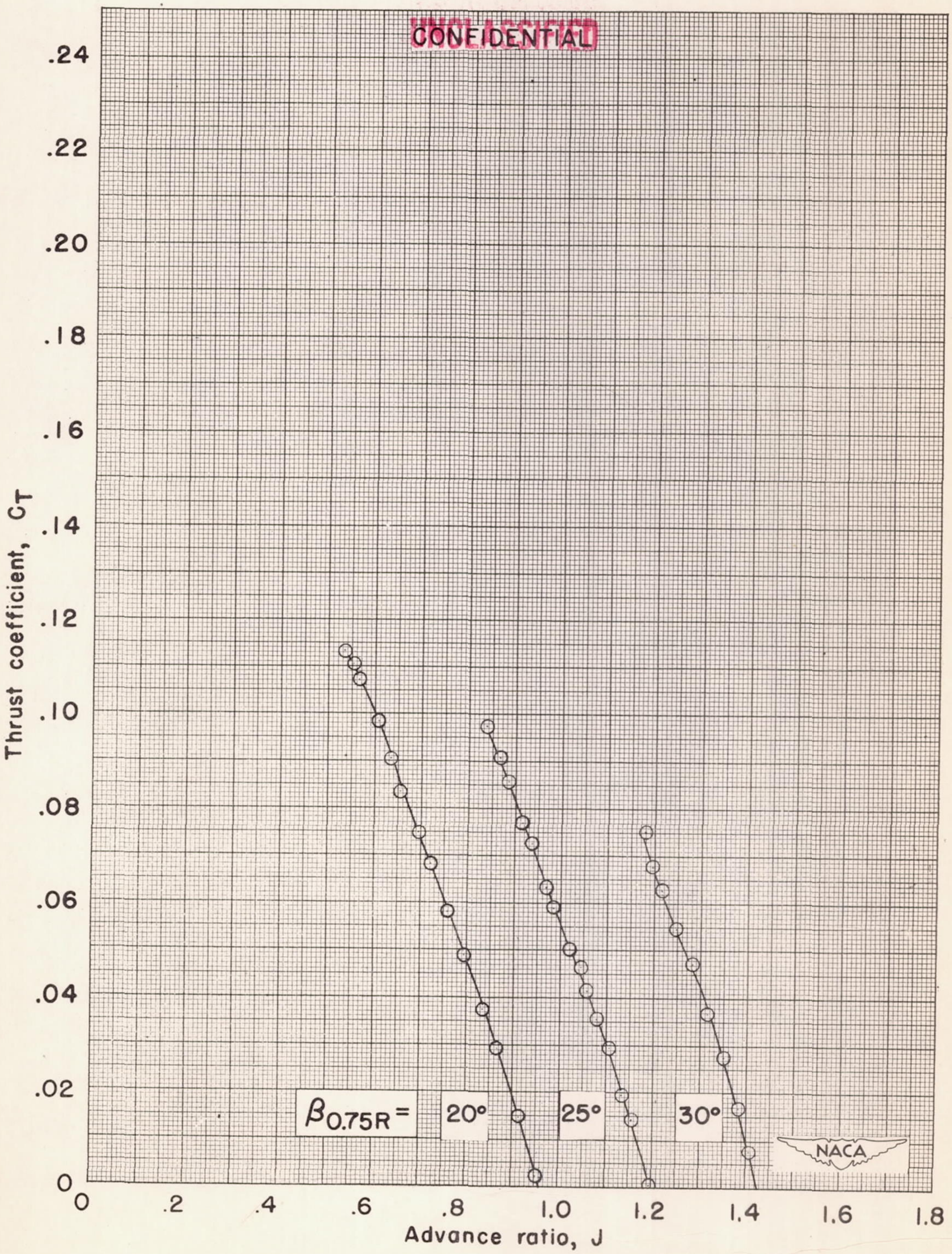
(b) Power coefficient.

Figure 21.- Continued. Rotational speed, 2000 rpm.



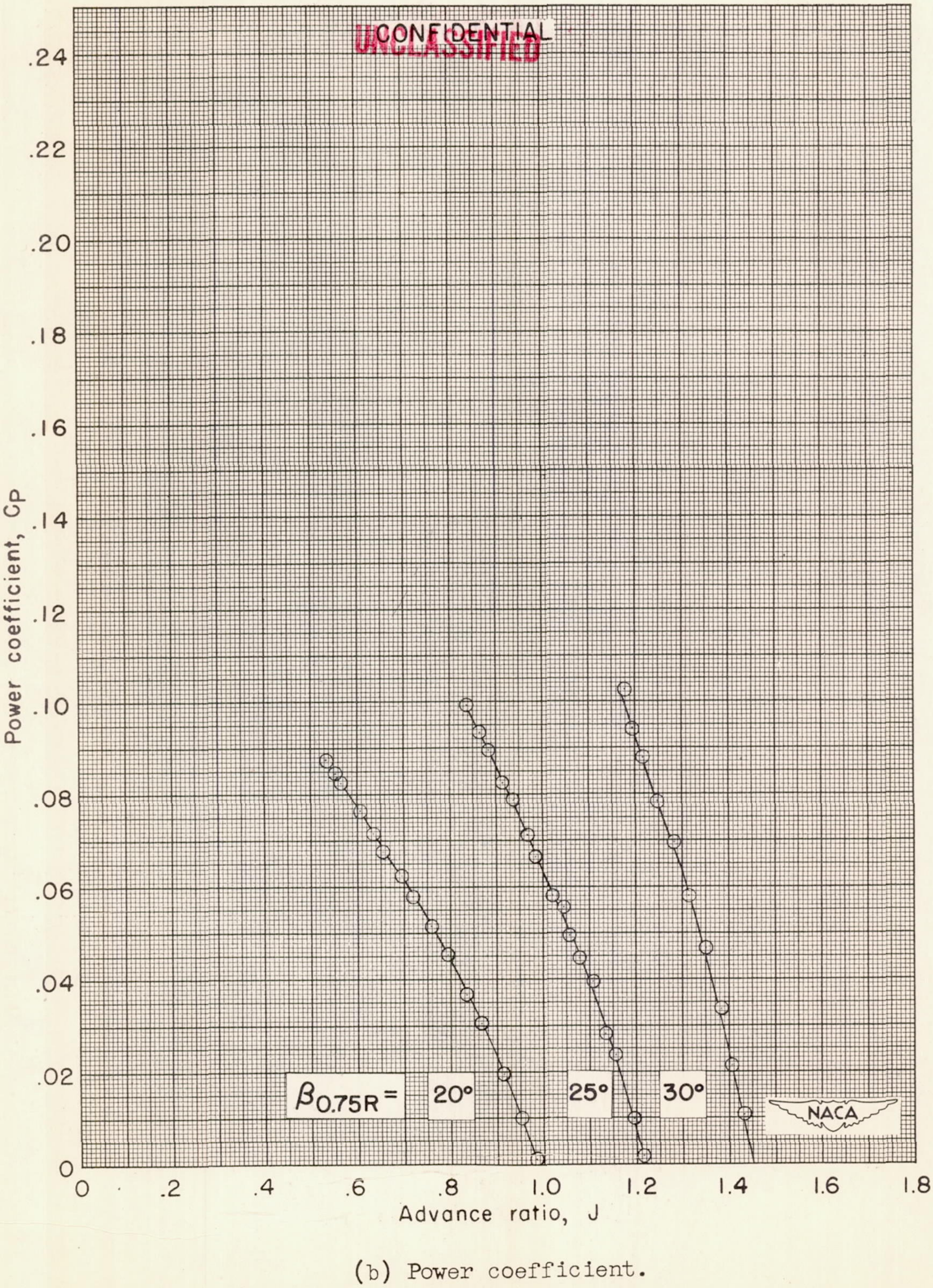
(c) Efficiency.

Figure 21.- Concluded. Rotational speed, 2000 rpm.



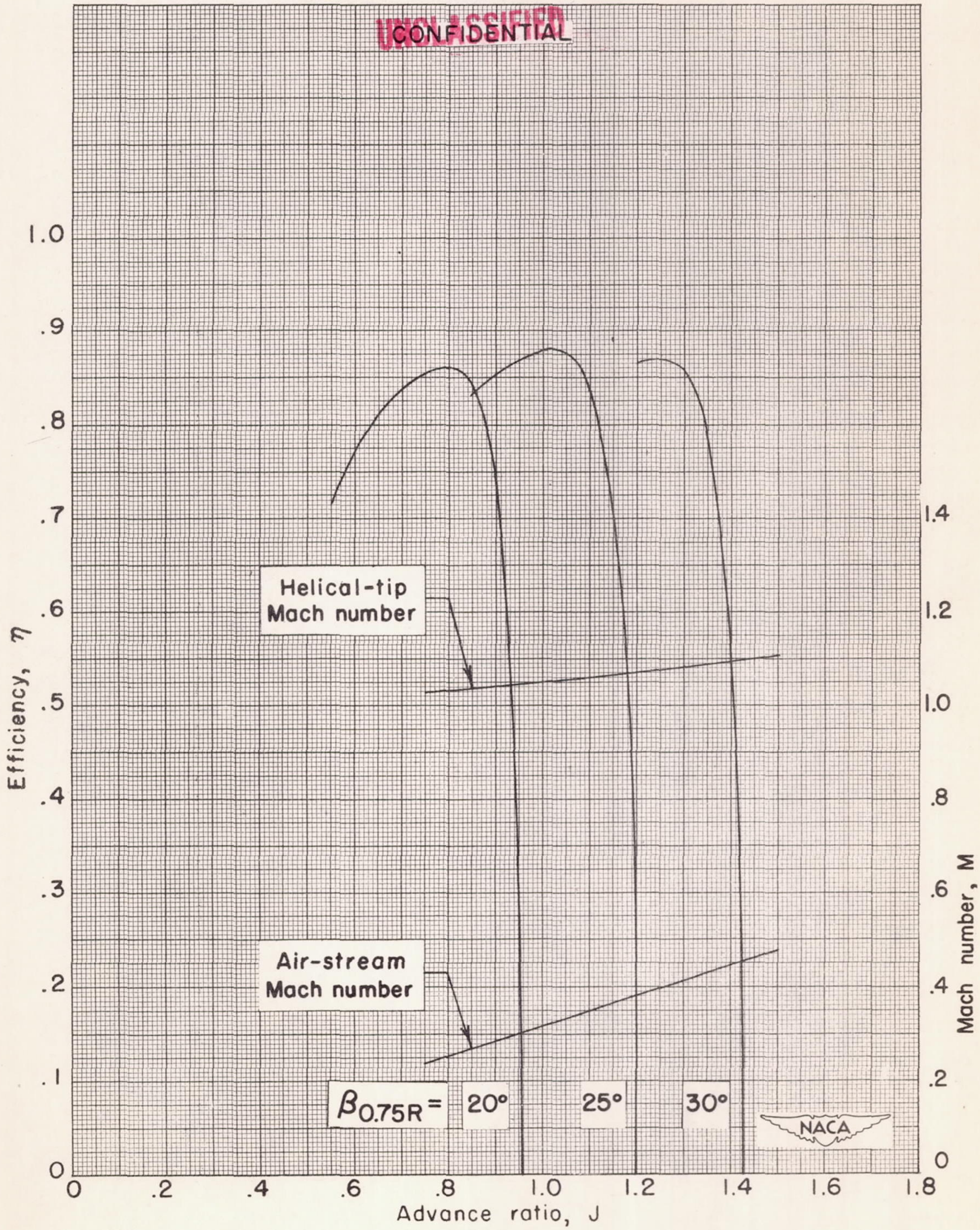
(a) Thrust coefficient.

Figure 22.- Characteristics of NACA 10-(3)(05)-045 propeller. Rotational speed, 2160 rpm.



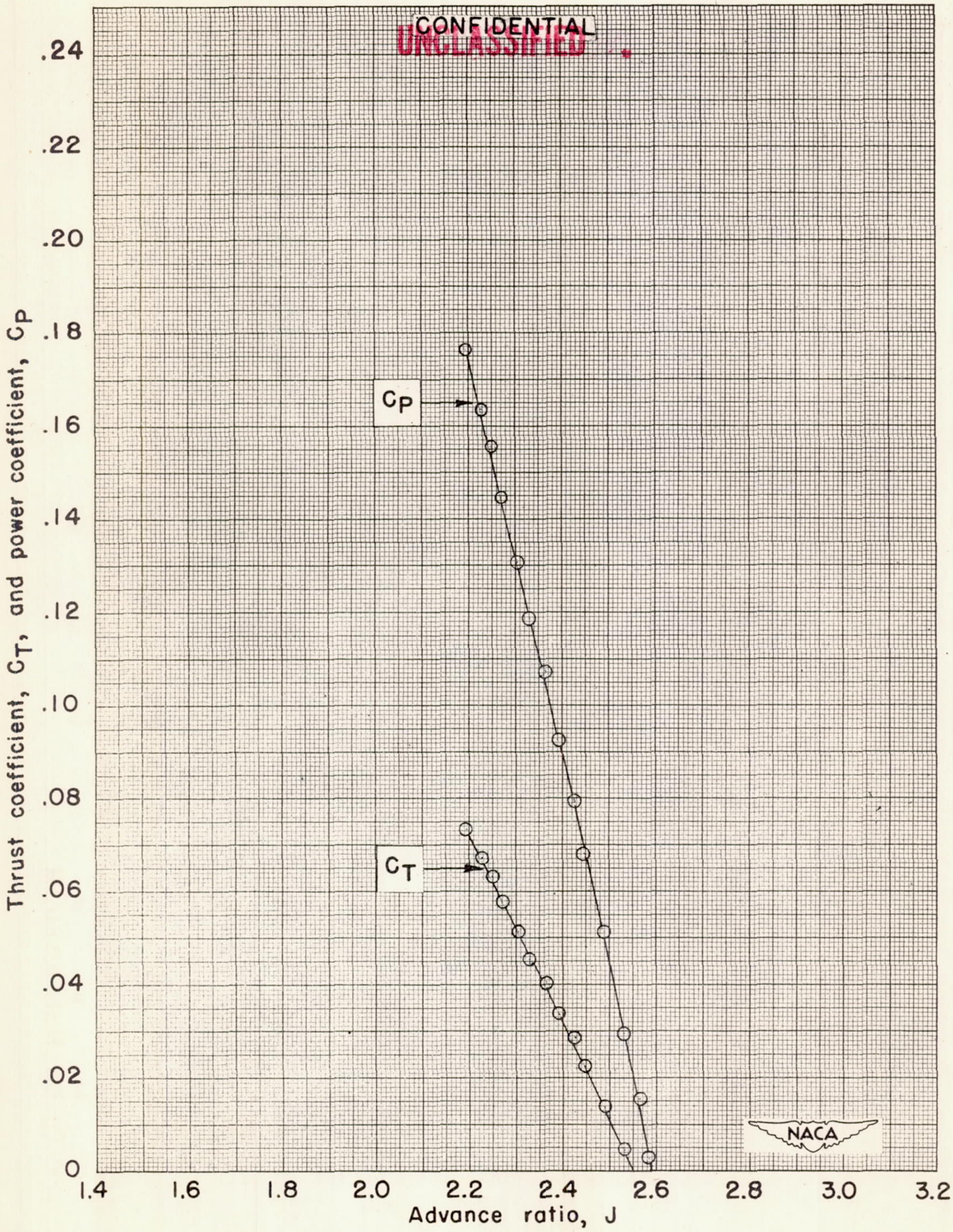
(b) Power coefficient.

Figure 22.– Continued. Rotational speed, 2160 rpm.



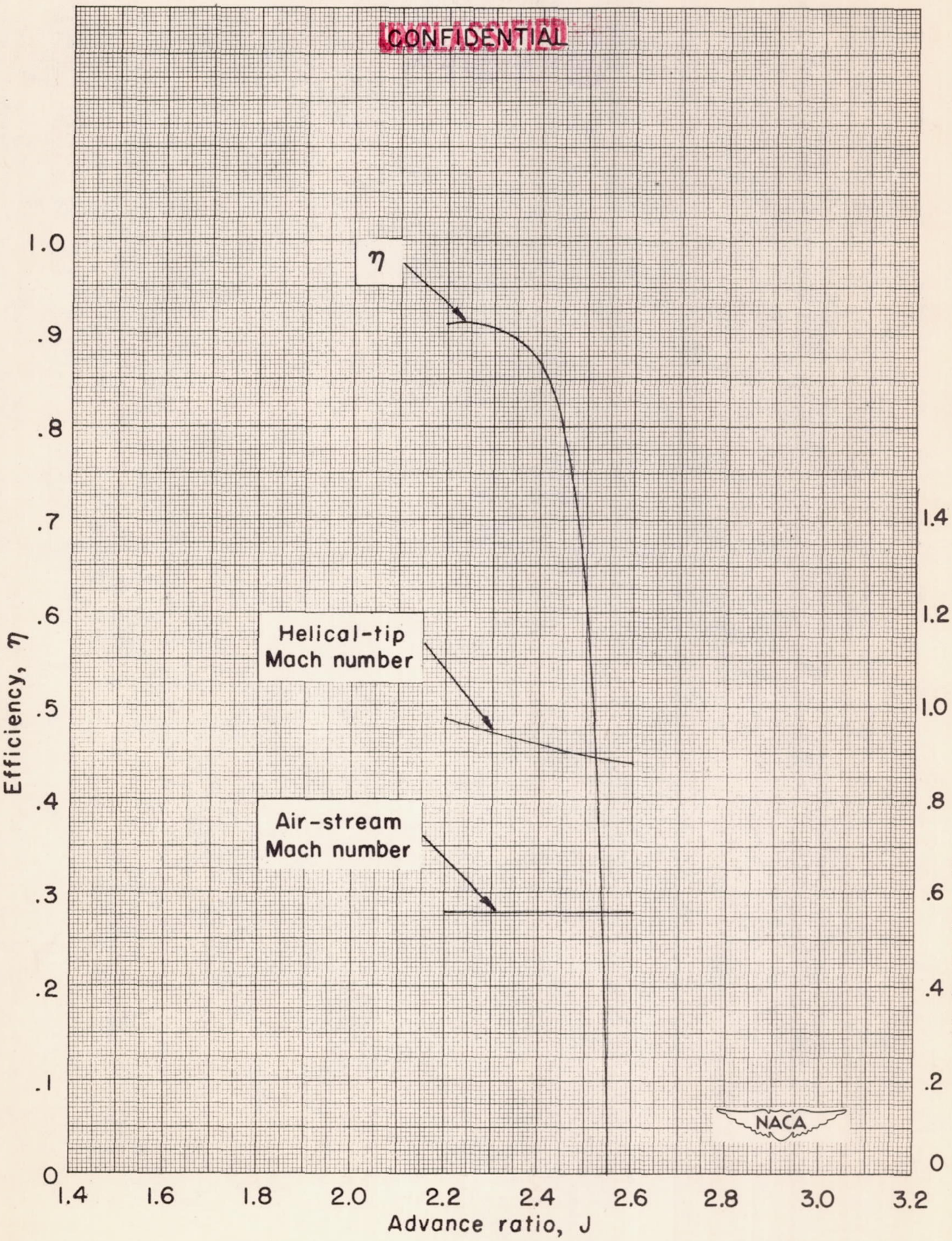
(c) Efficiency.

Figure 22.– Concluded. Rotational speed, 2160 rpm.



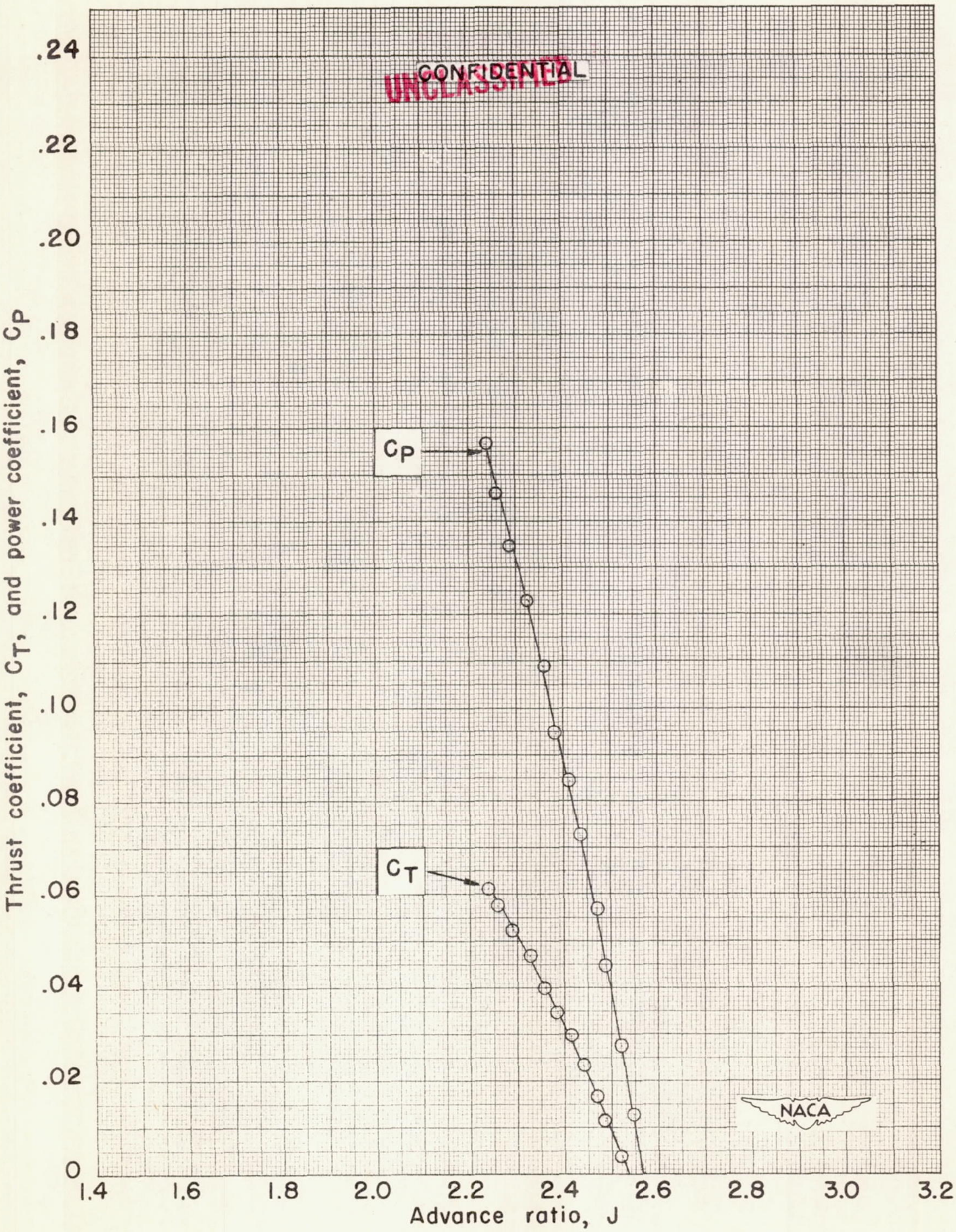
(a) Thrust and power coefficients.

Figure 23.- Characteristics of NACA 10-(3)(05)-045 propeller at high forward speeds. Air-stream Mach number at maximum efficiency, 0.558; $\beta_{0.75R} = 45^{\circ}$.



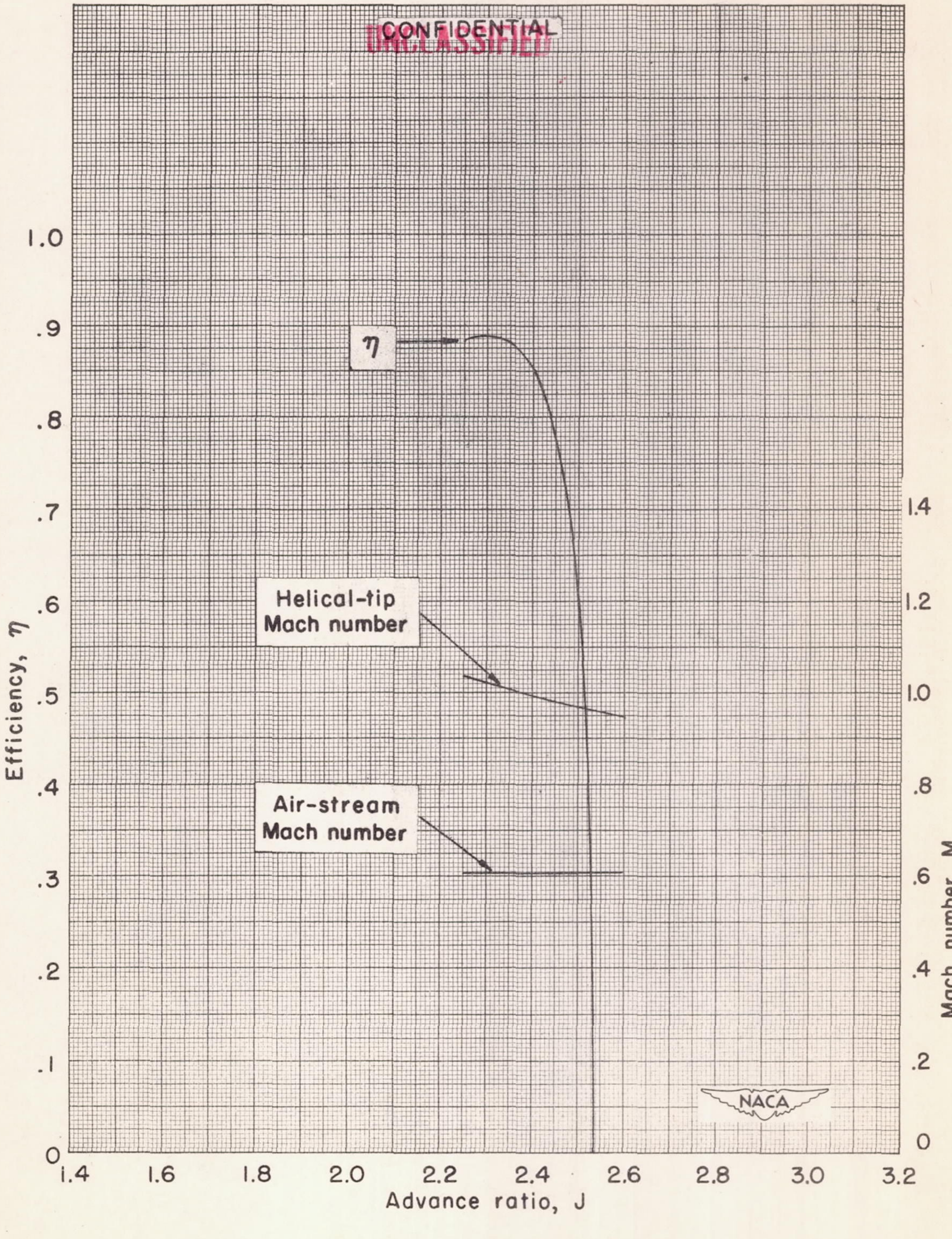
(b) Efficiency.

Figure 23.– Concluded. Air–stream Mach number at maximum efficiency, 0.558.



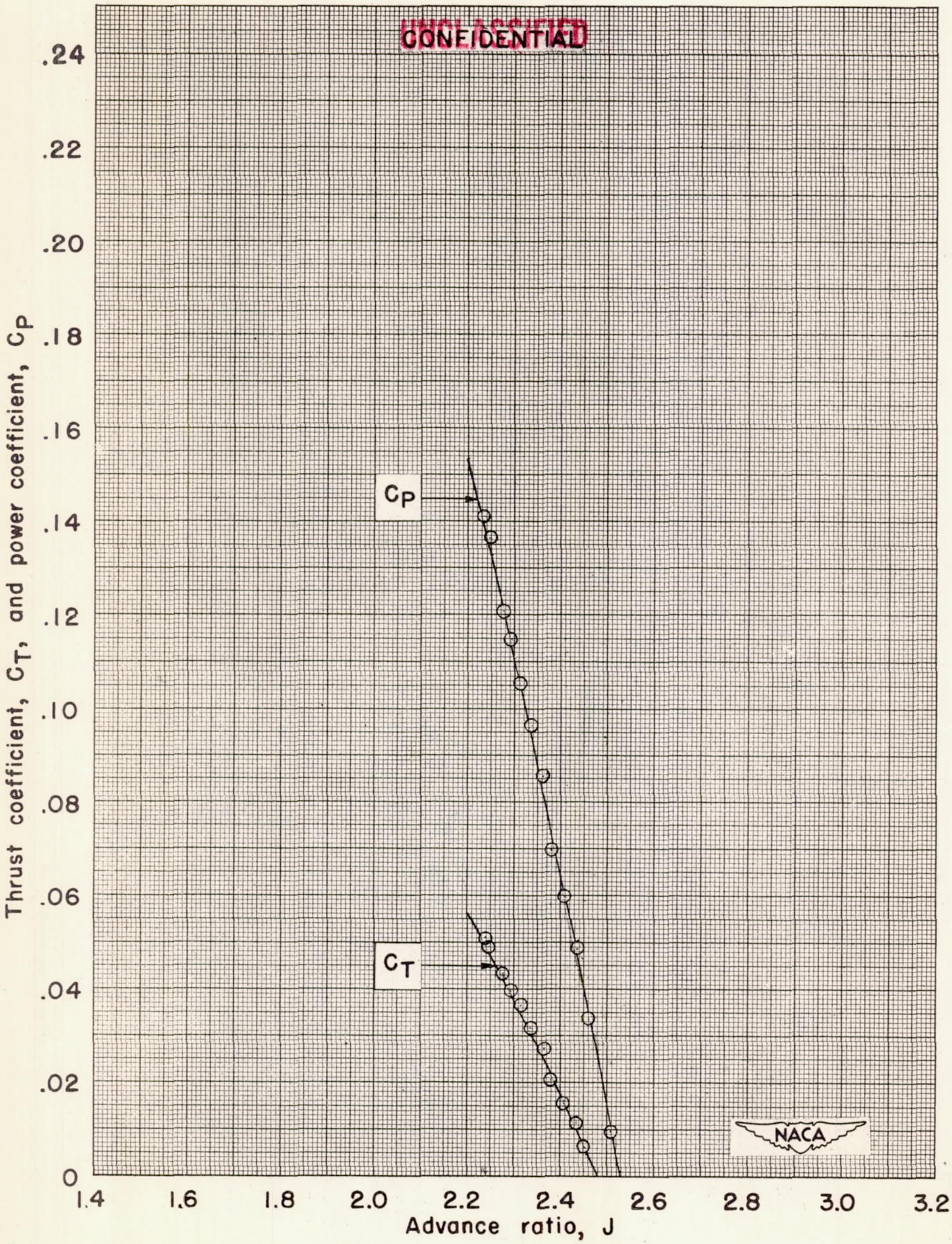
(a) Thrust and power coefficients.

Figure 24.– Characteristics of NACA 10–(3)(05)–045 propeller at high forward speeds. Air-stream Mach number at maximum efficiency, 0.603; $\beta_{0.75R} = 45^{\circ}$.



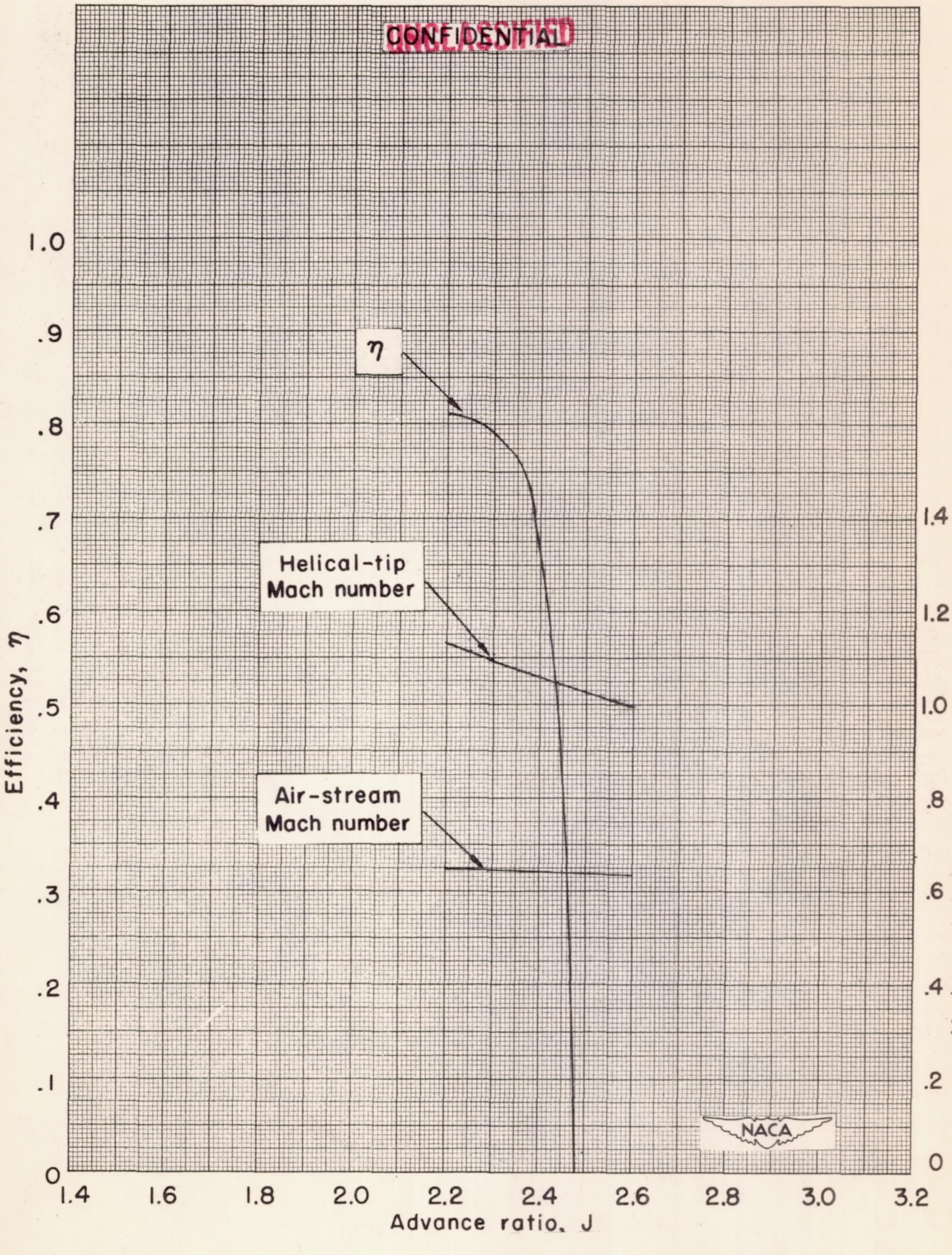
(b) Efficiency.

Figure 24.– Concluded. Air-stream Mach number at maximum efficiency, 0.603.



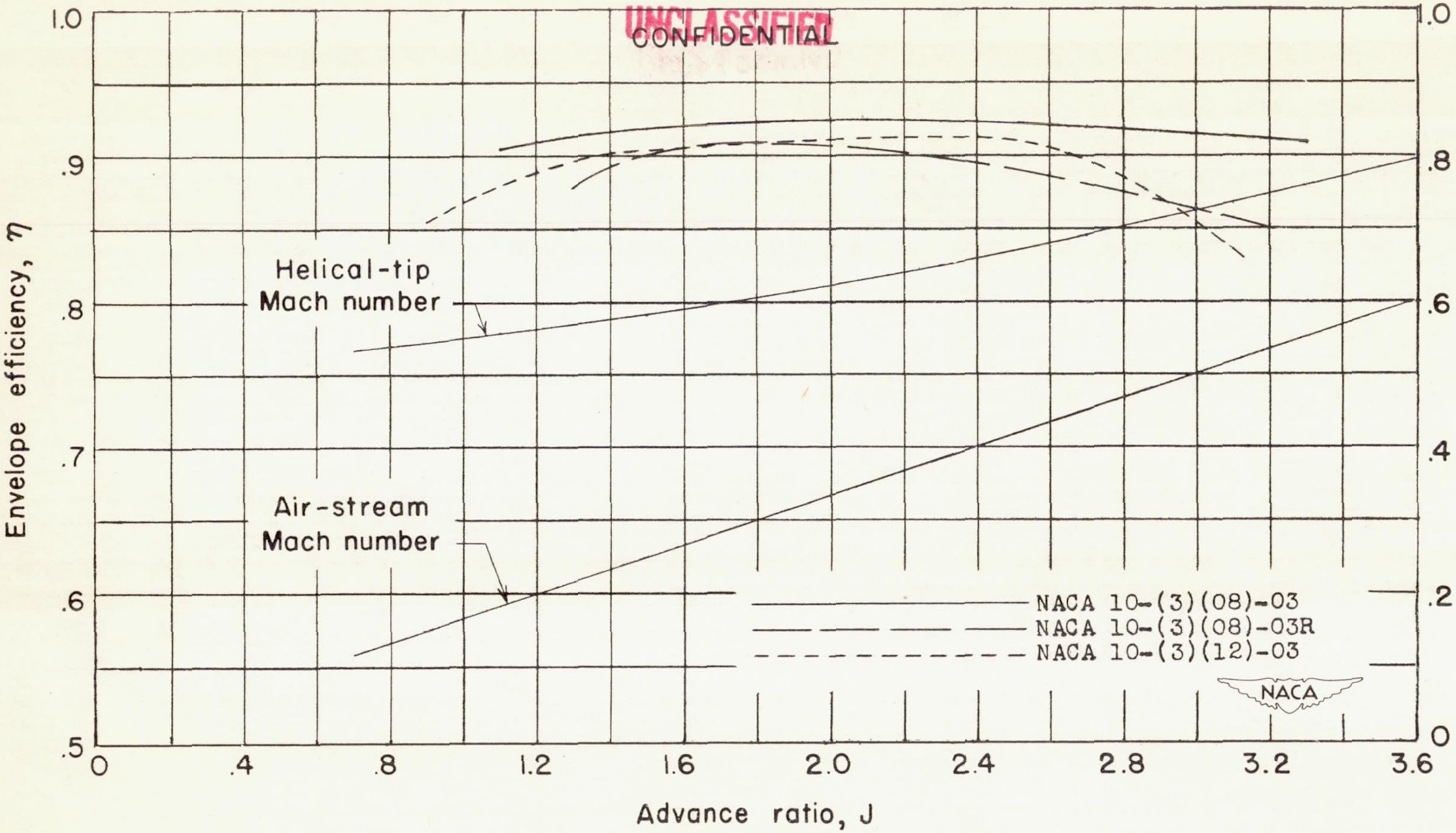
(a) Thrust and power coefficients.

Figure 25.- Characteristics of NACA 10-(3)(05)-045 propeller at high forward speeds. Air-stream Mach number at maximum efficiency, 0.650; $\beta_{0.75R} = 45^{\circ}$.



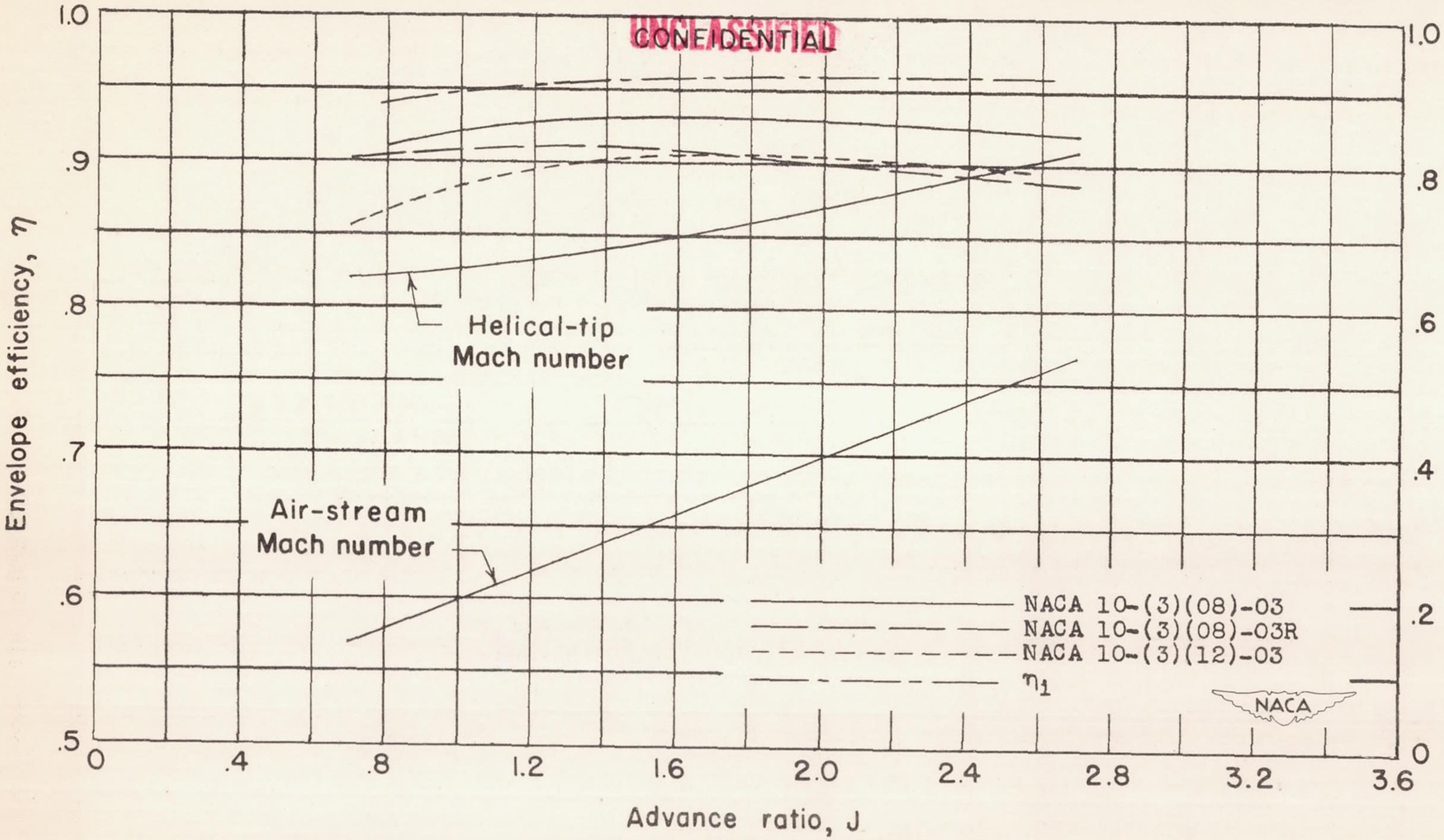
(b) Efficiency.

Figure 25.- Concluded. Air-stream Mach number at maximum efficiency, 0.650.



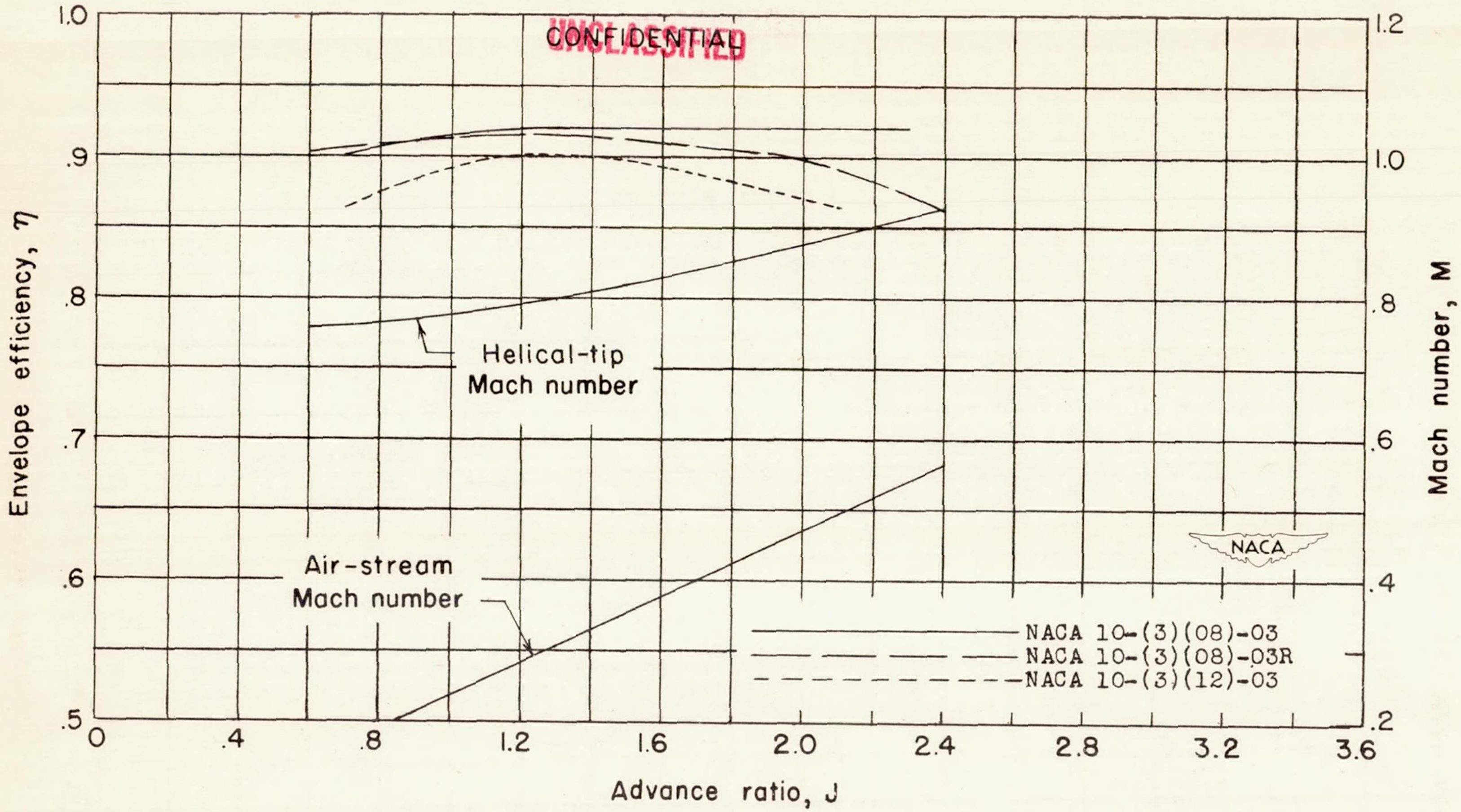
(a) 1140 rpm.

Figure 26.- Comparison of the envelope efficiencies of NACA propellers having a solidity of 0.03 per blade at the 0.7 radius.



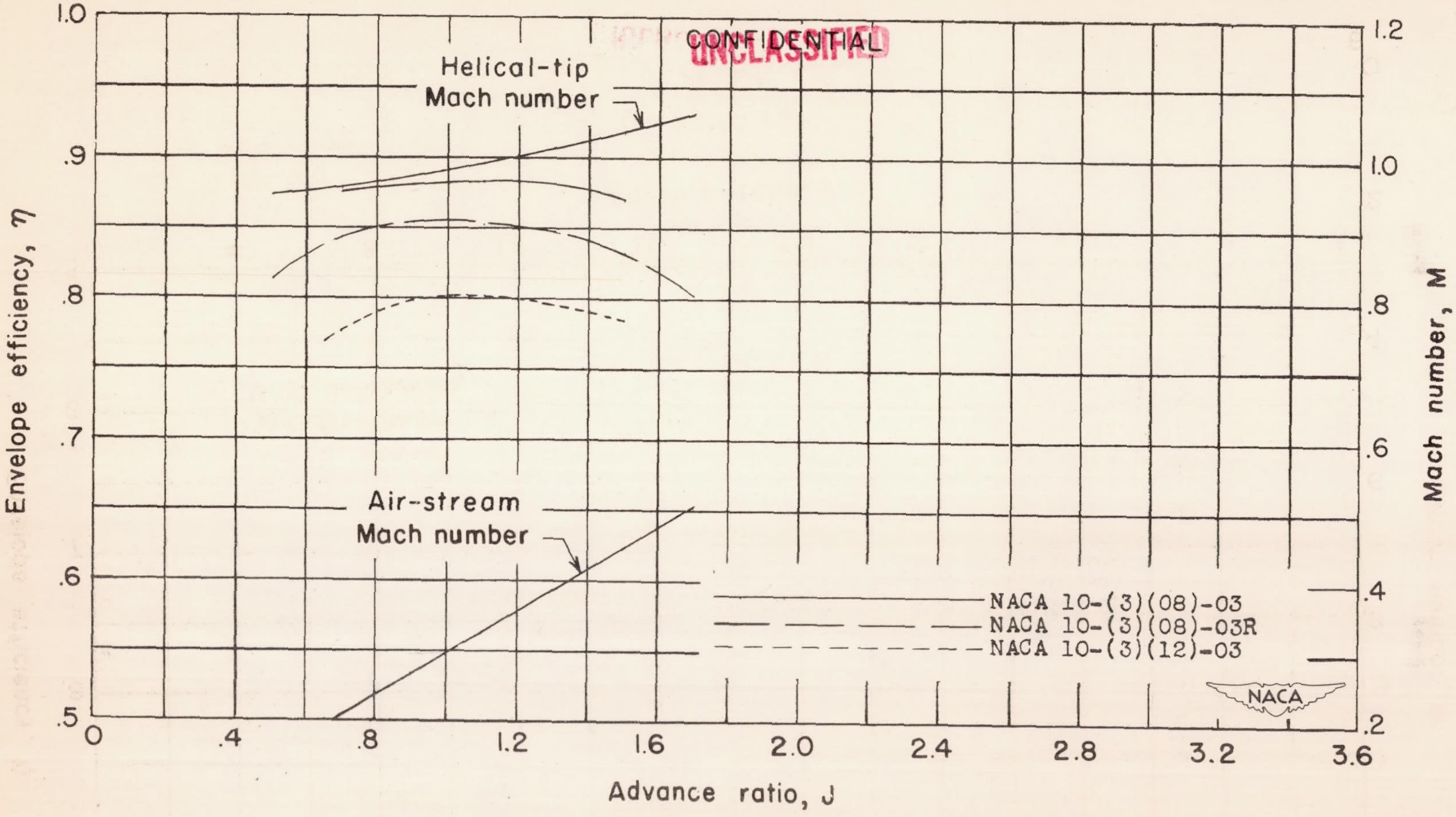
(b) 1350 rpm.

Figure 26.– Continued.



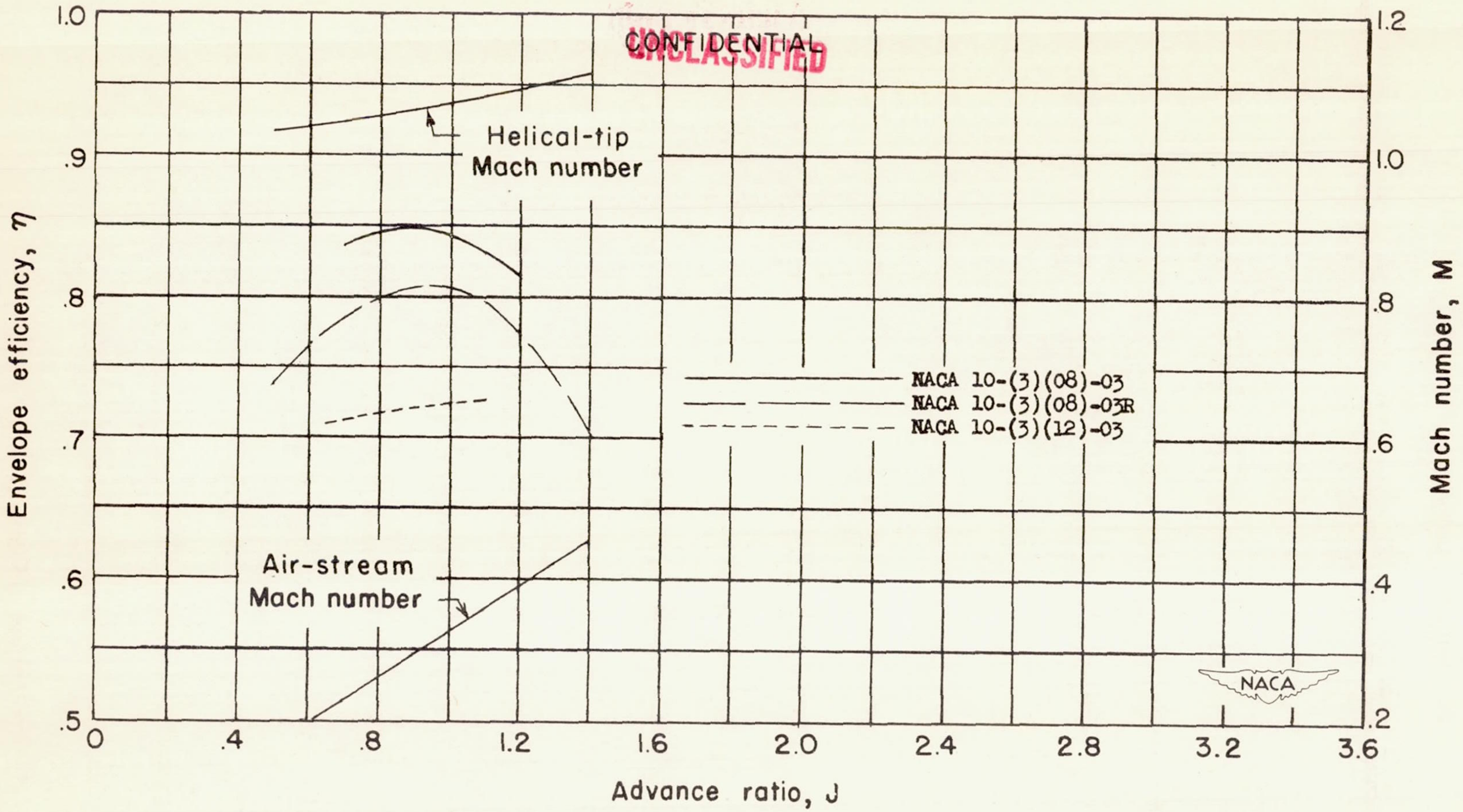
(c) 1600 rpm.

Figure 26.- Continued.



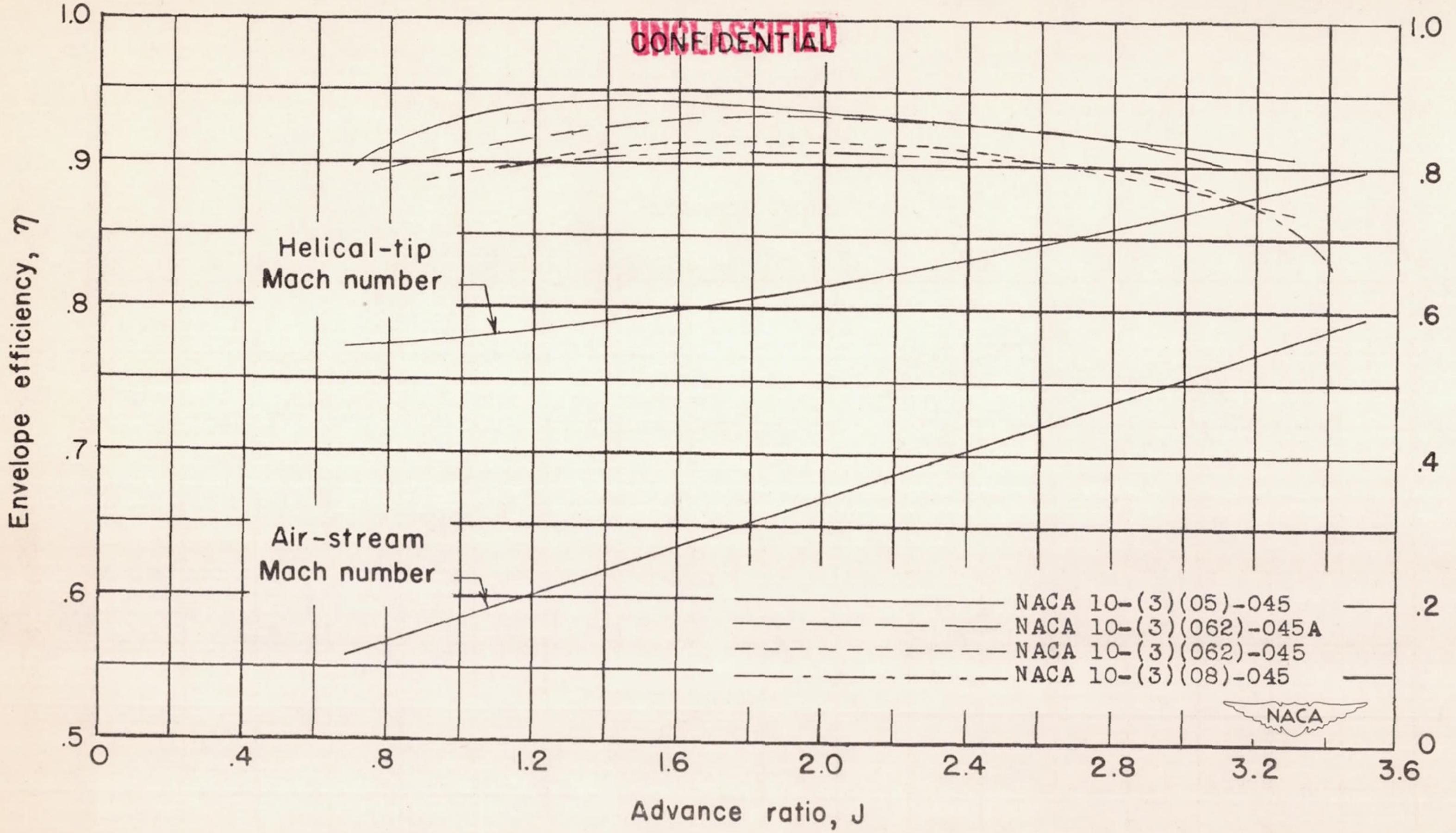
(d) 2000 rpm.

Figure 26.- Continued.



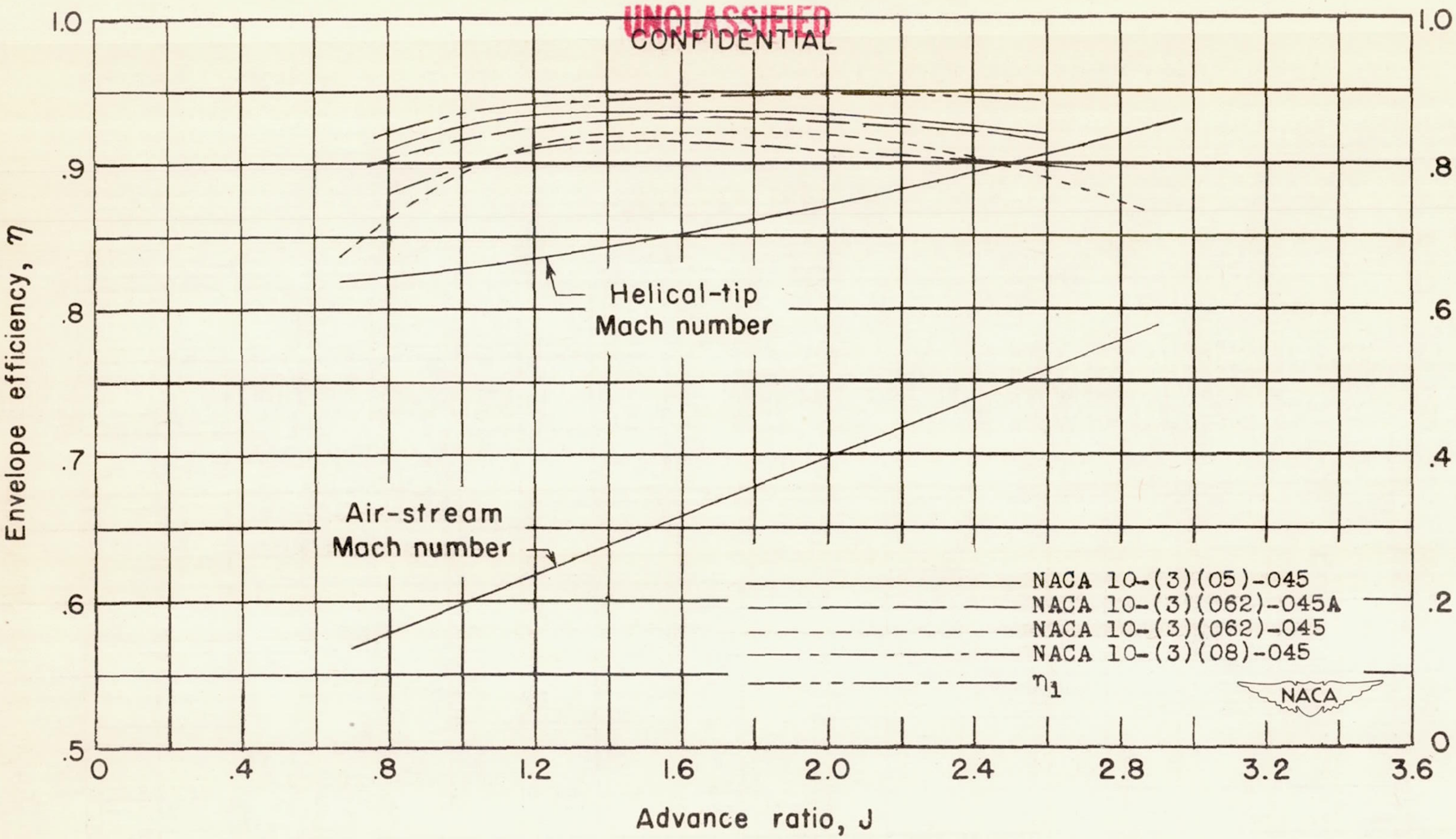
(e) 2160 rpm.

Figure 26.– Concluded.



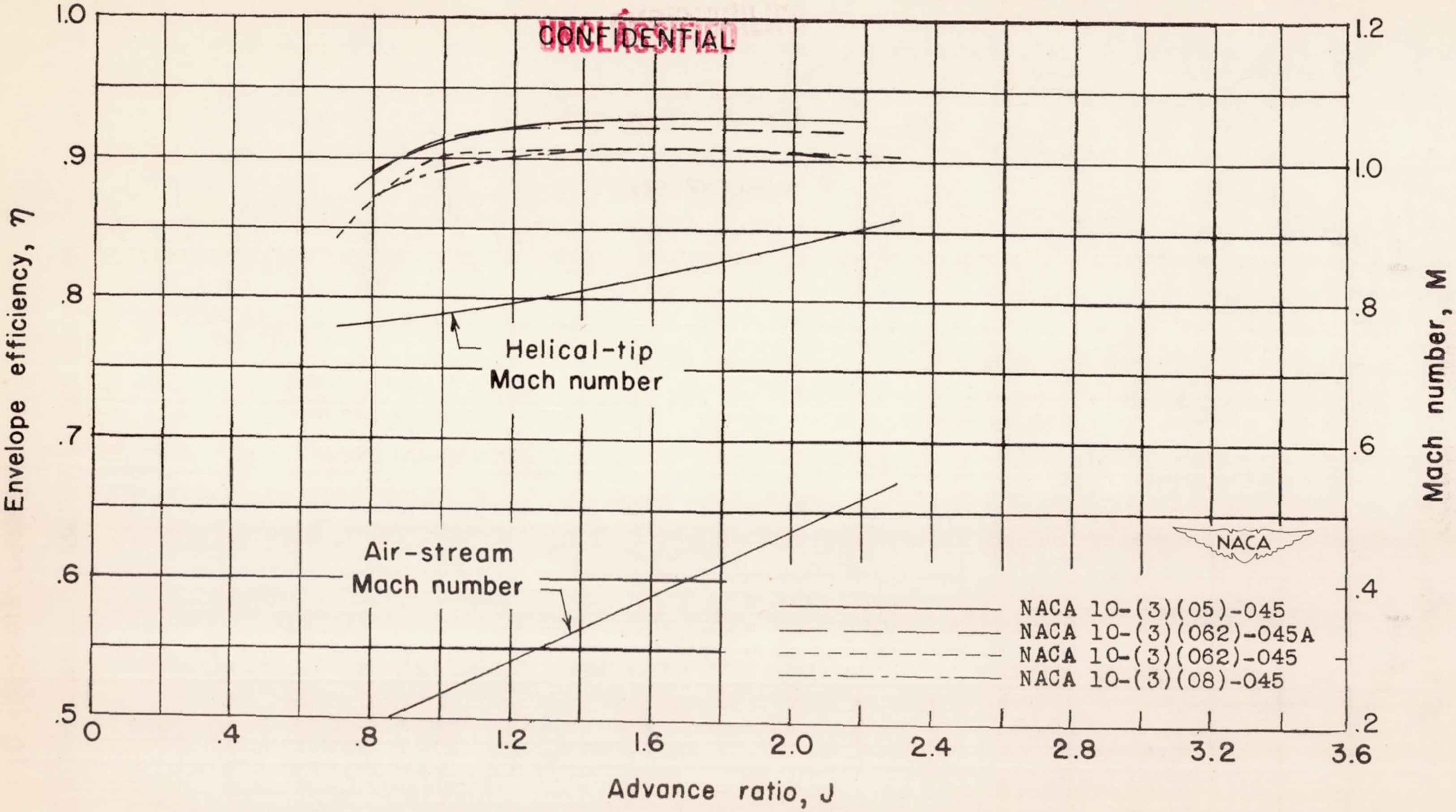
(a) 1140 rpm.

Figure 27.- Comparison of the envelope efficiencies of NACA propellers having a solidity of 0.045 per blade at the 0.7 radius.



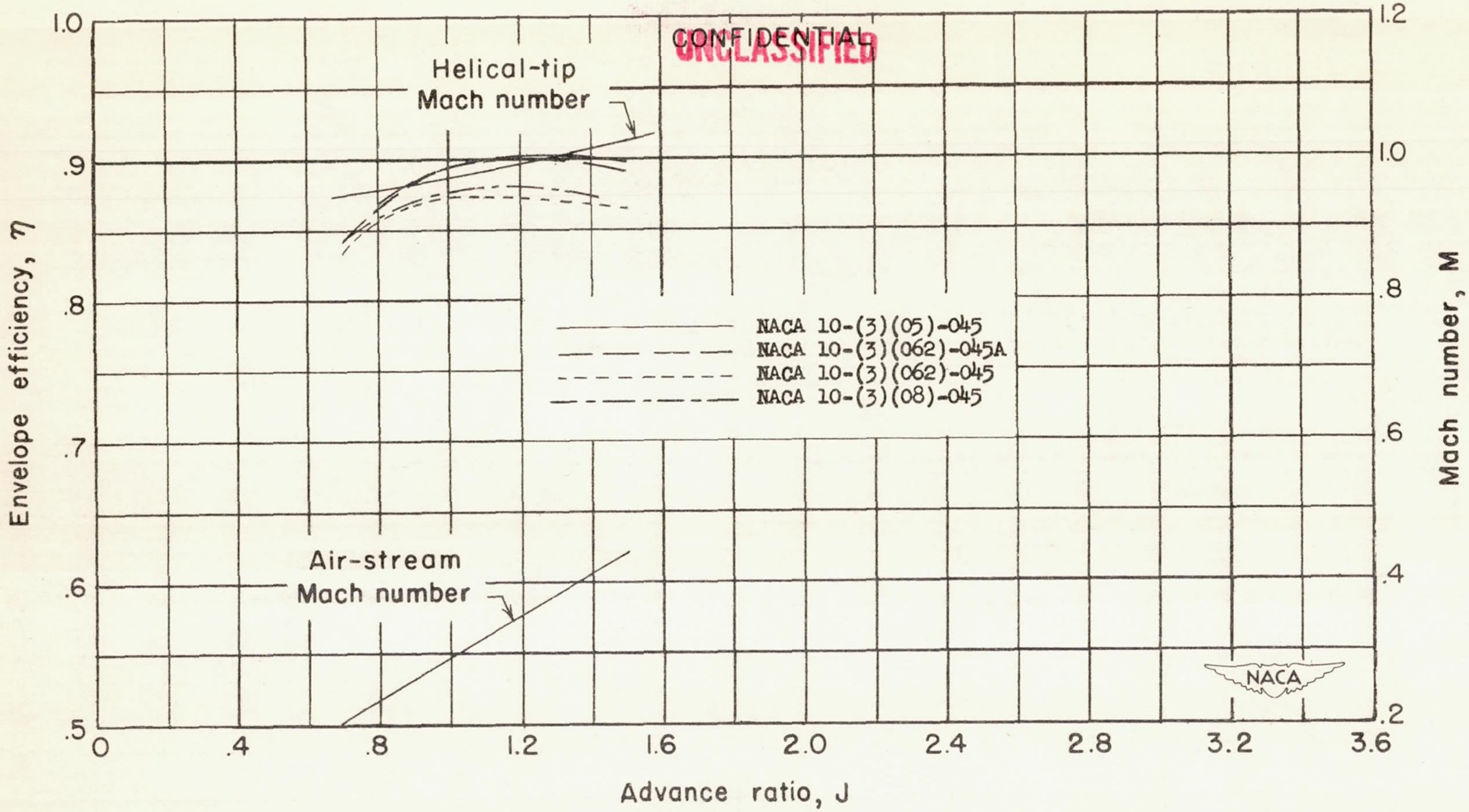
(b) 1350 rpm.

Figure 27.— Continued.



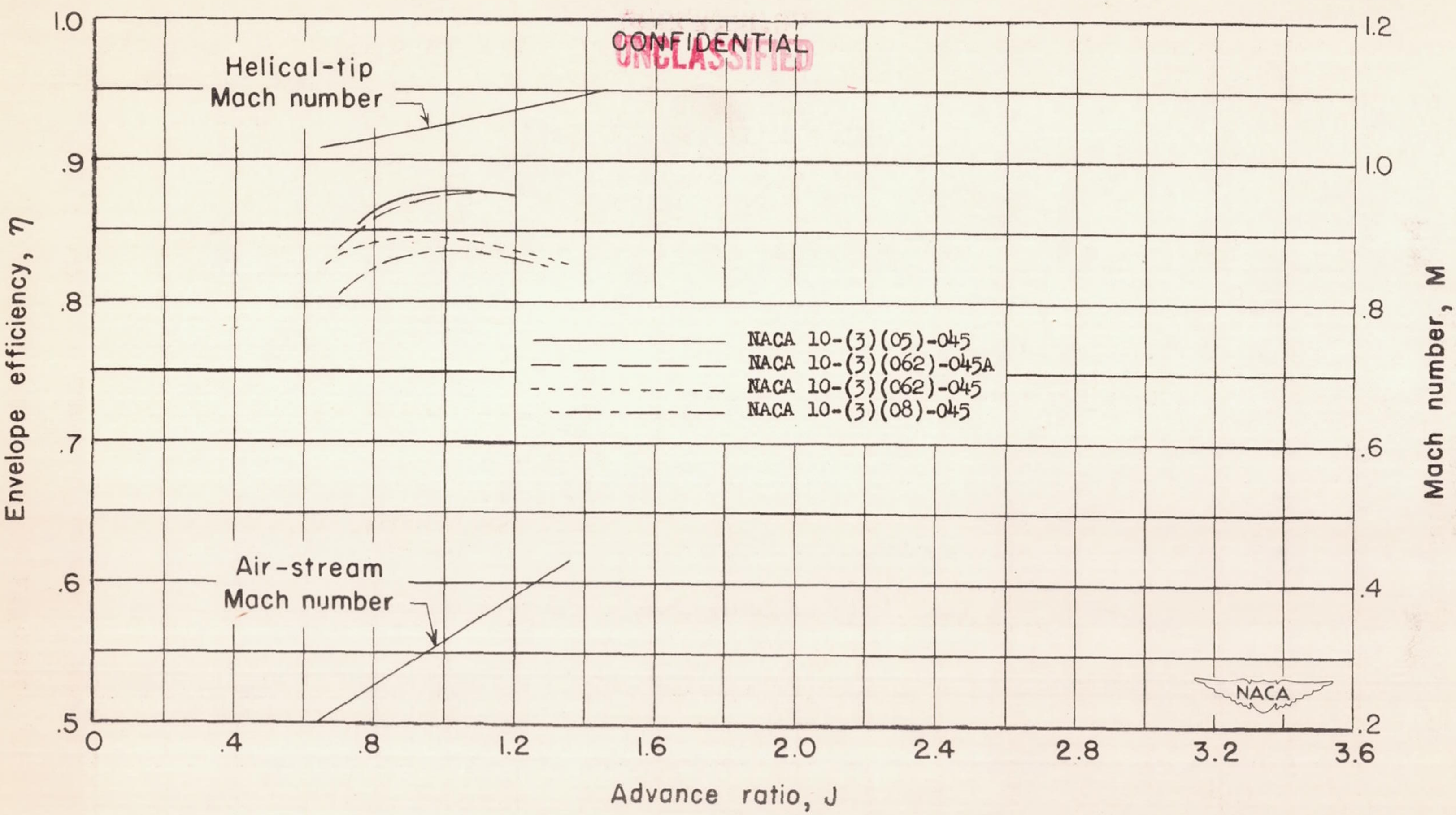
(c) 1600 rpm.

Figure 27.– Continued.



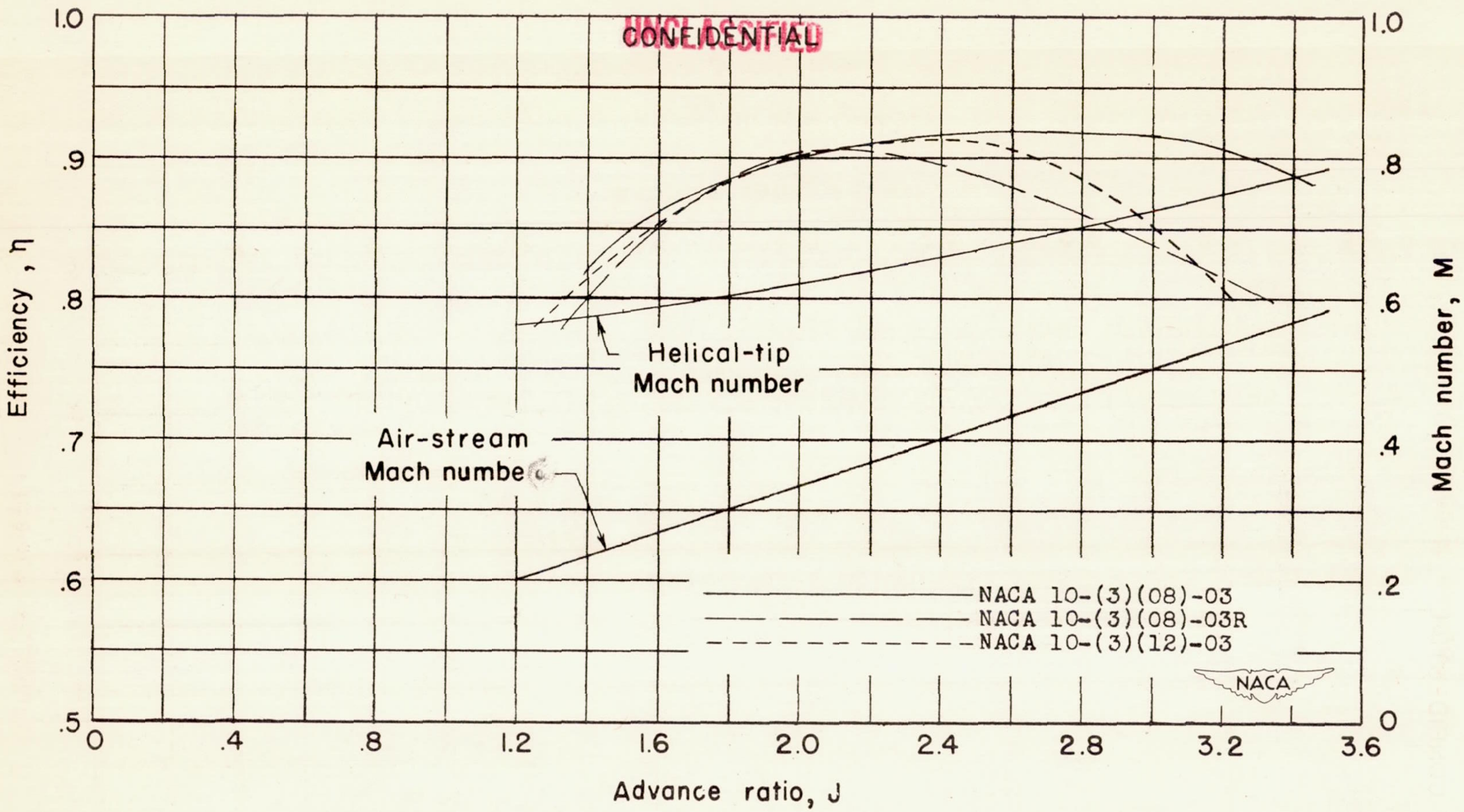
(d) 2000 rpm.

Figure 27.- Continued.



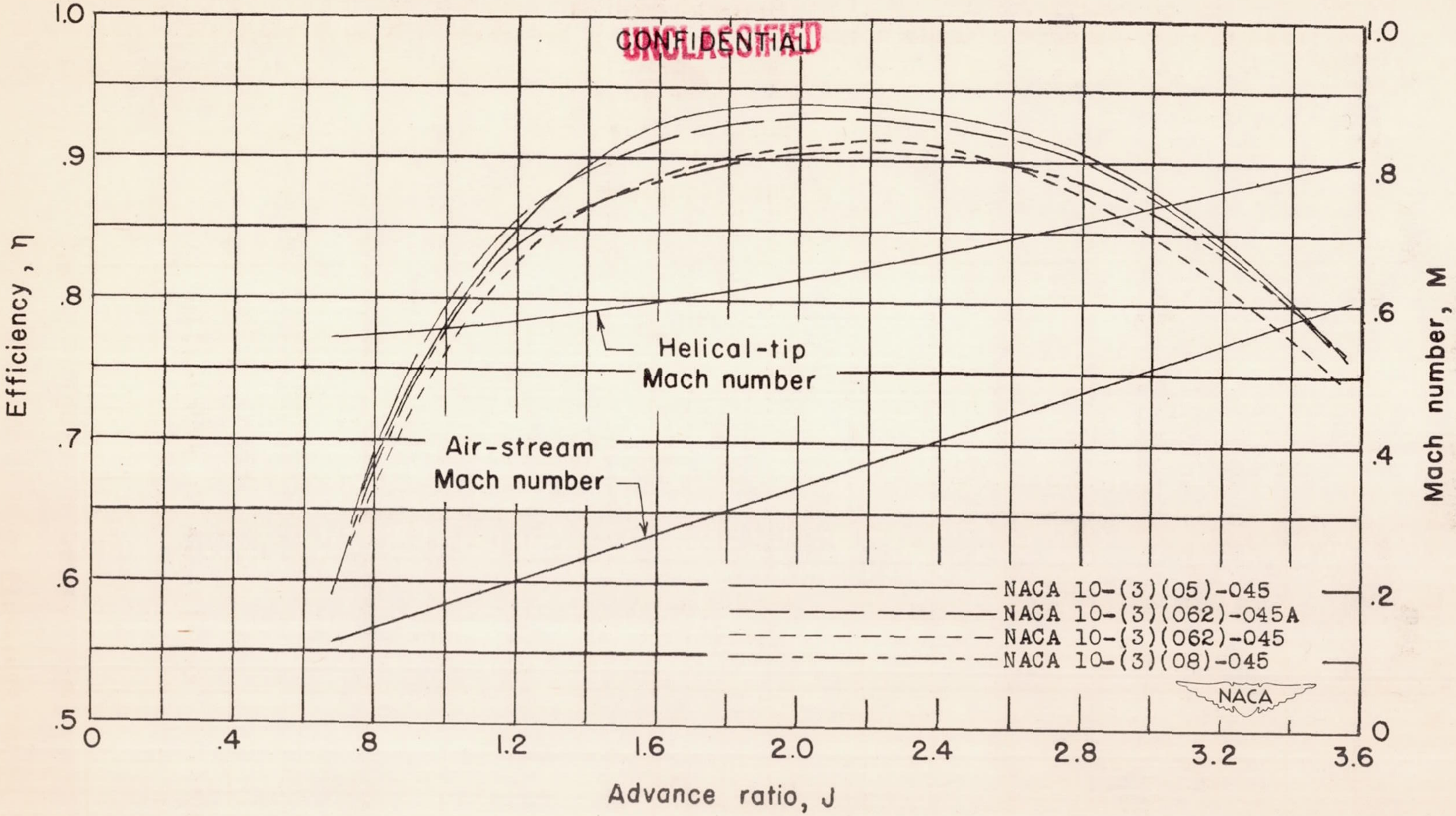
(e) 2160 rpm.

Figure 27.– Concluded.



(a) σ/B at 0.7R = 0.03.

Figure 28.- The efficiency of NACA propellers having different blade-section thicknesses when operating at a constant power coefficient of 0.15 and a rotational speed of 1140 rpm.



(b) σ/B at $0.7R = 0.045$.

Figure 28.- Concluded.

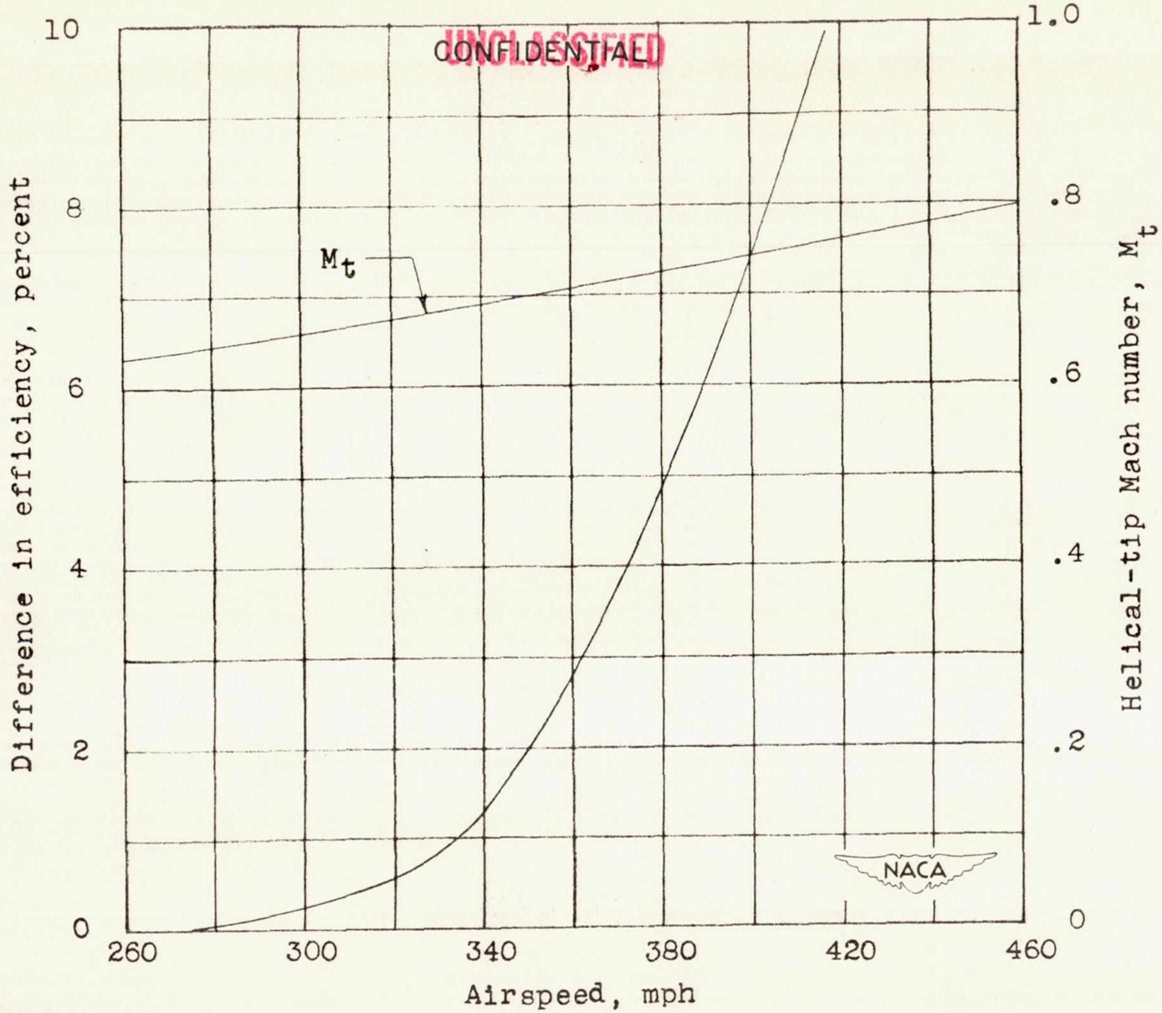


Figure 29.- The effect of airspeed on the difference in efficiency between the NACA 10-(3)(08)-03 and NACA 10-(3)(12)-03 two-blade propellers. Constant propeller rotational speed, 1140 rpm; constant C_P, 0.15.

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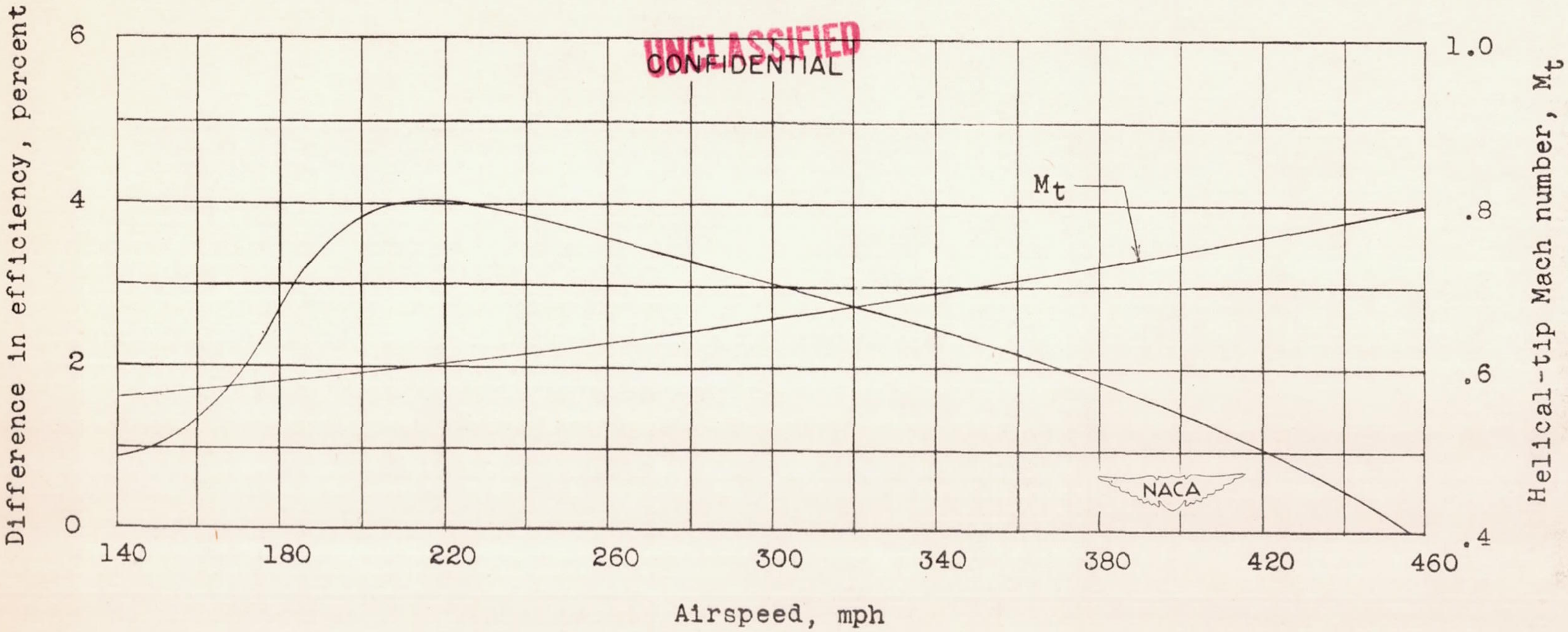

Figure 30.– The effect of airspeed on the difference in efficiency between the NACA 10–(3)(05)–045 and NACA 10–(3)(08)–045 two–blade propellers. Constant propeller rotational speed, 1140 rpm; constant C_P, 0.15.

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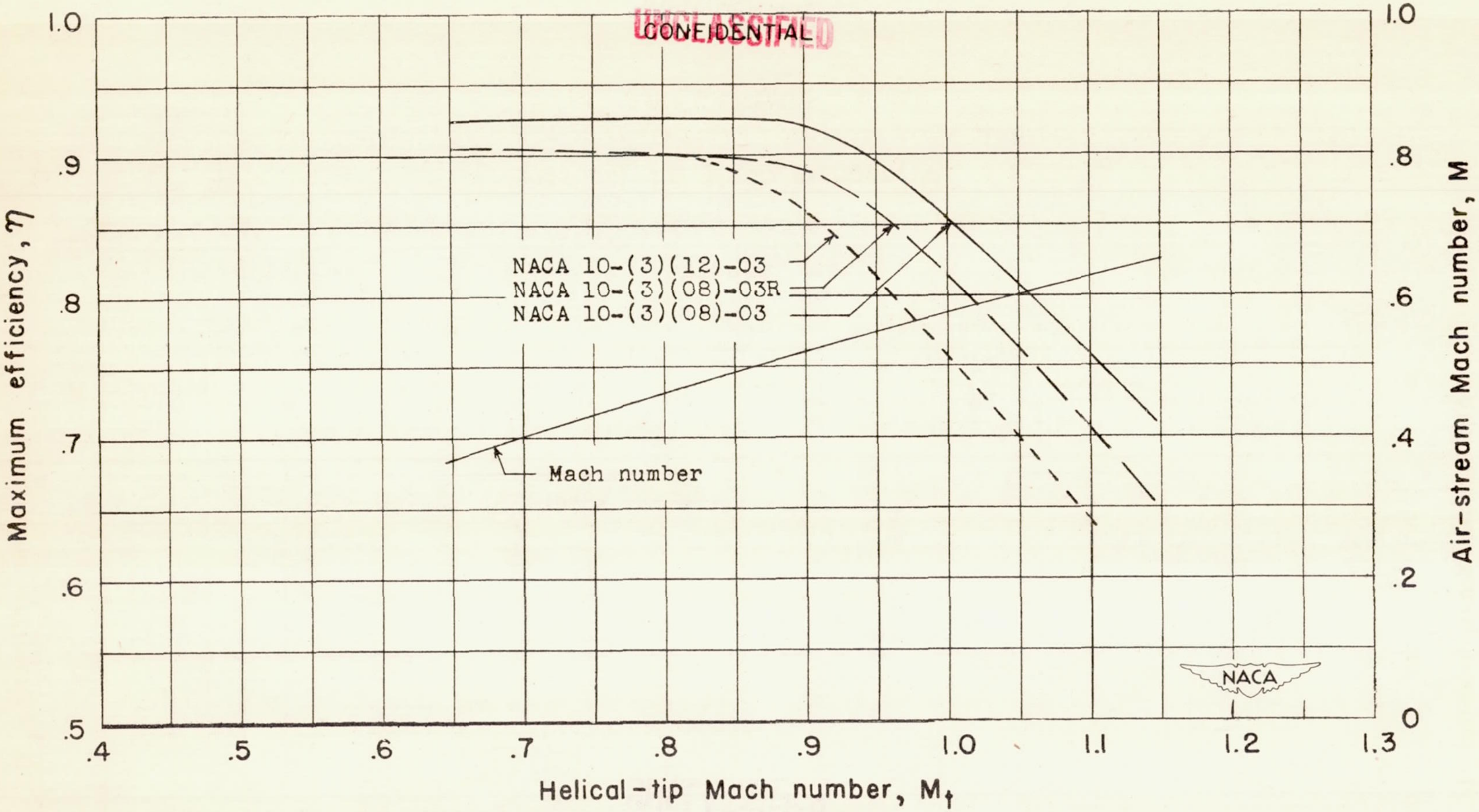
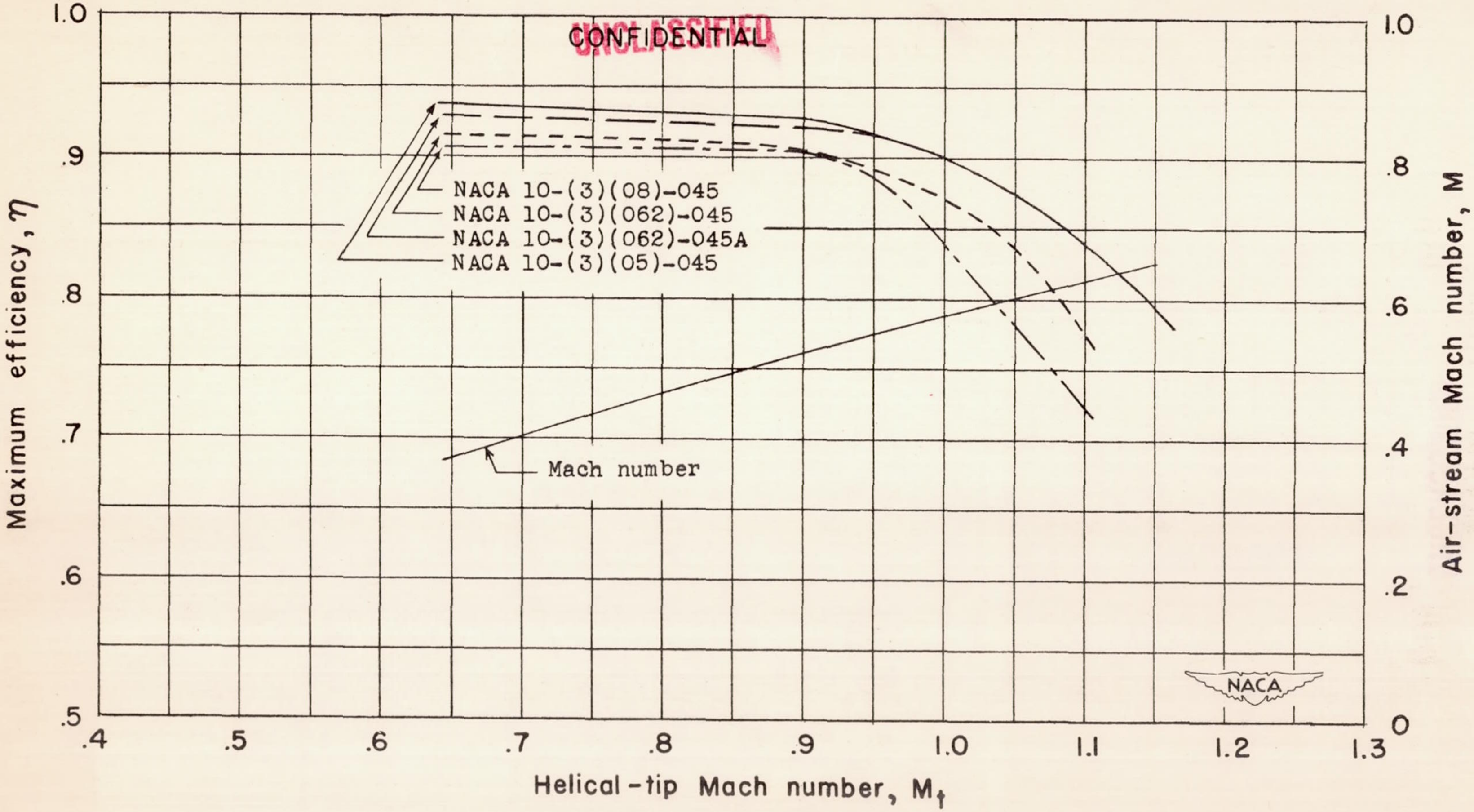


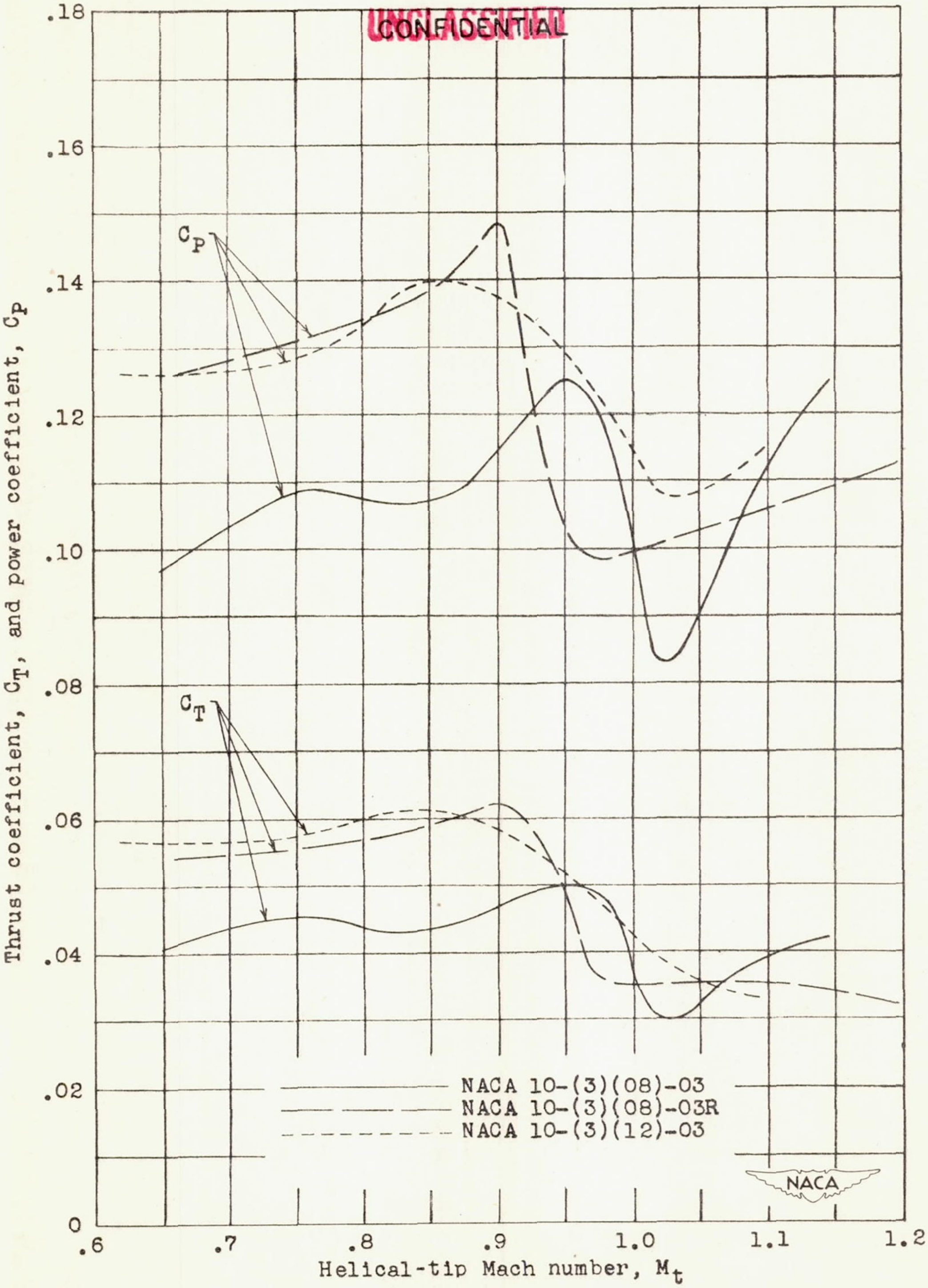
(a) σ/B at $0.7R = 0.03$.

Figure 31.- The effect of compressibility on the maximum efficiency of NACA propellers having different blade-section thicknesses. $\beta_{0.75R} = 45^{\circ}$.



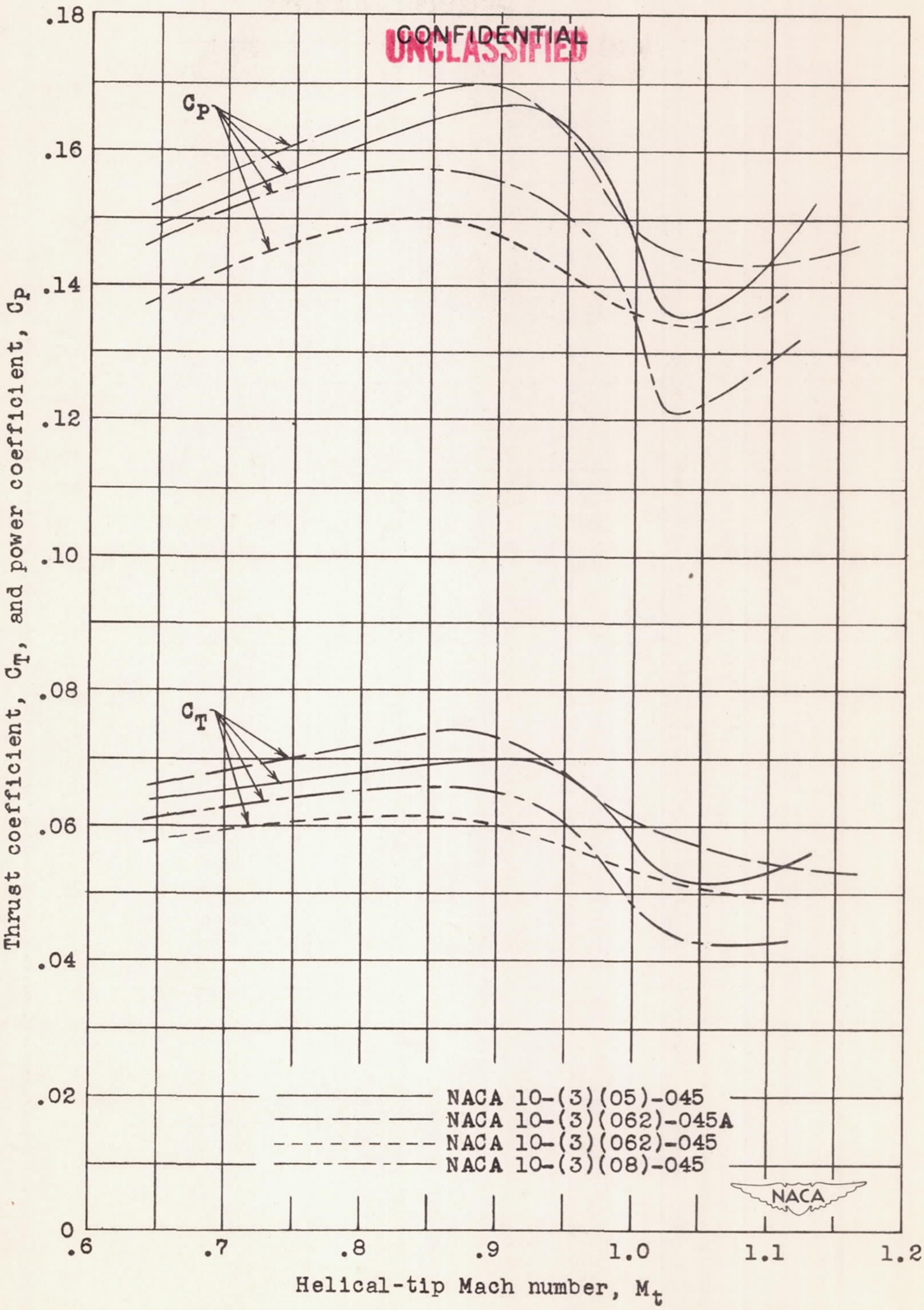
(b) σ/B at $0.7R = 0.045$.

Figure 31.— Concluded.



(a) σ/B at $0.7R = 0.03$.

Figure 32.- The effect of compressibility on the thrust and power coefficients for maximum efficiency of NACA propellers having different blade-section thicknesses. $\beta_{0.75R} = 45^{\circ}$.



(b) σ/B at $0.7R = 0.045$.

Figure 32.– Concluded.

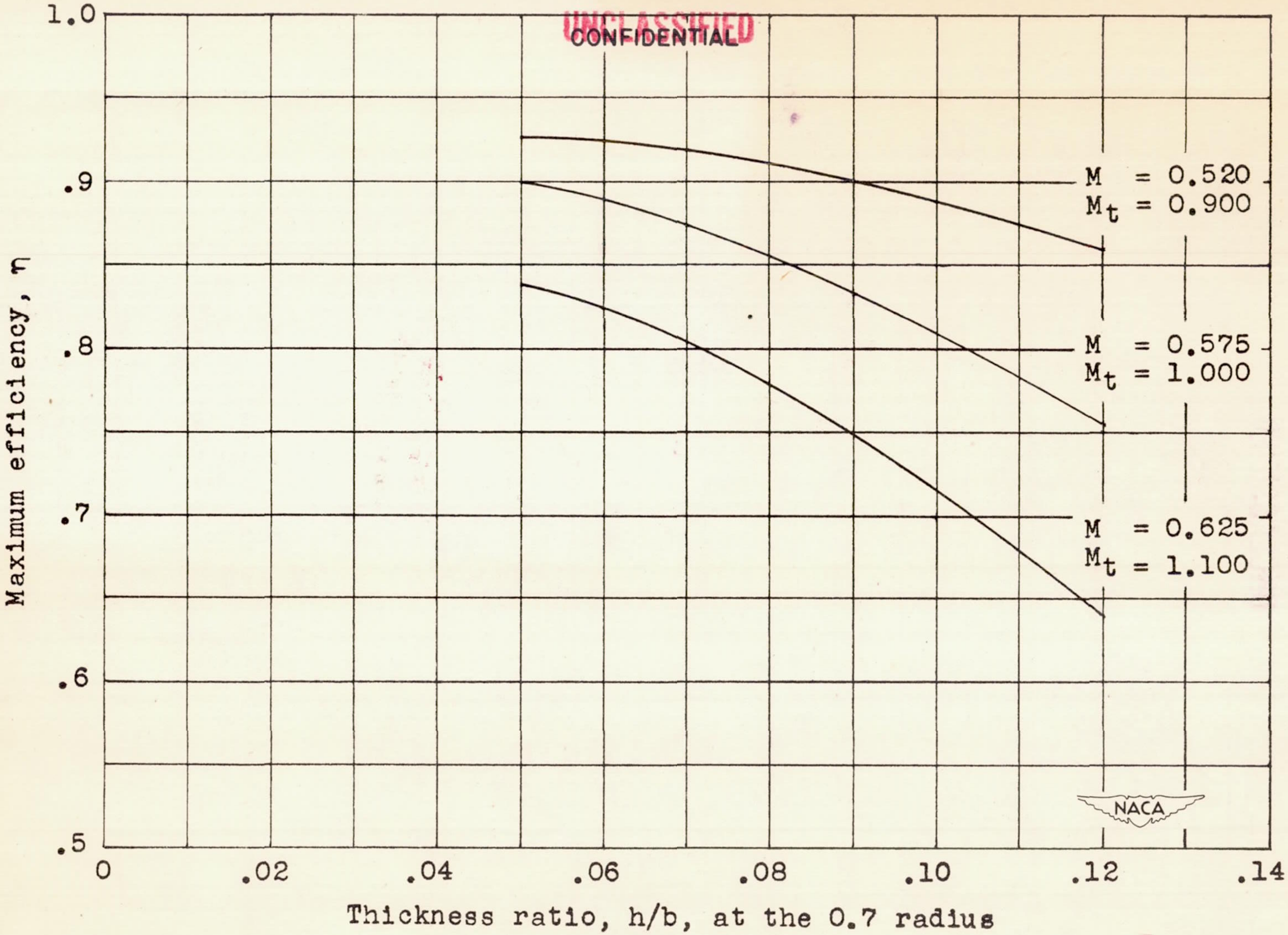


Figure 33.– The effect of thickness ratio and compressibility on the maximum efficiency of the NACA propellers. $\beta_{0.75R} = 45^{\circ}$.