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PROPELLER-DESIGN PROBLEMS OF HIGH-SPEED AIRPLANES

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SUMMARY

It is shown that on the basis of existing high-speed airfoil data, propeller efficiencies appreciably in excess of 40 percent do not appear possible at speeds above 500 miles per hour at 20,000 feet. The assumption that present propeller-blade thicknesses cannot be reduced radically, is implied. Until the reliability and applicability of the airfoil data are established, this conclusion must not be regarded as infallible. Dive tests with airplanes equipped with thrust meters and torque meters are proposed to provide an urgently needed check.

The design of high-speed propellers is dictated wholly by compressibility considerations. The blade width, thickness, and pitch distribution; also the airfoil sections, the lift coefficient, the propeller diameter, and rpm must all be adjusted if reasonable efficiencies are to be maintained at airplane speeds that are now being approached.

Research is urgently needed on:

- 1) Airfoils at subsonic, sonic, and supersonic speeds.
- 2) Propellers at high forward speeds in wind tunnels
- 3) Propellers in free flight at high speeds
- 4) Jet propulsion and related devices

The breakdown of propeller efficiency indicated by airfoil data, should serve as an incentive for accelerated research on jet propulsion. This device may extend the attainable speed of current airplanes to the neighborhood of 550 miles per hour at 20,000 feet.

INTRODUCTION

The problem of propeller design for high-speed airplanes is the familiar one of extrapolating conflicting experimental data by means of inadequate theory. Airplanes have actually flown at speeds in excess of 400 miles per hour and are being designed for higher speeds; yet, to the author's knowledge, there is available not a single reliable test on a propeller at forward speeds of this magnitude. The assistance afforded by theory is little more than qualitative in the subsonic regime. Therefore, the only recourse is to the calculation of propeller performance from airfoil tests and data. Although there are many legitimate objections to the validity of the results of such calculations, certain trends of considerable interest can be established. The effects of three-dimensional flow, particularly near the tips, the influence of centrifugal force on the behavior of the boundary layer, and the effect of the afterbody in modifying the flow through the propeller, are some factors which are difficult to account for in calculations of propeller efficiency at high speeds from airfoil data. If these factors are borne in mind, however, it should be possible to determine the effect of changing airfoils and to establish the limitations imposed on propellers by compressibility effects.

COMPRESSIBILITY EFFECTS - AIRFOIL DATA

This section includes a brief review of well-known compressibility effects on airfoil characteristics.

Effect on Lift and Pitching Moment

The variation of lift coefficient with air speed at constant angle of attack, as shown in references 1, 2, and elsewhere, tends to follow the variation predicted by Glauert's formula for thin airfoils, up to the critical speed, when the shock wave forms. This variation is shown in figure 1. Above the critical speed, the lift at constant angle of attack drops abruptly, and then increases again. Below the critical speed, the increase of lift coefficient with speed at constant angle of attack is obtained through greater slope of the lift curve, the angle for zero lift remaining unchanged until the shock wave is formed. The

effect of compressibility on the pitching moment is similar to that on lift, except that the experimental data available appear to indicate a less consistent and less severe variation than the theoretical.

Drag

The most predominate compressibility effect is the increase in drag. A typical variation of airfoil section drag coefficient with speed is shown in figure 1. The sudden increase in C_D which is caused by the dissipation of energy as heat in the shock wave and by the attendant separation of flow from the surface, is preceded by a more gradual rise. This rise is due to the fact that the pressures involved are beginning to be of sufficient magnitude that the compressibility of the air is causing an appreciable change in temperature. The pressures are thus different from those that would correspond to an isothermal process. In figure 1, the increase in dynamic pressure over that calculated by the formula $\frac{1}{2} \rho V^2$ (an increase which appears in the force coefficients) is plotted for comparison.

It will be shown that high-speed propellers must operate with a considerable portion of their blades above the critical Mach number, so that the drag variation above this speed is of primary importance. The theoretical factors which govern the drag when the flow is partially subsonic and partially supersonic, are little understood - in airplane-design circles, at least. Experimental difficulties arise from the magnitude of the forces involved and the power required, from the effect of the shock wave on tunnel-velocity distribution, from wall corrections and tare drags, and from Reynolds number effects. Hence much of the available experimental data extend only up to the formation of the shock wave and the attendant precipitous drag increase. When the drag above the critical speed is indicated, some inconsistencies appear. Figure 2 is a comparison of typical drag curves from several sources with data from the NACA 11-inch, high-speed, closed-throat tunnel.

Figure 2a compares results from the open-jet Guidonia high-speed tunnel (reference 2) with the NACA data for the same airfoil (reference 8). Figure 2b shows the type of variation obtained by Douglas and Perrin in a series of propeller tests (reference 13) in which the airfoil charac-

teristics were deduced from experimental thrust and torque grading curves. The substantial agreement between these results and the Guidonia curves in figure 2a has previously been recognized (reference 2). The NACA data for the same airfoil are shown in comparison. Figure 2c contrasts results typical of early tests at the Bureau of Standards (reference 11), which show only a very slight drag increase at the critical speed. The NACA results are typical of a large number of recent NACA tests (references 1 and 17) except that with the more modern airfoils, the drag increase occurs even more suddenly, particularly at low lift coefficients. At the higher angles of attack, the agreement between the NACA results and the British propeller tests is excellent, but the sudden drag increase at zero angle of attack shown by the airfoil tests was not realized with the propellers. Nevertheless, the agreement is sufficient to lend weight to the contention that propeller losses may be predicted from airfoil tests.

The fact that the NACA data show a sudden drag increase at the critical speed at all angles of attack, is of primary importance. The practicability of flight above the critical speed depends, of course, only upon the rapidity and magnitude of the drag increase near that speed.

One striking characteristic of all the NACA compressibility data is that no maximum drag coefficient is shown near the critical speed. It is apparent from figure 2b that this is due only to the fact that high enough speeds were not reached. That a maximum must exist, is substantiated by recent results from the Guidonia tunnel (reference 16), which show that a minimum drag coefficient of the order of magnitude of 0.03 was obtained with airfoils of simple shape at Mach numbers in the neighborhood of 2. It may probably be assumed that the coefficient decreases continuously from the values shown in figure 2, to the more moderate values at speeds where the flow is entirely supersonic. Some ballistic studies, described in reference 5, also verify that the drag coefficient reaches a maximum just above the critical speed and then decreases continuously. The shape of the drag curve in figure 1, above the critical speed, follows these ballistic data. In applying the NACA results to propeller calculations, it is difficult to estimate the magnitude of the maximum drag coefficient. It is therefore necessary to assume that the drag just above the critical speed is not less than the highest values shown on the NACA curves. Thus, only the minimum reduction in propulsive efficiency can be calculated from

these data. A careful study indicates that the drag coefficients in table I are typical of the highest values shown for a large number of airfoils in references 1, 8, and 17.

TABLE I

Profile Drag Coefficient above Critical Speed

Percent t	C_L		
	0	0.2	0.4
6	0.05	0.05	0.08
9	.08	.08	.10
12	.12	.12	.12

The Reduction of Compressibility Effect on Drag

It will be of interest to determine the extent to which the compressibility effect on the drag of propeller airfoils can be controlled. In effect, this means the extent to which the critical Mach number of the airfoil can be raised by changing the airfoil shape and characteristics, and the conditions under which the airfoil operates.

The shock wave, with its attendant sudden drag increase, occurs when the local velocity at any point in the field of flow exceeds the local speed of sound (reference 17). Therefore, any effect which decreases the maximum local velocity, causes an increase in the critical Mach number. Since local speeds generally increase with an increase in either section lift coefficient or thickness, the critical speed is reduced by an increase in either of these two parameters. This effect is evident in figure 3. The decrease in critical Mach number near zero lift is due to the high local velocities created by this airfoil at small negative angles of attack and is not a general result. Otherwise the effect of both lift coefficient and thickness is typical of normal airfoils. These effects are discussed at length in reference 12.

From these considerations, it is obvious that the maximum possible critical Mach number which could be obtained

with any airfoil operating at a given lift coefficient, would be obtained with an airfoil which had zero thickness and a uniform chordwise pressure distribution. The chordwise distribution of circulation with such an airfoil would produce the least possible maximum local velocity. This fact has been recognized by Lock (reference 12) and Taylor (reference 14). The latter has discussed means of deriving airfoils of finite thickness with the desired constant chordwise pressure distribution. This procedure may therefore be considered as well established. Since a propeller composed of constant-pressure, zero-thickness sections would have the least efficiency loss at high speeds, such airfoils will be referred to as "ideal propeller airfoils." They represent the absolute limit of refinement of airfoil design from the standpoint of increase in critical Mach number. The variation of critical compressibility speed for the ideal propeller airfoil is plotted against section lift coefficient in figure 4. (These data and all subsequent critical speeds shown, are for a standard altitude of 20,000 feet, selected arbitrarily to approximate the conditions with which the designer is most likely to have to deal.) The critical speed is determined from the formula developed by Jacobs (reference 6) which gives the critical speed as a function of the maximum negative pressure at low speed. The lift coefficient at high speed is then determined from the low-speed coefficient by multiplying by Glauert's factor $(1 - M^2)^{-1/2}$.

The effect of adding thickness to the ideal propeller airfoil must now be considered. By adjusting the chordwise thickness distribution, the increase in local velocity with thickness can be kept to a minimum (reference 1). The distribution used for the NACA OOX-35 and for the OOX-64 tested (reference 1), probably approaches the limit in this regard. The maximum suction encountered with the basic pressure distribution of such airfoils, appears to be about 70 percent of that of the conventional NACA four-number series and the Clark Y. (The basic pressure distribution is the distribution at zero lift for the uncambered airfoil.) Taking a thickness effect equivalent to that of the OOX-64 airfoil and combining the resulting basic pressure distribution with the lift effect of the ideal airfoil, a variation of critical speed with thickness and lift coefficient has been determined. This variation, plotted in figure 5, is believed to be near the practical limit attainable with any airfoil whatsoever. If any further improvement in thickness effect is possible, it will be offset by the fact that an absolutely uniform

pressure distribution due to lift cannot be obtained. These critical speeds may be compared with the comparable data given in figure 3 for the Clark Y airfoil, widely used for propellers. The Clark Y curves are based on the results of reference 8, supplemented by pressure-distribution data.

It is interesting to note that some of the sections tested (reference 1) have critical speeds very close to the practical limit. A comparison is shown in figure 6 for 9-percent-thick airfoils. This would seem to indicate that from the critical-speed standpoint, very little improvement in airfoil sections is possible. Figure 6 is, of course, a comparison of theoretical with experimental data. It has been shown (reference 17) that the critical speeds attained in airfoil tests, fall somewhat below those predicted from low-speed pressure-distribution data.

EFFECT OF COMPRESSIBILITY ON PROPELLER DESIGN

In this section an attempt is made to evaluate quantitatively the effect of the foregoing considerations on propeller efficiencies at high airplane speeds. Owing to the scarcity of data, it is possible only to determine the least compressibility effect - i.e., the highest efficiency that appears likely from the airfoil data available.

Consider first, figure 7: This figure gives the variation of blade thickness-chord ratio with propeller diameter assumed hereinafter. This thickness-chord ratio is taken as slightly less than the thinnest propellers now available. Due to the considerable increase in structural loads from compressibility effects and to the fact that diameters for high speed must be large, it is felt that thinner blades are not likely to be developed in the near future, even with improvement in materials. A spinner will be assumed to cover the inner 22 percent of the diameter and cuffs to extend from the spinner out to 35 percent of the diameter. In order to keep the sections near the spinner down to a reasonable thickness ratio, the cuffs must assume huge proportions. The maximum cuff chord would probably have to be 24 inches or more, in order to maintain the ratio shown.

For a propeller with Clark Y airfoil sections and thicknesses in accordance with figure 7, critical section speeds are plotted in figure 8 against propeller radius,

for two section lift coefficients. From this figure, it is seen that a shock wave would form near the spinner at a section speed of about 350 miles per hour at 20,000 feet. A shock wave would form near the tip at section speeds between 500 and 600 miles per hour, depending upon the section lift coefficient. The influence of three-dimensional flow at the tip, which would tend to increase the critical speed slightly over the outer 5 or 10 percent of the radius (reference 10), has been neglected. It will be seen that this is not an important factor.

The two curves on figure 8 which are concave upward represent the section speeds at airplane speeds of 450 and 500 miles per hour, for a certain diameter and rpm which will be mentioned later. A comparison of the two sets of curves permits some interesting conclusions. First, at a speed of about 450 miles per hour at 20,000 feet, this propeller will become covered from root to tip with a shock wave. Second, by comparing the slope of the two sets of curves, it is apparent that at high forward speeds, the shock wave forms almost simultaneously over most of the propeller, and that even with large blade-shank fairings, the root is as critical as the tip. At low forward speeds with high tip speeds, only the tip is subjected to the shock wave. Therefore, although low forward speed tests have indicated small reductions in efficiency due to compressibility, it is not to be presumed that the reductions at high forward speeds will be moderate.

Figure 9 shows a similar set of curves for two other propellers. The first propeller is called the "best practical propeller," because it is made up of the best propeller airfoils whose critical speeds are shown in figure 5, and the probable minimum practical blade thickness, shown in figure 7. These airfoils, it will be recalled, were intended to have the maximum possible critical speed for a given section lift coefficient and thickness. Therefore, the critical speeds of the "best practical propeller" are believed to be the highest attainable with any practical propeller. The second propeller, represented on figure 9, is the "ideal propeller" of zero-blade thickness and least lift-coefficient effect. Its critical speeds are the absolute maximum for any propeller, whatever. These critical speeds are based on theoretical considerations, without reference to airfoil test data.

Shown for comparison in figure 9, are propeller-section speeds for an airplane speed of 500 miles per hour. It is

seen that, were it possible to keep the propeller section lift coefficient below 0.4, an airplane speed of 500 miles per hour could be attained with this propeller before the entire blade was covered with a shock wave. With even lower coefficients, slightly higher speeds could be reached with a small part of the blade still below the critical speed.

Now, the results of figure 9 will have little significance until the seriousness of the effect of the shock wave upon propulsive efficiency is established. Before attempting this, however, some of the compromises which confront the designer will be discussed.

Practical propeller design for these speeds must compromise between section speed and section lift coefficient. Any effort to decrease the lift coefficient by increasing either the rpm or the diameter will, of course, only result in increased section speeds, so that no gain will be realized. The number of blades and the blade width can be increased, provided the thickness ratio is maintained. Without increasing the section speeds, this will reduce the lift coefficients. It will also have an admirable effect on the blade loading at take-off which, with high-speed airplanes, is always likely to be excessive. There are limitations on the extent to which this may be carried, however. A reduction in coefficient from 0.3 to 0.2 would require a 50-percent increase in blade width but, from figure 9, would only yield a 15-miles-per-hour increase in permissible section speed. Also, the centrifugal force creates a couple which must be resisted by the pitch control mechanism. This couple increases rapidly with blade width and blade angle. Since the torque which the pitch mechanism can exert is limited, the effect is to limit the blade width which can be employed.

Another compromise is brought about by the fact that the section L/D ratio has an important effect upon the efficiency. The low lift coefficients desirable from the compressibility standpoint, are generally considerably below the maximum L/D point. Fortunately, as the profile drag is reduced, the C_L for best L/D shifts downward. If it can be assumed that airfoils designed for the reduction of compressibility effects will have lower profile drag than is now current, the compromise required will not exact severe penalties.

The importance of adjusting the section lift coefficient to obtain high critical speeds has been indicated. With present data, however, it would be impossible to determine the angle of attack required at supercritical speeds to give a certain lift coefficient. Therefore, the lift coefficient at which the sections are to operate, cannot be controlled within wide limits by adjusting the pitch distribution. The result would be nullification of the advantages gained by the use of high-speed sections. Moreover, it is likely that even with complete data, a pitch distribution set to maintain the desired lift coefficients throughout the propeller diameter would result in a distribution at low speeds so completely unsuitable that the take-off and climb would be seriously affected.

In order to determine the effect of the shock wave, the propulsive efficiency will be checked for a propeller designed for 500 miles per hour at 20,000 feet. A three-blade propeller will be used to absorb 2000 brake horsepower. Since in the practical case a reasonable efficiency in climb must be obtained, this will require that the blade be unstalled at 250 miles per hour at 10,000 feet. The effect of this requirement will be to place a reasonable lower limit on the rpm for any diameter. The take-off will, of course, be sacrificed since the blades will be stalled at all speeds below the climb speed. For a conventional Hamilton Standard 6101 blade form with Clark Y sections, the minimum diameter that will satisfy the above conditions is plotted against the rpm in figure 10. Also shown, is the tip speed for a forward speed of 500 miles per hour. It is seen that this tip speed varies slowly with diameter. The section speeds shown on figures 8 and 9, correspond to the 13-foot 9-inch propeller on figure 10.

Now the effect of an extensive shock wave on the propulsive efficiency, will be determined by calculation for a propeller of 13-foot 9-inch diameter at 960 rpm. The airfoil sections will be those for the "best practical propeller," so that the critical speeds shown in figure 9 will apply. It is assumed that the airfoil characteristics are sufficiently well known at supercritical speeds, that the pitch distribution can be adjusted as desired. A uniform lift coefficient throughout the radius will be used, except over the blade-shank fairings, which are most advantageously set at zero lift.

Using simple blade-element theory, the propeller effi-

ciency has been calculated, assuming that the profile drag coefficients above the critical speed are in accordance with table I. No values greater than 0.12 were used. As noted above, these are the lowest coefficients that can conceivably result from interpretation of the NACA airfoil data. The fact that the maximum drag is not attained immediately at the critical speed, is offset by the previously noted difference between the calculated and the actual critical speed. Below the critical speed, the profile drag is assumed to be zero. The resulting efficiency appears in figure 11 as the curve marked " η_{max} ". The upper curve is calculated from the test data of reference 10, without tip-speed correction. Owing to the manner in which the assumptions have been built up, the curve of η_{max} is believed to represent the highest efficiency which can be attained with any practical propeller, provided only that the NACA airfoil data are applicable to propeller calculations. The lower curve in figure 11 is typical of propellers employing "best propeller airfoils" but having conventional pitch distributions.

Considerable investigation has shown that the efficiency at 500 miles per hour cannot be raised appreciably above the η_{max} curve by varying the usual propeller parameters, including the blade loading (number of blades) within reasonable limits. The primary variable which determines the magnitude of the efficiency at these speeds, is the drag coefficient in the supercritical range.

The sharp drop in efficiency (fig. 11) would be expected to occur at somewhat higher speeds, near sea level - perhaps between 500 and 550 miles per hour.

The efficiencies shown in figure 11 are high enough so that the possibility of flight above 500 miles per hour is not altogether precluded but are low enough to render such speeds impractical for the present unless some auxiliary means of propulsion become available. If it becomes possible to reduce present propeller-blade thicknesses materially, the speed at which the sudden efficiency drop occurs, can be shifted upward.

The results of reference 16, which indicate low drag coefficients at very high speeds, point to the possibility of improving the propeller efficiency by increasing the section speeds, once the entire blade has passed its speed for maximum drag coefficient. These results also indicate that compressibility imposes no absolute limit to useful propeller speeds.

EXPERIMENTAL CHECK

Because the available airfoil data indicate compressibility effects of immediate importance to high-speed airplanes, it becomes imperative that these data be checked.

Fortunately, this should be possible at an early date. Two experimental methods are suggested.

Airplanes which, by diving, can attain speeds in excess of 500 miles per hour, are now available. With an extremely simple test set-up, employing thrust meters and torque meters, the propeller efficiency can be measured over a wide range of speeds. The results can then be compared with predictions of the airfoil tests.

Thrust meters and torque meters were employed by the Lockheed Aircraft Corporation in 1939, to measure propeller efficiencies at moderate speeds, with satisfactory results. Results within plus or minus 5 percent would provide useful information, as present propeller calculations may well be in error by several times this amount at high speeds. It is felt that this accuracy could easily be obtained.

While flight tests would furnish an immediate answer to the question of validity of the airfoil data, a propeller-development program would probably require wind-tunnel tests at high forward speeds. When wind tunnels become available which can produce speeds of 500 miles per hour at working-section densities corresponding to about 20,000 feet, the duplication of full-scale compressibility effects becomes a simple matter. Figure 12a shows the range of airplane conditions which it would be desirable to cover. Figure 12b shows the model powers and rpm which would be required to duplicate the full-scale conditions exactly, except for Reynolds number. With a model-propeller diameter of 2.5 feet, a relatively small tunnel would suffice. The maximum model power required, would be 130 brake horsepower at 8720 rpm. High-frequency geared synchronous motors, to meet this requirement, could easily be built to fit inside a 12-inch nacelle. By correlation with the flight tests, the validity of the wind-tunnel tests could be established.

THE PROSPECTS FOR JET PROPULSION

The limitations which practical propellers place upon airplane speeds should stimulate the development of jet propulsion. Conventional airplanes, with engines available at present, appear to be limited to speeds in the neighborhood of 550 miles per hour at 20,000 feet, due to compressibility effects on portions other than the propeller. If the practical propeller characteristics derived in the preceding section be accepted, there remains a region some 50 miles per hour in extent which could hardly be explored immediately without the aid of jet propulsion. On the surface, at least, the development of this means does not appear to be particularly elaborate. In its embryonic form, it has been used for the last year or two on a number of airplanes here and abroad. Considerable research will be required before it will be advantageous to feather the propeller and proceed on jet thrust alone, but the results of development work are certain to receive widespread attention and universal application in high-speed airplanes.

It is beyond the scope of this paper to deal with jet propulsion, except in passing. It will suffice to mention that, in addition to being relatively free from compressibility limitations, the jet has the added advantage that its thrust is independent of speed. The propeller, whose thrust varies almost inversely with speed, may be described as an inherently low-speed device.

Lockheed Aircraft Corporation,
January 1941.

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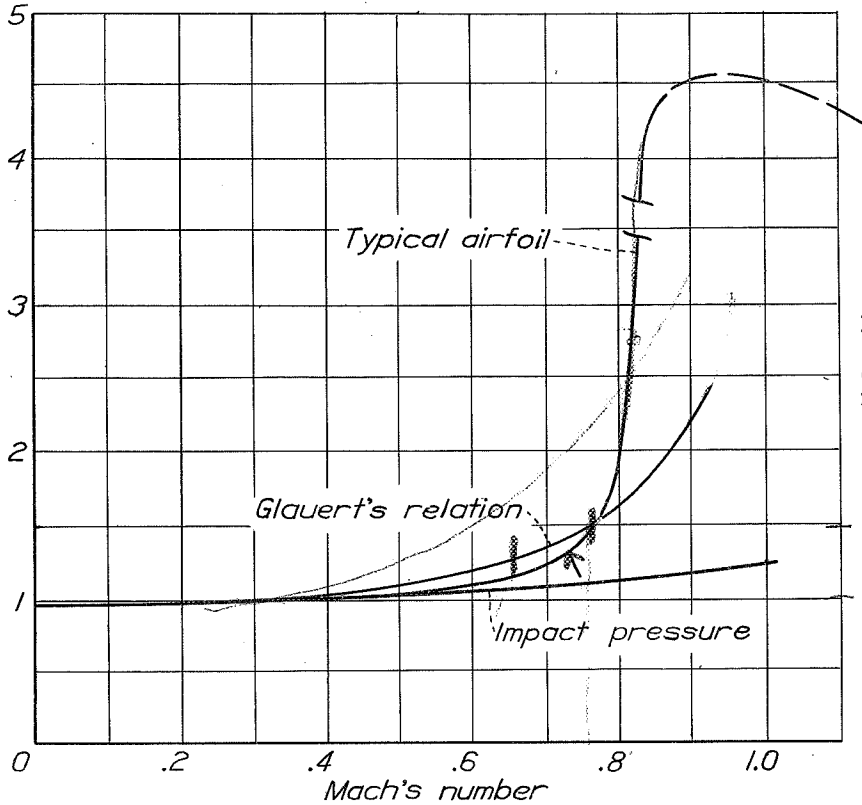


Figure 1.- The variation of drag with Mach's number.

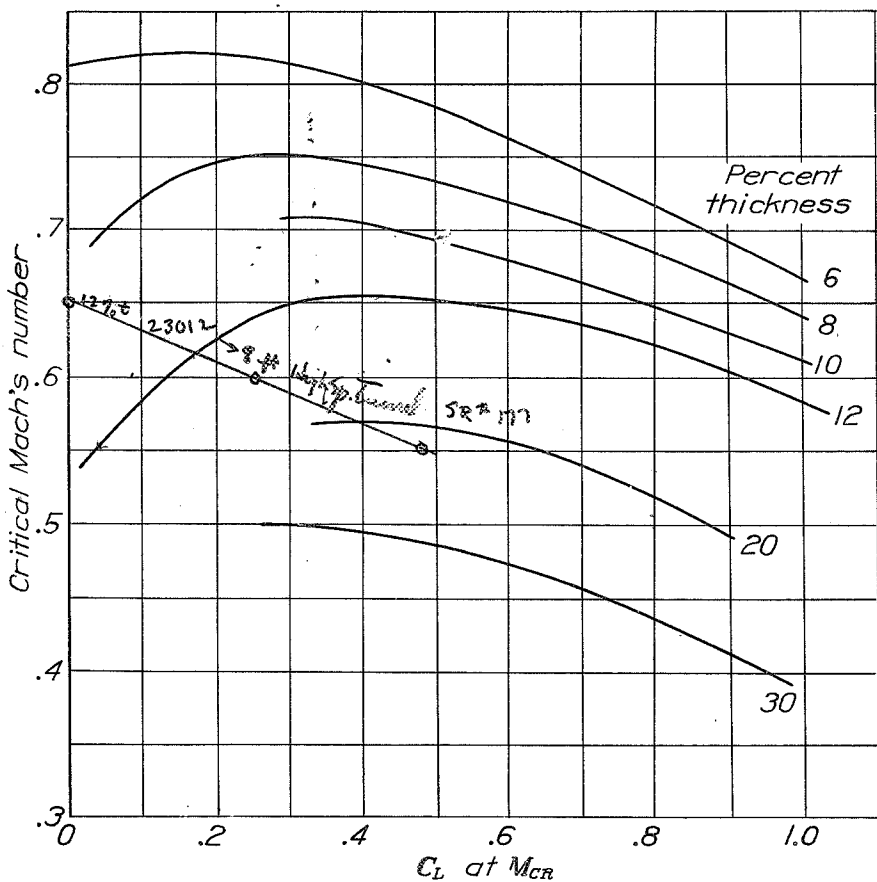


Figure 3.- The effect of thickness and lift coefficient on the critical Mach's number, Clark Y airfoil (ref. 8 and 9).
Data from NACA H.S. Throckmorton

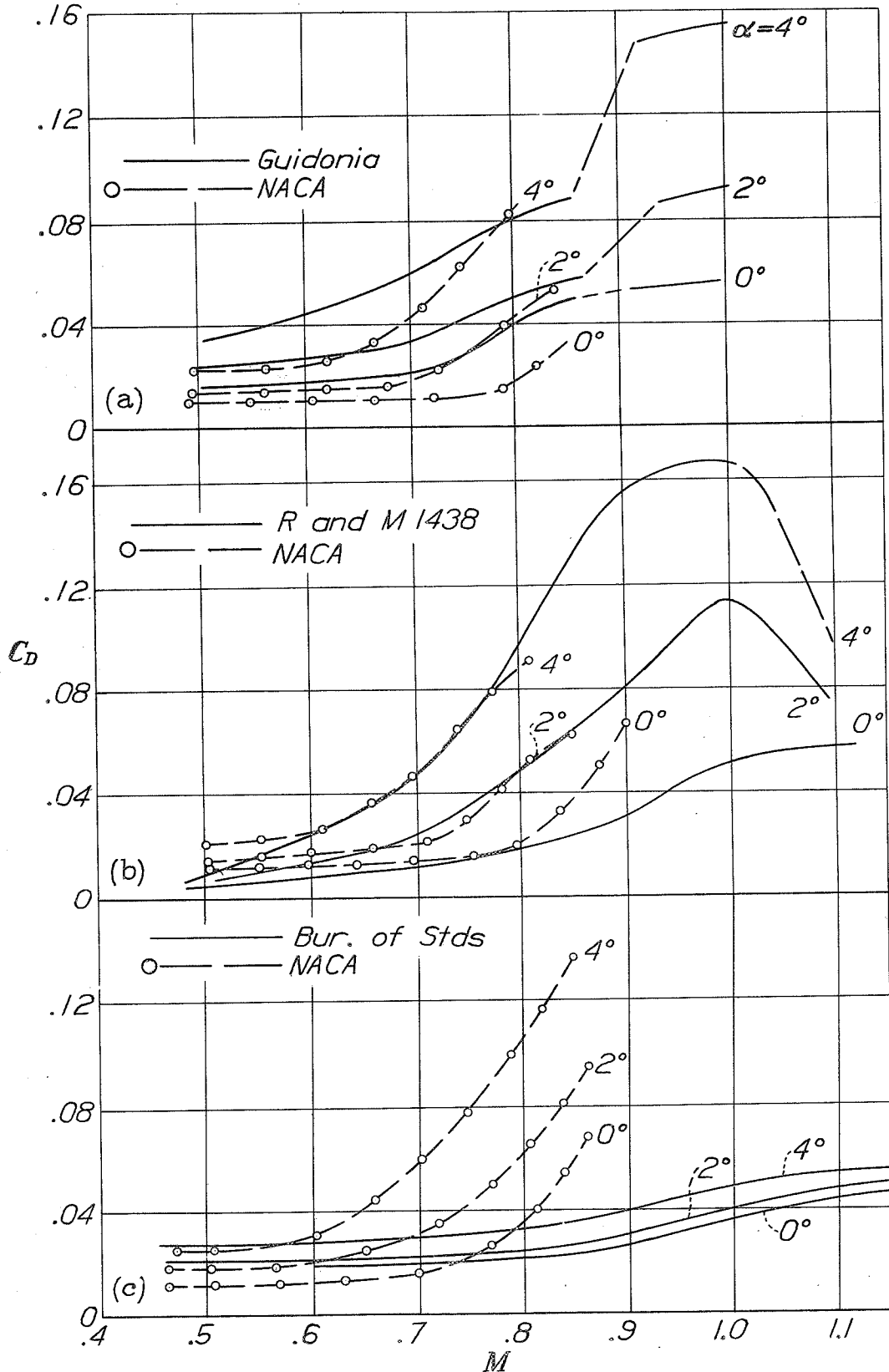


Figure 2.- Drag increase at the critical speed from several sources. (a) 6% Clark Y airfoils (b) RAF 6 airfoils (c) 8% Clark Y airfoils

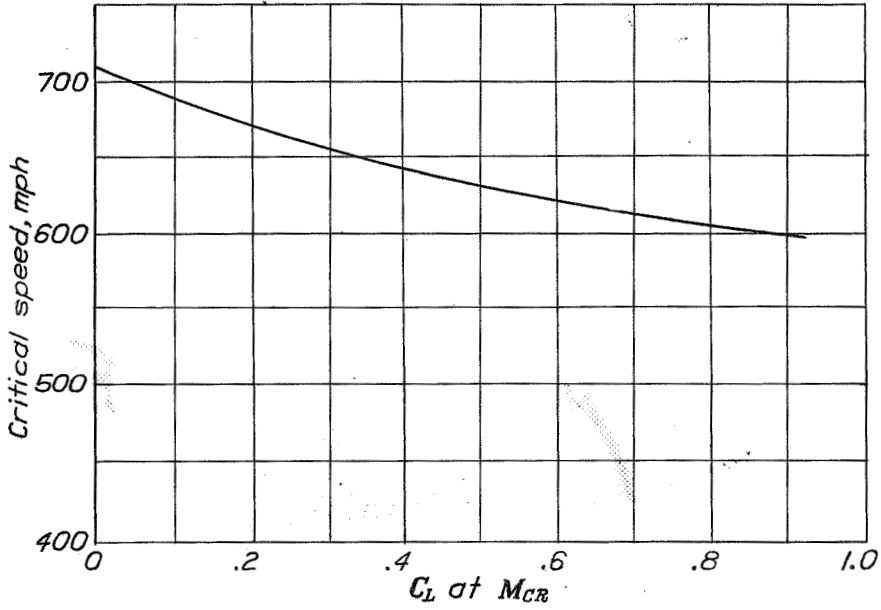


Figure 4.- Critical speeds for the ideal propeller airfoil at 20,000 feet. Effect of lift coefficient.

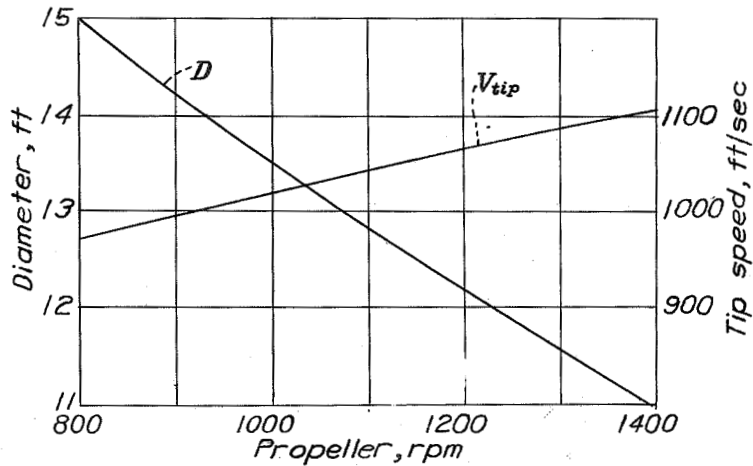


Figure 10.- Variation of tip speed with diameter and rpm. $V = 500$ mph.

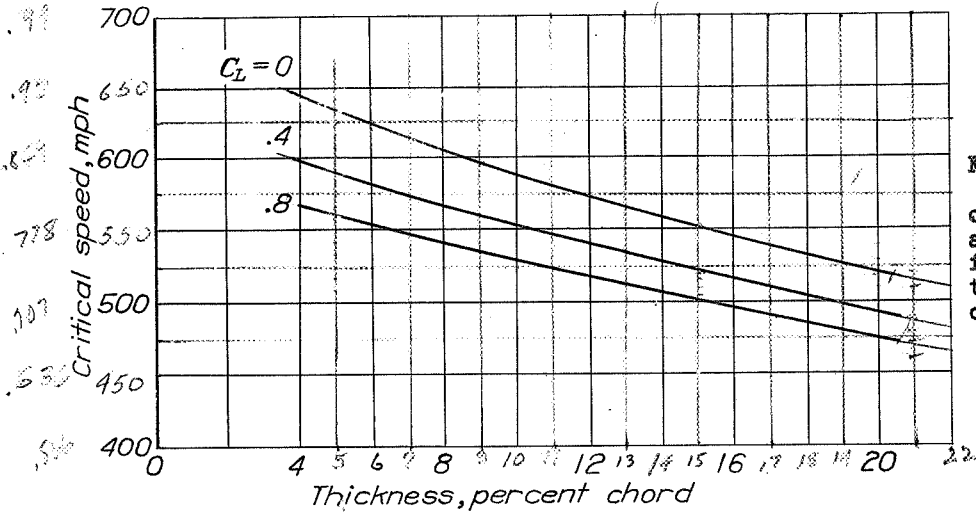


Figure 5.-Critical speeds of best propeller airfoil at 20,000 feet. Effect of thickness and lift coefficient.

$V_c = 706.75$

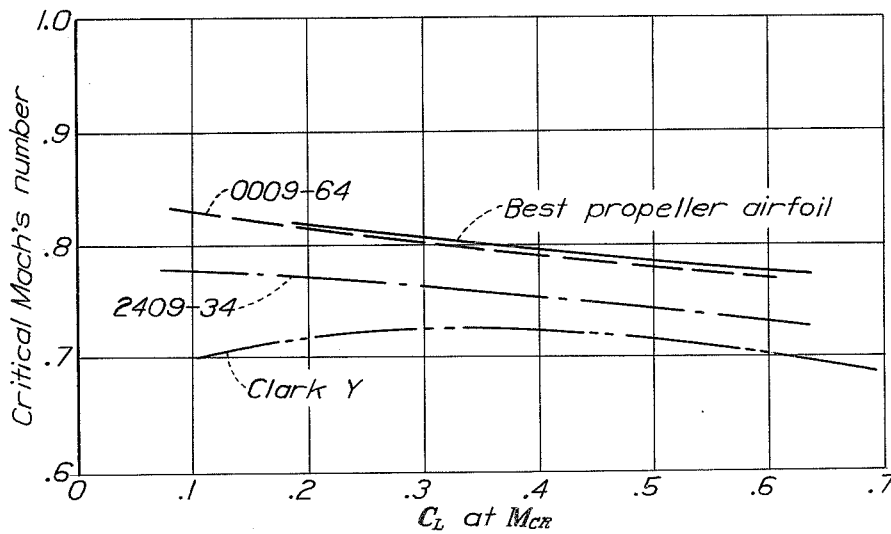


Figure 6.- Comparison of critical speeds of 9% thick airfoils.

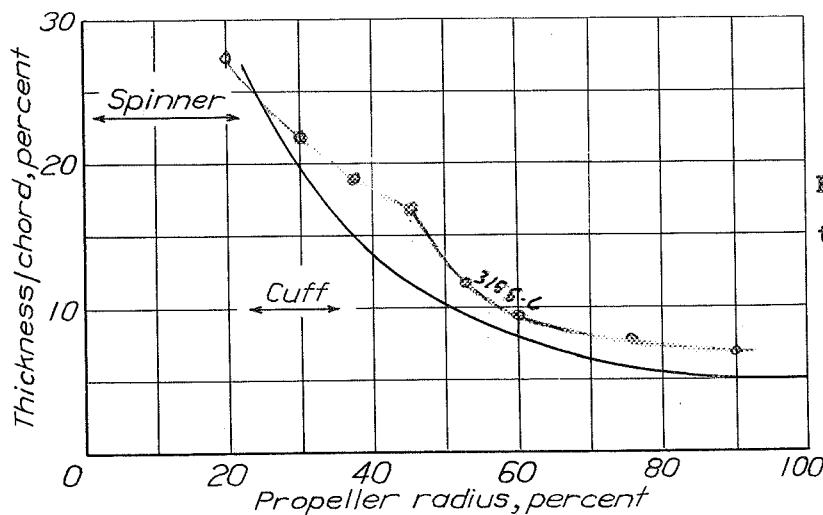


Figure 7.- The present minimum practical blade thickness.

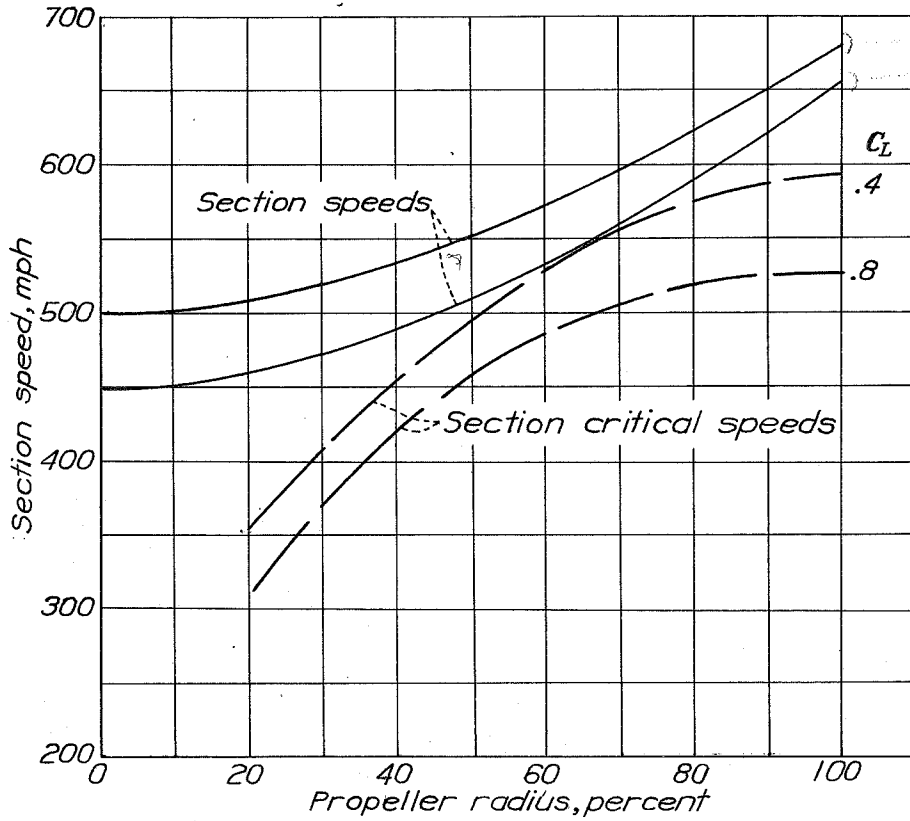


Figure 8.- Critical section speeds for propeller with Clark Y sections.

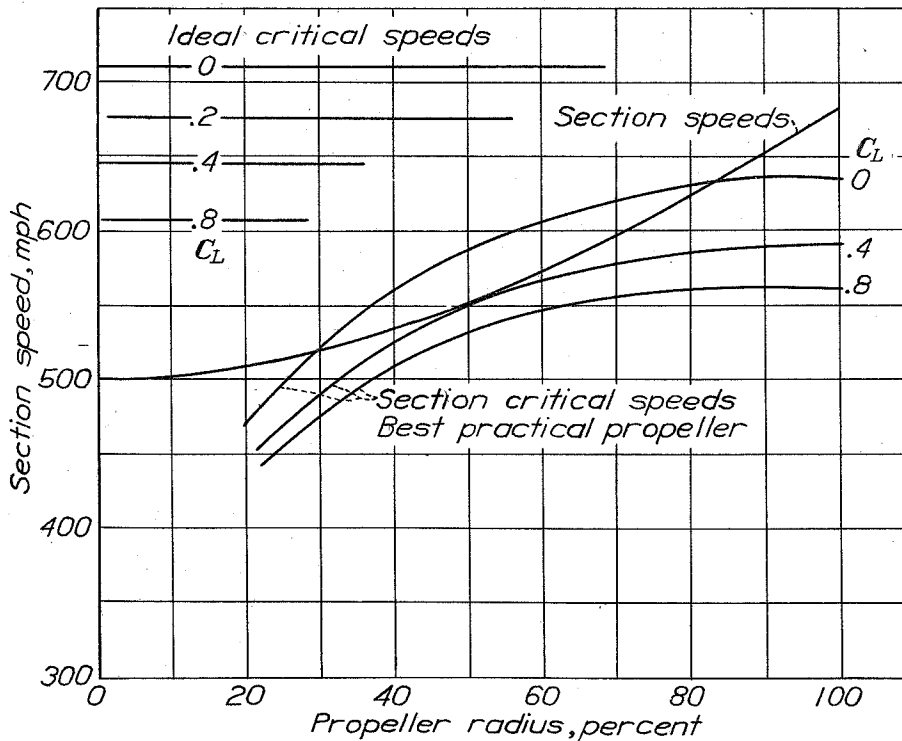


Figure 9.- Critical section speeds for best practical propeller.

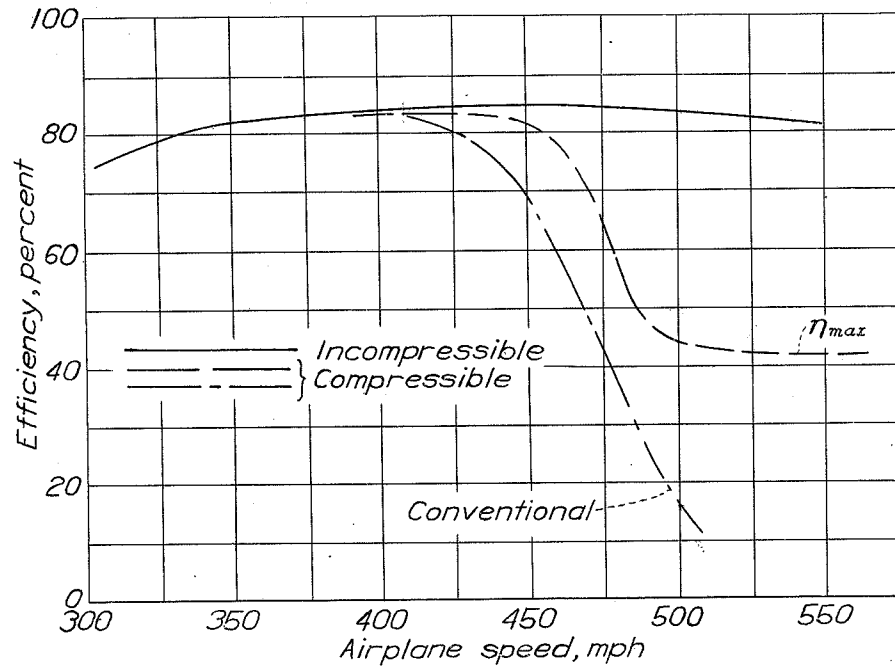


Figure 11.- Propeller efficiency at high forward speeds at 20,000 feet.

Figure 12.- (a) The range of airplane propeller parameters required for flight at 495 mph at 25,000 feet. $M = .647$
 (b) Wind tunnel power requirements to stimulate flight at 495 mph at 25,000 feet. $M = .647$
 Notes: $D = 2.5'$, $t = 59^{\circ}\text{F}$, $\rho/\rho_0 = .533$

