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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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# COMPRESSIBILITY EFFECTS IN AERONAUTICAL ENGINEERING

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## INTRODUCTION

Compressible-flow research, while a relatively new field in aeronautics, is very old, dating back almost to the development of the first firearm. Over the last hundred years, reasearches have been conducted in the ballistics field, but these results have been of practically no use in aeronautical engineering because the phenomena that have been studied have been the more or less steady supersonic condition of flow. Some work that has been done in connection with steam turbines, particularly nozzle studies, has been of value. In general, however, understanding of compressible-flow phenomena has been very incomplete and permitted no real basis for the solution of aeronautical engineering problems in which the flow is likely to be unsteady because regions of both subsonic and supersonic speeds may occur.

In the early phases of the development of the airplane, speeds were so low that the effects of compressibility could be justifiably ignored. During the last war and immediately after, however, propellers exhibited losses in efficiency as the tip speeds approached the speed of sound, and the first experiments of an aeronautical nature were therefore conducted with propellers. Results of these experiments indicated serious losses of efficiency, but aeronautical engineers were not seriously concerned at the time because it was generally possible to design propellers with quite low tip speeds. With the development of new engines having increased power and rotational speeds, however, the problem became of increasing importance.

The earliest experiments with airfoils were conducted at McCook Field. The results were reported in reference 1. These early tests of airfoils did not disclose the really difficult nature of compressibility phenomena because the highest speeds at which the tests were conducted were too low (approximately 600 fps). A short time later the NACA, foreseeing the trend toward higher engine speeds and appreciating the difficulties that might be expected with propellers for these engines, sponsored new experiments under the direction of Dr. L. J. Briggs and Dr. H. L. Dryden of the National Bureau of Standards. This work (references 2, 3, and 4) led to several important conclusions and clarified somewhat our ideas of the manner in which forces change as the result of compressibility effects. All this work suffered somewhat because of a lack of proper equipment, which could not at that time be made available partly because sufficient knowledge to determine the proper equipment was not available.

In the latter part of 1927, at the instigation of Dr. G. W. Lewis, research in high-velocity air flow was started at this laboratory. The first experiments were conducted with a small model tunnel from which was developed the 11-inch high-speed wind tunnel, the first really important compressibility-research instrument from an aeronautical standpoint. A few years later, the 24-inch and then the 8-foot high-speed wind tunnels were developed. The general nature of all this apparatus is quite well known and it need not be detailed here. Descriptions may be found in references 5, 6, and 7.

Recently the 11-inch high-speed wind tunnel was replaced by a new rectangular-type tunnel approximately 18 by 4 inches. A general view of the tunnel is given in figure 1. This tunnel is ideally suited to work of a fundamental character. The actuating jet and auxiliary equipment is for the most part the same as, or similar to, that previously used.

The first aerodynamic investigations conducted at this laboratory on compressible-flow problems were high-tip-speed propeller tests. These tests were made in the propeller-research tunnel at low forward speed (100 mph) and high rotational speeds. The results established the tip-speed limitation of 0.9 the speed of sound, a value that has been commonly used in design since that time. Shortly after this investigation, a program of Clark-Y and RAF-6-type blade sections at high speed was concluded in the then new 11-inch high-speed wind tunnel. These results were correlated with the propeller tests and, while a discrepancy was noted as regards the speed at which the propeller efficiency loss due to compressibility effects occurred, it was found that the general form of the propeller efficiency loss was closely related to the changes found in airfoil characteristics at high speeds.

Research with airfoils was continued principally with a view to developing improved airfoils for propeller operation, the propeller being at that time the only part of the airplane that was a compressibility problem. A fair measure of success was immediately achieved with the development of the class of airfoil having the maximum thickness at 40 percent of the chord (reference 8). It became apparent, however, that detailed knowledge of the flow phenomena was required to permit the immediate development of optimum airfoil shapes.

Fundamental investigations were therefore undertaken with marked success in both the 11-inch and the 24-inch high-speed wind tunnels. The results obtained from these fundamental investigations permitted the rapid development in the last few years of aerodynamic forms more suitable for high speeds.

## FUNDAMENTAL CONSIDERATIONS

The significance of the speed of sound in aeronautical engineering problems is more readily understood when one appreciates that it is the rate of pressure propagation. General methods employed in aeronautical engineering are based on theories of fluid flow for incompressible fluids or, in other words, for fluids which have an infinite rate of pressure propagation. Hence, in the application of this theory to any problems, the assumption that the speeds are small in relation to the rate of pressure propagation is made automatically. For fluids such as air, which have a fairly low speed of sound (normal rate of pressure propagation), the theory can be expected to apply only when the velocities are quite low. Failure of the theory to describe the actual flow can be expected as speeds increase and, finally, when the speed of sound is approached, a radically different type of flow should be expected.

From an engineering standpoint it is important to know at first how great are the energy losses in a new type of flow which may be established. Unfortunately, it has been shown that the type of flow which occurs as air speeds approach the speed of sound causes very great energy losses. The new type of flow is, of course, complicated, and it cannot in any sense be concluded that sufficient detailed knowledge of this type of flow has been obtained to eliminate restriction in design work. Nevertheless, experiments made at this laboratory over the last 6 years have illustrated many of the principal difficulties and have shown, as well, methods for overcoming the compressibility losses in the speed range of importance in the present emergency.

Early photographs (reference 9) illustrate that compression shock forms in flows as they approach the speed of sound. These compression shocks cause such large energy losses that normal flight is rendered impracticable, and it is therefore necessary in designing to avoid these losses. Photographs of the flow for a typical airfoil taken in the new rectangular high-speed tunnel are shown in figures 2 to 5. These photographs illustrate the same sort of phenomena as our early photographs so far as the establishment of compression-shock phenomena is concerned, but they show, in addition, considerable wake detail. Technically, the significance of the new pictures is very great, in that changes shown in the wake aid in explaining some of the phenomena that had been observed from total pressure loss measurements, which up to now had not been very clear.

The phenomenon has been named the compressibility burble and is described in some detail in references 9 and 10. In addition to the breakdown of flow which occurs at high speed, there are important flow changes that occur progressively as the speed is increased.

Starting at very low speeds, there occurs a close representation of the potential flow of the theory. With increase of speed the lift, drag, and moment coefficients increase numerically until finally a critical speed is reached at which a new type of flow involving compression shock occurs. When the critical speed is reached, the lift drops and the drag rises abruptly. Concurrently with the changes in the force and moment coefficients the pressures acting on the airfoil also increase in magnitude.

Theoretical analyses by Glauert and Ackeret have shown that the lift, moment, and pressure coefficients given by the incompressible-flow theory are increased by the factor $1/\sqrt{1 - M^2}$, where $M$ is the ratio of the translational speed of the body to the speed of sound. This result was derived by assuming that the speed of sound through the whole flow was the same as that for the undisturbed stream. It can be shown that this is equivalent to assuming that induced velocities are zero so far as they may influence the effects of compressibility for the flow for the whole airfoil or body. Thus, while the factor, from an engineering standpoint, is reasonably accurate, it can, in the simplest case, be expected to underestimate the effect of compressibility by an amount that increases with the induced velocities. For a thin airfoil the theoretical factor is reasonably accurate, but it tends to be of decreasing accuracy as thickness ratio or lift coefficient increases.

A further consequence of the increase in local pressures indicated by the theory is the steepening of pressure gradients with increasing Mach number. Thus, if the local pressures are increased in the ratio $1/\sqrt{1 - M^2}$, the increment in pressure at points where high negative pressures occur is greater than the increments in pressure at points on the body where the local pressure is near stream velocity. Hence, pressure gradients become greater with increase in Mach number. Actually, such steepening of pressure gradients has been found and, in most instances, the gradient is much steeper than the theory would indicate. This is, of course, a consequence of the effective neglect of the induced velocities. As pointed out earlier, the theoretical variation of the peak pressure with Mach number underestimates the effect of compressibility by amounts that increase with the induced velocity. Thus, the underestimation is greatest where the induced velocity is greatest. For bluff bodies or even conventional airfoils very large increases in the pressure gradients have been found.

In summary of the basic theory, then, it is found that the lift, moment, and pressure coefficients and the pressure gradients are increased by important amounts. The theory is substantiated by experiments, and the experimental results plus basic consideration of the theoretical assumptions show that the theoretical variation $1/\sqrt{1 - M^2}$ underestimates the effects of compressibility by an amount that increases with the induced velocity.

The theory, being a potential flow theory, neglects the effects of viscosity and thus gives zero drag regardless of the Mach number. It is not to be inferred, however, that important drag changes are absent. Basically, the drag is determined by the skin friction and by what is sometimes called "pressure" drag which arises as a result of flow separation. The skin friction drag is determined, of course, by the local velocities just outside the boundary layer and the location of the transition point. It has been shown that the pressures acting on a body, and so the local velocities, are increased as the Mach number is increased. Consequently the skin friction drag is increased, even if there are no changes in the character of the boundary layer or the transition-point location.

Effects of compressibility on the transition-point location are not clear at present and considerable further basic research is necessary, but it is probably fair to assume in the light of present information that the transition-point location at high Reynolds numbers will not be greatly affected, provided the location of the peak negative pressure remains fixed. In interpreting model results from wind-tunnel tests at low Reynolds number and particularly in nonturbulent tunnels where transition may occur in a region of adverse pressure gradient, some forward movement of the transition point may be expected with increasing Mach number because of the tendency of compressibility effects to steepen the adverse gradient.

For bodies having some pressure drag, the steepening of the adverse pressure gradient as a result of compressibility effects brings about still earlier separation as the Mach number is increased and so very large drag increases at speeds well below the critical. In many instances forms having, for all practical purposes, no pressure drag at low speeds, and hence no flow separation, ~~has~~ have shown pronounced separation at high speeds. This effect is evidenced by the shape of the drag curve plotted against Mach number. Thin, efficient airfoils, for example, usually show only a very slight variation with Mach number until the critical speed is reached, when the drag rises abruptly. With increase in thickness ratio, however, the same basic form may show a considerable increase in drag with Mach number in the subcritical speed range. An example is shown in figure 6 for two 16-series airfoils. The data are presented as drag coefficients plotted against the ratio of the Mach number to the critical Mach number for each of the two airfoils. Shown in this manner, the drag curves for the two airfoils would be essentially parallel if adverse gradients did not influence the drag coefficient. Actually the curves are very nearly parallel for speeds up to approximately 60 percent of the critical Mach number, but at higher speeds the difference in drag for the two airfoils increases. At low speeds the essential difference in the flow for the two airfoils is in the slightly higher peak negative pressure and the slightly higher adverse gradient for the thicker airfoil. With increase of speed the peak negative pressure for both airfoils is increased in very nearly the same amount, and the location of the peak negative pressure remains unchanged. It would be expected, therefore, that the increments in skin friction drag would remain the same and thus should not disturb the parallelism of the two curves. The adverse gradient for the thicker airfoil is, however, greater than for the thinner airfoil, and hence the tendency toward separation effects is greater for the thicker airfoil. As the Mach number increases, fundamental considerations have shown that the adverse gradient steepens and the thicker airfoil, having the greater initial adverse gradient, is likely to show drag increases at lower speeds than the thin airfoil. The problem is by no means clearly understood, but numerous similar examples have been found. The effect seems more pronounced with conventional airfoils and with thick airfoils. Even if the present incomplete state of our knowledge of the problem is considered, the generally conservative procedure indicated is to adopt the thinnest sections having the highest critical speeds consistent with other requirements of the wing.

The danger of flow separation is, of course, greatest for those forms or attitudes of forms which have large adverse gradients. An example of considerable importance is shown by the maximum lift data of figure 7. These data, taken from tests of an NACA 0012 in the NACA 19-foot pressure tunnel, show the usual variation in maximum lift coefficient with Reynolds number to speeds somewhat above 100 miles per hour; beyond this speed the maximum lift coefficient decreases and the decrease is due to the failure of the flow to overcome the steeper adverse gradients that occur with increasing Mach number. In substantiation of this conception there is shown a second curve from identical tests of the same model in the pressure tunnel, but at $2\frac{1}{2}$ atmospheres pressure. Thus, at two different Reynolds numbers it is noted that the maximum lift coefficient decreases at exactly the same Mach number. This result is not of academic interest only, but may be of considerable importance in wind-tunnel-testing techniques for maximum-lift-coefficient investigations of airfoils. Speeds less than 100 miles per hour are indicated unless the trend to extreme wing loadings is continued, in which event tests at the correct Mach number may be required, and higher Reynolds numbers must be obtained with larger models in larger wind tunnels or by tests under increased pressure. These results are also of importance in relation to the comparison of sections suitable for propellers where the take-off and climb are important. The blade-section speeds are generally high and selection of sections showing high maximum lift coefficients at low speeds may be very misleading, particularly with conventional sections for which the high maximum lift coefficients are obtained by very high loading over the leading-edge region.

## PREDICTION OF THE CRITICAL SPEED

Phenomena in the supercritical speed range where compression shock occurs are very complicated and quite interesting. From a practical aeronautical engineering viewpoint these phenomena are not yet of great importance because it is now generally practicable to design shapes having sufficiently high critical speeds. It is important from the aeronautical viewpoint, however, to know the critical speed so that shapes having sufficiently high critical speeds can be selected to eliminate serious limitation of the airplane performance.

Experiments have shown and fundamental consideration indicates that compression shocks form when the local speed of sound is attained in any part of the general flow field. Some instances have been found in which speeds slightly greater than the local speed of sound have been attained without the presence of compression shock, but these cases have been few and the amount the local speed of sound has been exceeded has been only a very small percentage. For engineering applications, therefore, the critical speed has been defined as the translation velocity at which the sum of the translational velocity and the maximum induced velocity equals the local speed of sound. It can be calculated from either theoretical incompressible flow-pressure distribution or from measured low-speed pressures and the compressibility modification factor $1/\sqrt{1 - M^2}$. The methods for the prediction of the critical speed have been discussed in detail in references 9 and 10. Reference 11 treats many particular examples in detail including interference effects and is, for engineering problems, extremely useful and important. It is important, however, in engineering applications to appreciate the limitations.

It has been pointed out that the theoretical factor of $1/\sqrt{1 - M^2}$ underestimates the effect of compressibility; hence calculations of the critical speed based on this factor tend to overestimate the critical speed. Recently Von Kármán has derived a new relation which appears to permit a better approximation. With either the simple theory or Von Kármán's relation it is important to realize, however, that the estimations decrease in accuracy as the flow departs from the simple potential flow. Abnormal boundary-layer changes that can influence the external flow may cause large discrepancies in the determination of the critical speed, considering the critical speed as the speed at which compression shocks are established. Any separation phenomena that may occur tend to lower the peak pressures and so raise the speed at which compression shocks may occur. Likewise, any bodies that have steep adverse pressure gradients at low speeds may separate at higher speeds because of further steepening of the adverse gradient. Such separation effects result, of course, in increased drag but also raise the speed at which compression shock is formed. An interesting example is the variation of the drag and the critical speed of cylinders shown in figure 8. The drag curves of the small-diameter cylinders at low Reynolds numbers show apparently the same critical speeds as the drag curves for the large cylinders at higher Reynolds numbers. This is apparently a paradoxical result because the maximum negative pressures for the cylinder at the low Reynolds number are very much less than the maximum negative pressures for the cylinders at the high Reynolds numbers, and large differences in critical speed should be expected. A few experiments in the new, rectangular high-speed wind tunnel during trial runs to check tunnel operation and the schlieren apparatus have given the explanation. For the small cylinder of low Reynolds number the compression shock actually does not occur until Mach numbers of the order of 0.55 are reached. The rise in drag in the Mach number region from 0.4 to 0.55 is due, as shown by flow observation in the new rectangular high-speed wind tunnel, to a forward movement of the separation point with increased Mach number. Admittedly the cylinders are an extreme case, but they illustrate in somewhat magnified form some of the effects that may be expected in lesser degree with better aerodynamic bodies. Such severe effects are not ordinarily found except for quite thick airfoil forms or bad wing-body junctures. Research with airfoils (reference 9) has led to the general conclusion that the critical speed can be quite accurately determined for bodies that are not susceptible to radical flow changes. For most good aerodynamic bodies and, it is perhaps true to add that for the only shapes that can be used on high-speed aircraft, the critical speed can be quite accurately predicted. A curve based on Von Kármán's new relation rather than the older Glauert-Ackeret approximation to enable the prediction of the critical speed is given in figure 9. For the purpose of comparison figure 10 illustrates the accuracy of the two relations as compared to experimental results.

## THE PRESENT STATUS

Airfoils.- The bulk of the development of new forms has been done mainly with airfoils, and the results of this work have been applied to other forms, such as cowls and fuselages. Figure 11 illustrates the present status so far as airfoil forms are concerned. Critical speeds are shown in miles per hour at 25,000 feet plotted against thickness ratio. The lower two curves show the critical speeds for airfoils of the 230 series, and the newer 16-series airfoils (which have been designed to have minimum induced velocities), for a lift coefficient of 0.2, approximately the design high-speed lift coefficient for airplanes with normal wing loadings. The upper curve shows the variation in critical speed for a 16-type airfoil at zero lift coefficient. The root-thickness range marked on the chart from 12 to 16 percent illustrates the range of minimum root-thickness ratio, which seems currently practicalbe for most classes of airplanes. With the 230 series of airfoil, critical speeds of the order of 450 miles per hour are indicated at 25,000 feet; with the 16-series, critical speeds of the order of 500 miles per hour are indicated. It is apparent that important changes in wing design are in order almost immediately.

It is not to be assumed, on the basis of results shown on this chart, that it is practical to design up to the critical speed of the wing section. Aerodynamic interference effects may lower the critical speed, and increased skin friction or separation effects, brought on by the subcritical compressibility phenomena, may bring about large increase in drag.

Figure 12 illustrates the general effect of compressibility for an NACA 0012 airfoil, for which important separation phenomena are not found. The variation of drag with Reynolds number, as illustrated from low-speed tests, departs considerably from the variation shown by results in the same Reynolds number range but at higher speeds. The amount of the departure increases with increasing Mach number until finally the critical speed is reached, when the drag rises precipitously. Differences in drag below the critical speed may be as great as 15 percent, depending upon the speed. For this particular example, drag increases due to compressibility appear to start at Mach numbers of the order of 0.21, or approximately 30 percent of the airfoil critical Mach number.

In the selection of a wing, therefore, it is important to select a form which gives reasonable clearance on critical speed. When wings of large thickness are considered, the variation just discussed may be much greater because some separation may occur as a result of the increasing adverse gradient. For practically all military applications, except trainers and certain types of ground-cooperation airplanes, airfoils with very low peak pressures and high critical speeds are indicated.

Aerodynamic interference.- It has been shown in reference 11 that if two bodies are operating together, such as a wing and a fuselage, the critical speed of the combination may be lower than the critical speed of either body operating alone. Actually, the condition is such that the body having the lower critical speed is operating in the superstream velocity field of the adjacent body. The critical speed of the combination then, to a first approximation, is less than the critical speed of the body having the lower value by an amount equivalent to the superstream velocity of the adjacent body at the critical Mach number of the combination. With some conventional arrangements decreases of critical speed at the wing root of the order of 8 percent can be expected.

It has been found possible and practical, however, to eliminate the adverse interference effect on critical speeds by reshaping the fuselage in the region of the juncture. The wing root chord can be increased and, if the basic shape and the absolute thickness in inches are not changed, the root-thickness ratio is reduced and so the critical speed at the juncture is increased.

Another and perhaps a better method is to reshape the fuselage so that the fuselage superstream velocities in the region of the wing are reduced. An indication of the practicability of this means of eliminating adverse interference effects is given in reference 15, from which the drag data for two different bodies tested on the same wing presented in figure 13 are taken. At the time these tests were made, it was, unfortunately, impossible to extend the tests to higher speeds, but the difference in shape of the drag curves for the two combinations indicates that nose 1 body 1 has the earlier adverse compressibility effects and so the lower critical speed. The likely cause for the higher critical speed of nose 2 body 2 is that lower fuselage superstream velocities exist in the region of the wing as a consequence of the long, parallel center body. Other tests made recently at lower speeds in the pressure tunnel following the lead indicated in figure 13 resulted in the development of a wing-root juncture at which the measured pressures were the same as for the wing alone. Thus, the induced velocities for the fuselage in the region of the wing were reduced to zero and adverse interference effect on critical speed was eliminated. The new fuselage shape had its maximum width slightly ahead of the wing, and the width decreased slightly between the wing leading and trailing edges. Though insufficient data are available at present to permit the establishment of a generalized form suitable for all applications, it does appear feasible to eliminate adverse interference effect for the usual applications.

Cowlings.- The first forms of NACA cowlings were developed many years ago and at a time when, except for the propeller, compressibility effects were relatively unimportant. The development program was conducted in low-speed wind tunnels, and the general lack of knowledge of compressibility phenomena precluded the possibility of interpreting or extrapolating the low-speed data for applications in the high-speed ranges now contemplated. It is not surprising, therefore, that cowl forms having low critical speeds resulted. Further, some modifications of the original NACA cowl forms introduced by designers led to the use of forms having very low critical speeds.

Some cowling forms in use a few years ago had critical speeds as low as 300 miles per hour at 25,000 feet. A brief summary of cowl development is shown in figure 14. NACA cowling C (reference 12) represents the result of the first research directed toward developing cowls having higher critical speeds. At 25,000 feet cowl C has a critical speed of 432 miles per hour. This form of cowl is in use on most of our present-day airplanes. Some modifications of this cowl have been introduced, however, and from the standpoint of compressibility phenomena these modifications have been uniformly bad. It is important to realize that these cowling forms cannot be extensively changed without developing high peak pressures, with the consequent tendency to flow separation and low critical speeds. Strict adherence to the basic forms becomes of vital importance with increasing speeds and cannot be overemphasized.

Recent development of cowl forms (reference 13) has led to a new type, the NACA high-speed cowl. The critical speed, as shown in figure 14, is 593 miles per hour at 25,000 feet. From the compressibility standpoint the cowling problem is well solved by this cowl, at least for the present emergency.

The development of the newer cowl forms for very high speeds is treated very thoroughly in reference 13. These forms, in addition to their high critical speed, have been developed to take in air without any detrimental effect on the external flow and, in fact, some applications of the new nose forms have shown a beneficial effect on the external flow.

Utilization of waste heat.- Ordinarily not considered a compressibility effect, but nevertheless a phenomenon definitely associated with the attainment of high speeds, is the possible gain through the utilitization of waste heat. When speeds are sufficiently high, the ratio of the stop pressure of the air to the static pressure yields compression ratios sufficiently high that the addition of heat in the region of high pressure causes an increase in the kinetic energy of the air when discharged. The theoretical basis is discussed by Meredith in reference 14, and the phenomenon has become known as the Meredith effect.

Experiments have been recently completed in the 8-foot high-speed wind tunnel to investigate the practical possibilities. These results are currently being analyzed. Some of the data are shown in figure 15. The possible gains are plotted against the compression ratio, which is, of course, a function of the speed. Measurements of the recovery possible were made by force tests of the complete model and also by wake measurements. The results from both methods are in agreement and check the theory as well. The numerous points represent values for several heat quantities. If a 2000-horsepower engine is assumed, the scale values of the heat input ranged from less than that of the cooling-air heat alone to twice the engine power. At high speeds, which correspond to high compression ratios, important gains are definitely practicable and can be realized if the cooling system embodies good design. The efficiency is shown clearly to be a function of the pressure ratio. With poor installations having high pressure drop, the compression ratio is reduced and so, in addition to the cooling power loss, the gain from waste heat is reduced.

Figure 16 has been prepared to illustrate the magnitude of the gains possible. The power recovered from the cooling air only has been considered. A pressure drop of 7 inches of water, a propeller efficiency of 80 percent, and heat rejection to the cooling air of one-half the brake horsepower has been assumed. At 500 miles per hour and 25,000 feet, the gain possible is approximately 6 percent of the brake thrust power. Further gain is, of course, possible through utilization of the exhaust gases, either as added heat at the high-pressure region or in ejector stacks. Since the heat in the exhaust gases is approximately twice that of the engine cooling air, the gains from this source would be proportionately increased.

Propellers.- The study of compressibility phenomena was initiated because of difficulties in propeller design. While marked gains have been made, the propeller still offers the most serious compressibility problem. The speed of the propeller is always appreciably greater than the speed of the airplane because of the rotational component. Further, because of structural and vibration problems that have been encountered, the blade-section thickness ratios, particularly inboard, have been very great and as a consequence have low critical speeds. Initially, the compressibility problem with propellers was associated with the tip portions only, but, because of recent and contemplated increases in airplane speeds, practically the entire propeller is affected. Some propellers, having exposed cylindrical blade shanks, offer difficulties at speeds slightly over 300 miles per hour.

One pursuit airplane investigated some time ago in the full-scale tunnel showed possibilities of attaining a speed approaching 400 miles per hour at altitude, provided reasonable propeller efficiency could be obtained. An examination of the propeller provided with the airplane at conditions of 400 miles per hour at 20,000 feet indicated that serious difficulty might be encountered. The blade-section speeds and the blade-section critical speeds are shown in figure 17. At this airplane speed and altitude, adverse compressibility effects exist over the entire blade. The likely efficiency is problematical but cannot be placed very high. Study of the problem in the light of new blade sections available (reference 16) indicates that with relatively small changes the propeller can be made to operate with normal efficiencies. The changes involve the use of cuffs having new late compressibility-type sections extending from the spinner to approximately 45 percent of the radius. The blade-section thickness ratio, after the installation of cuffs, is 25 percent. An increase in blade solidity over the outboard portions of approximately 14 percent to decrease the lift coefficient and the thickness ratio, and the use of the cuffs inboard permits sufficient gain in critical speed, as shown by the upper curve, to eliminate adverse compressibility effects except for the tip sections. A lower gear ratio and somewhat higher solidity are indicated.

For this particular design the blade efficiency can be maintained by slight changes. With further increase in speed and altitude, however, the problem becomes acute. An examination of the general type of propeller that may be required at speeds of 500 miles per hour and 25,000 feet is interesting. The curve shown on figure 18 gives the blade section speeds if it is assumed that the 2800 engine with the 0.4 gear ratio and an $11\frac{1}{4}$-foot diameter propeller are used. The points shown on the curve indicate the critical speeds of the sections that would be selected. The blade sections assumed are the late critical-speed type. The lift coefficient assumed is 0.3 at the 0.7 radius, and this is decreased toward the tip and the root. The blade-section thickness ratios vary from 0.04 outboard to 0.12 at the 0.4 radius. At these lift coefficients extreme solidities are required to absorb the power. The necessary blade plan form, with a three-blade propeller, is shown on the figure. Of course, if more blades are chosen, the blade width will decrease. It is important to realize, however, that neither the thickness ratio nor the lift coefficient can be increased because the critical speed would be exceeded.

2400
.90
2160

The blade, as shown, has approximately three times normal blade widths. If a six-blade counterrotating propeller were to be used, the blade widths would, of course, be reduced accordingly, but the same blade-section thickness ratios and lift coefficients would be required in order to avoid compressibility losses. Thus, a suitable propeller would be a counterrotating six-blade propeller, having blades each approximately $1\frac{1}{2}$ normal solidity and thickness ratios of one-half to three-quarters those now in use.

In the design of propellers for such high speeds and altitudes, clearance on critical speed is the primary condition. As pointed out above, low lift coefficients are necessary. An important consequence of the low lift coefficients with high solidity is improved efficiency in the take-off and climb conditions. The low operating lift coefficients at high speed effectively increase the useful angle of attack or blade-angle range and a wider range of V/nD between the high-speed condition and maximum thrust coefficient is obtained. Thus, development of wider blades offers gains both in high speed and in take-off and climb.

Flight experience.- The general nature of the compressibility phenomena has been disclosed entirely by wind-tunnel research. The phenomena, as found are in agreement with general fundamental concepts. Nevertheless, questions have arisen as to the validity of the general results in flight and these questions appear to be based on pilot reports. Admittedly, there may be some tunnel-wall effects, but, so far as the general nature of the phenomena is concerned, these effects are quite likely of second-order importance. Some authentic flight-test data have been obtained. The existence of compression shock with the consequent drag rise was found and, in general, the nature of the compressibility burble as shown by the wind-tunnel research was shown by the flight-test results.

Figure 19 illustrates the general nature of the flow as shown by pressure-distribution measurements in flight and in the wind tunnel. Exact correlation is, of course, not to be expected because airfoil sections differ, and, furthermore, the flight-test data are not for a unique value of the Mach number but rather are averages for the range of Mach numbers shown on each plot. The general rise in pressures with increasing Mach number is evident, as is the shock which is shown by the discontinuity in the pressure-distribution curves. It is clear that the phenomena as found in flight are in excellent agreement with the prior wind-tunnel research.

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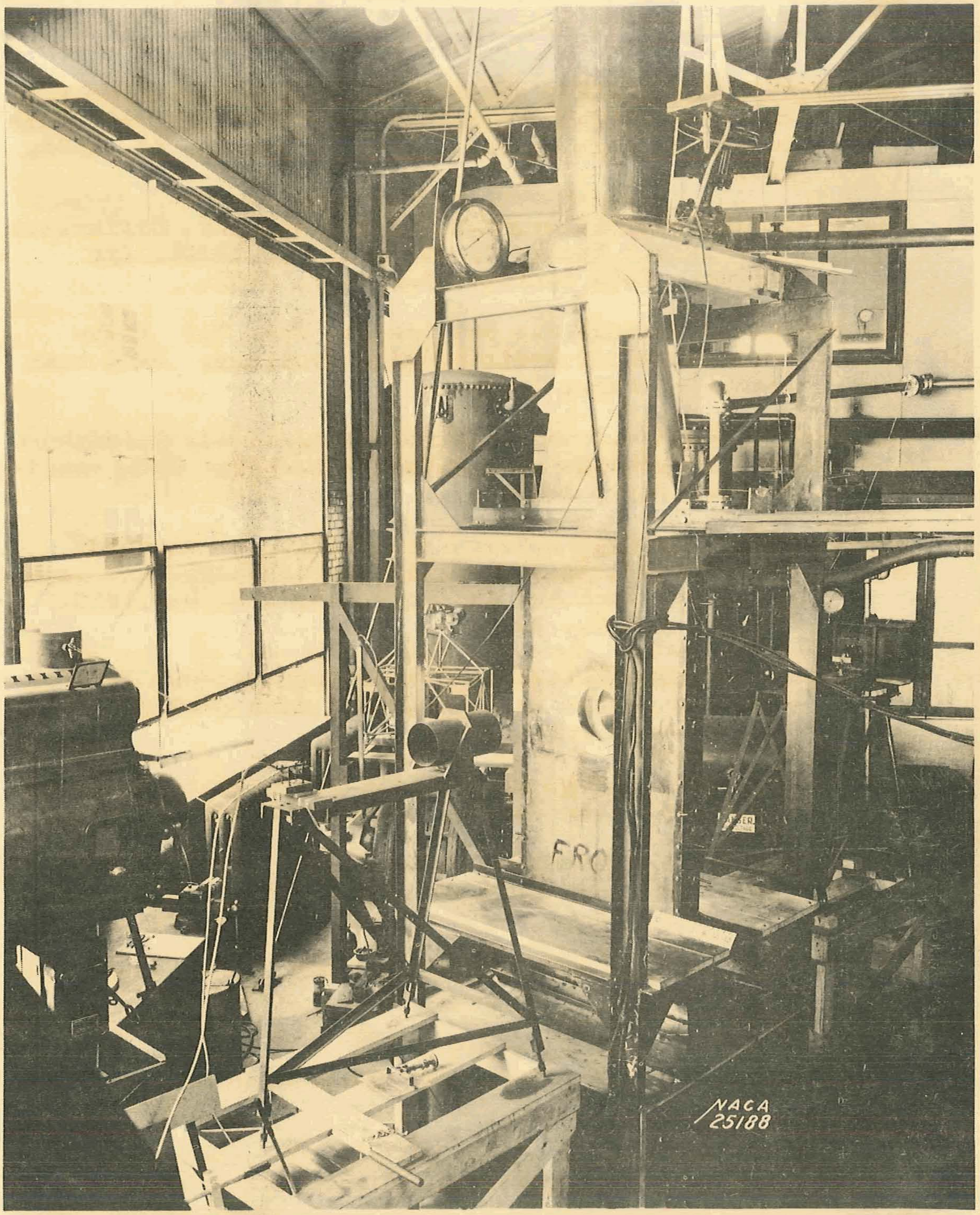


Figure 1.- General view of NACA rectangular high-speed wind tunnel and schlieren photography apparatus.

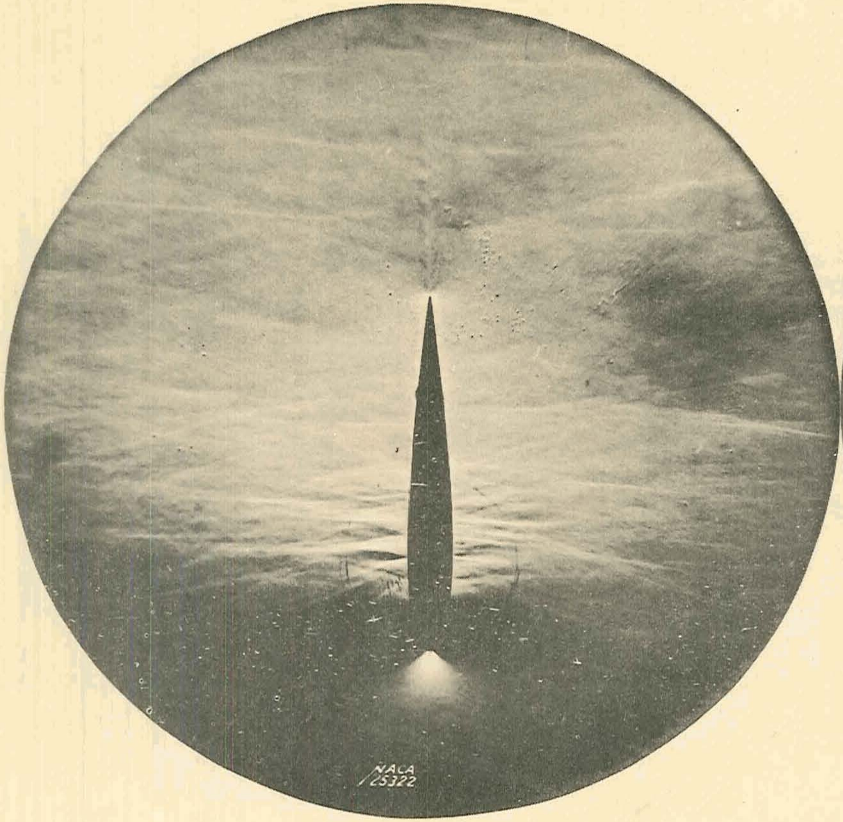


Figure 2.- Schlieren photograph of NACA 0012 airfoil of 2-inch chord. Incipient stage of shock formation. NACA 20-by 4-inch high-speed wind tunnel; Mach number, 0.764.

Figure 3.- Schlieren photograph of NACA 0012 airfoil of 2-inch chord. Shock front established and drag rising sharply. NACA 20-by 4-inch high-speed wind tunnel; Mach number, 0.835.

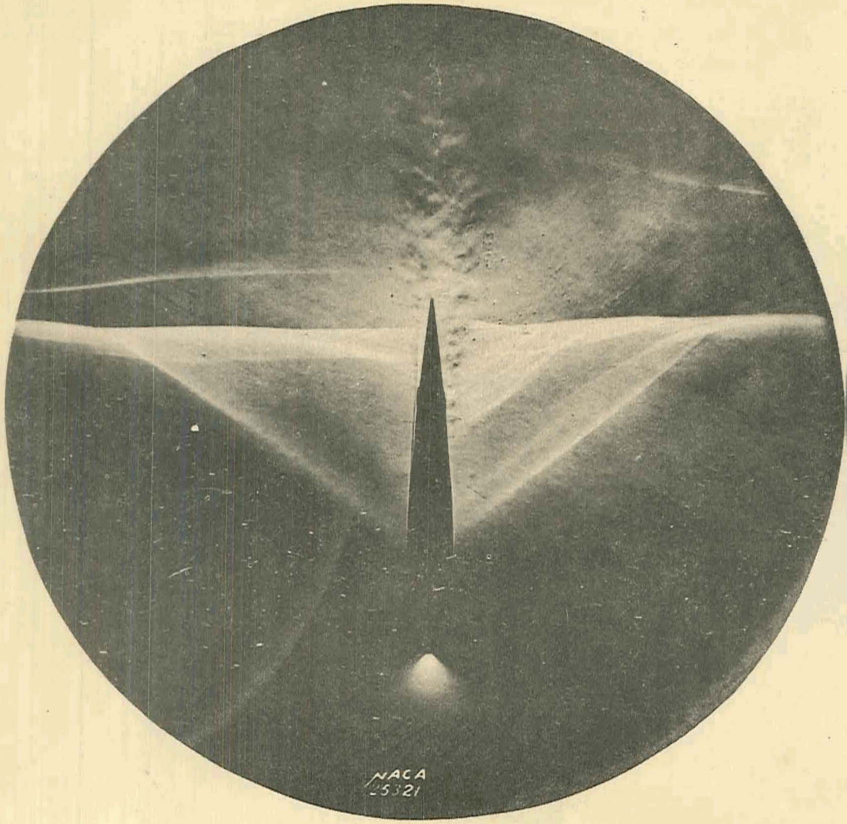


Figure 4.- Schlieren photograph of NACA 0012 airfoil of 2-inch chord.
Drag coefficients many times the law-speed values; flow unsteady. NACA 20-by 4-inch high-speed wind tunnel; Mach number, 0.893.

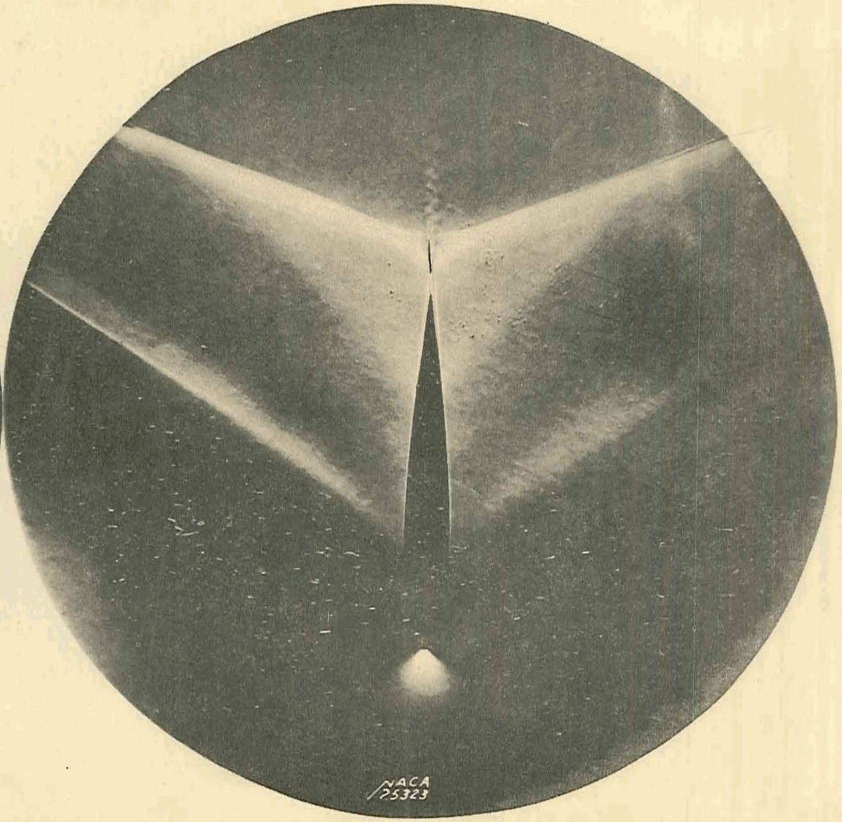


Figure 5.- Schlieren photograph of NACA 0012 airfoil of 2-inch chord.
Flow reasonably steady; drag coefficient may have reached peak value. NACA 20-by 4-inch high-speed wind tunnel; Mach number, 0.895.

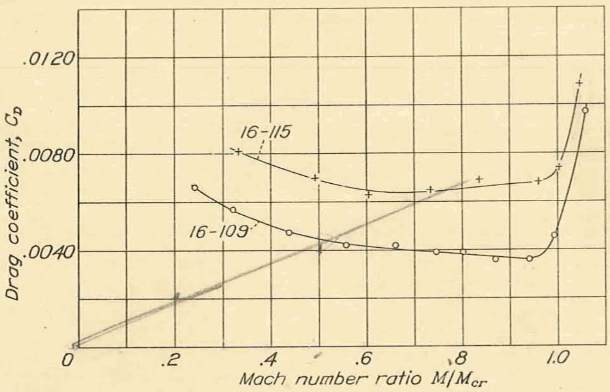


Figure 6.- Effect of Mach number on drag coefficient. NACA 16-series airfoils of 5-inch chord; NACA 24-inch high-speed wind tunnel; α,0°.

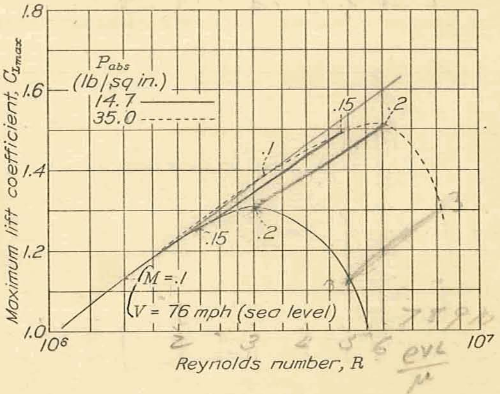


Figure 7.- Effect of Reynolds number and Mach number on maximum lift coefficient. NACA 0012 airfoil; 19-foot pressure tunnel.

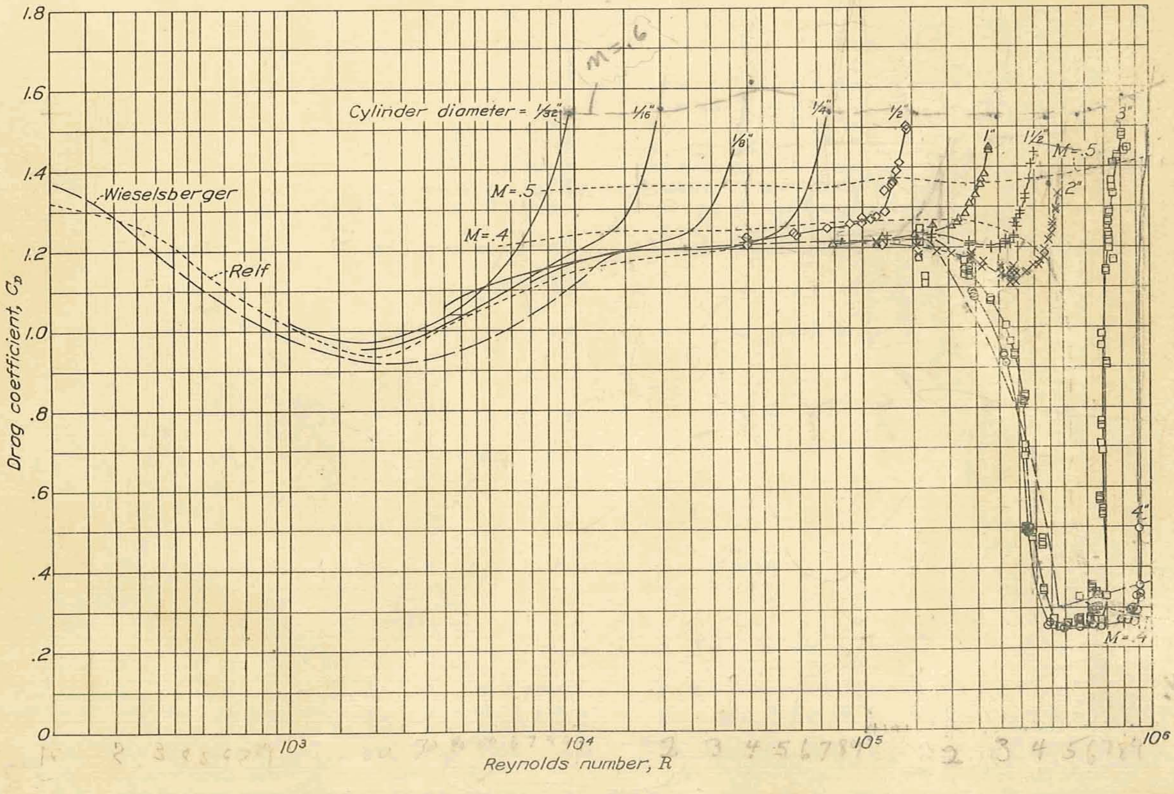
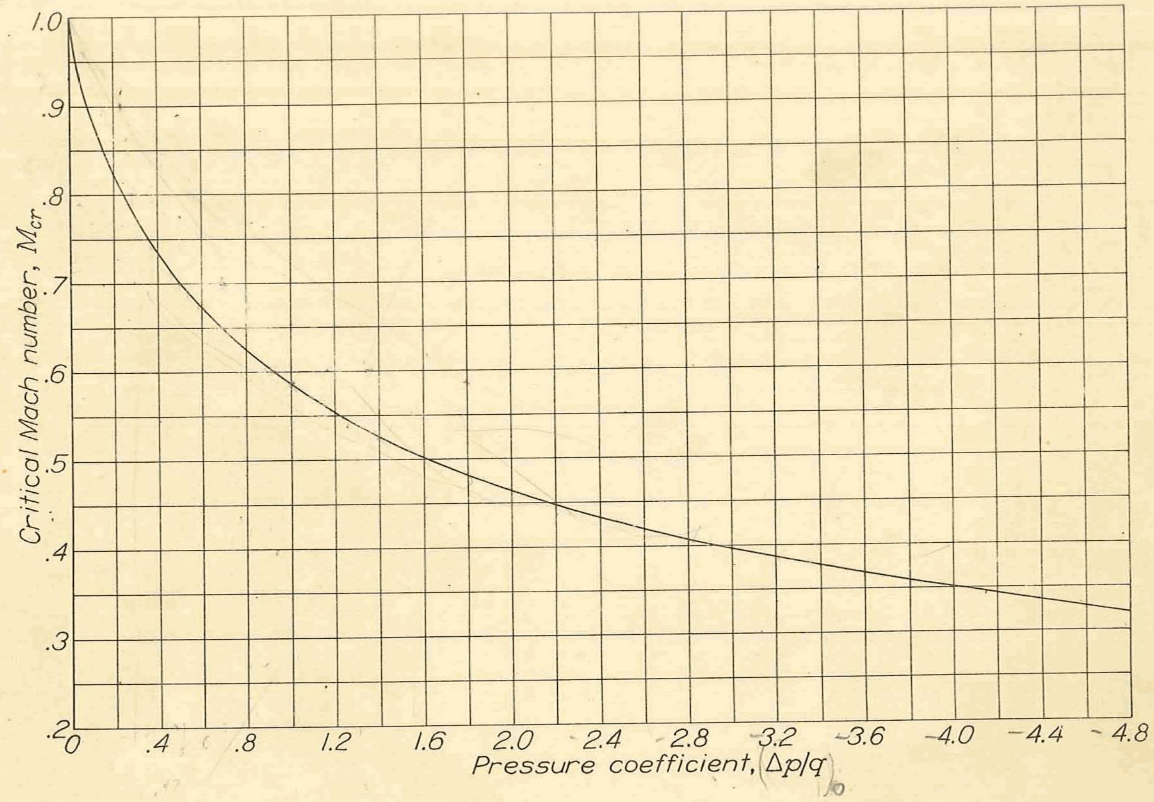


Figure 8.- Drag of circular cylinders.



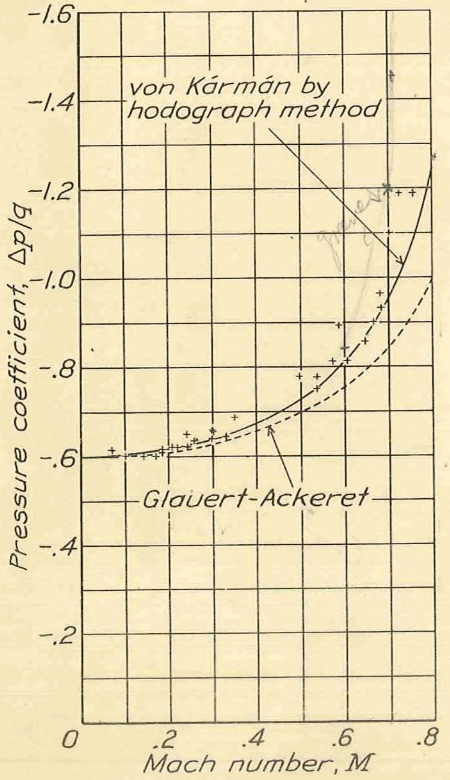


Figure 9.- Effect of critical Mach number on pressure coefficients for incompressible flow. Curve based on von Kármán derivation by hodograph method.

$$(\Delta p/q)_M = \frac{(\Delta p/q)_o}{\sqrt{1-M^2} + \frac{M^2}{2(1+\sqrt{1-M^2})}(\Delta p/q)_o}$$

Figure 10.- Effect of Mach number on pressure coefficients. Data from figure 12 of NACA report No. 646; from upper surface of NACA 4412 airfoil at $\alpha$ = -2° in NACA 24-inch high-speed wind tunnel.

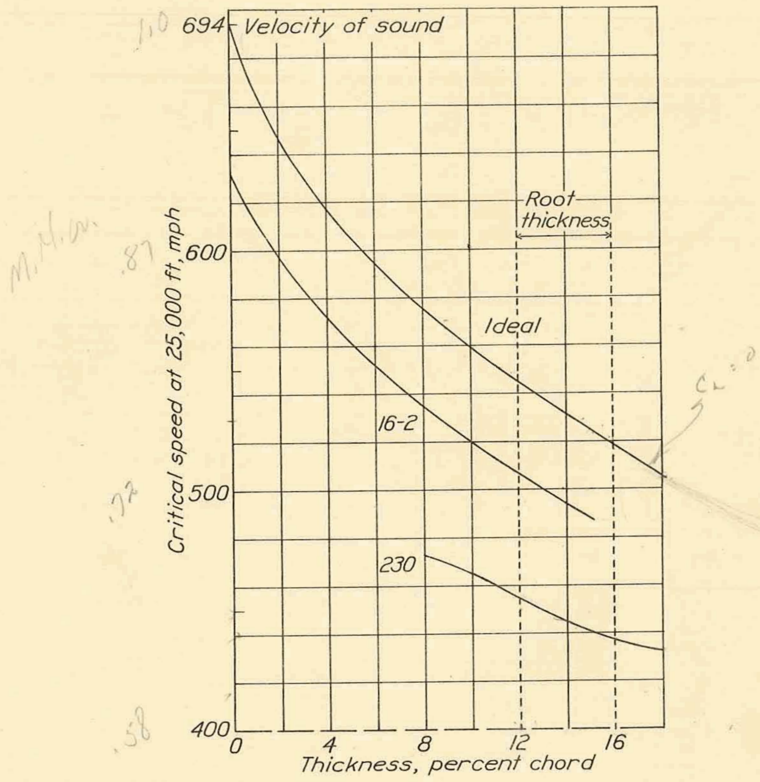


Figure 11.- Airfoil critical speeds.

$C_L = .20$

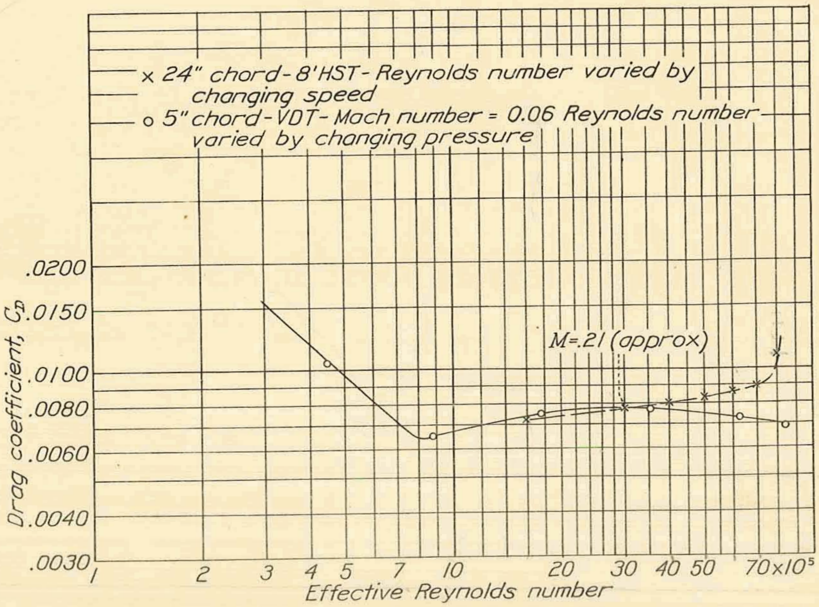
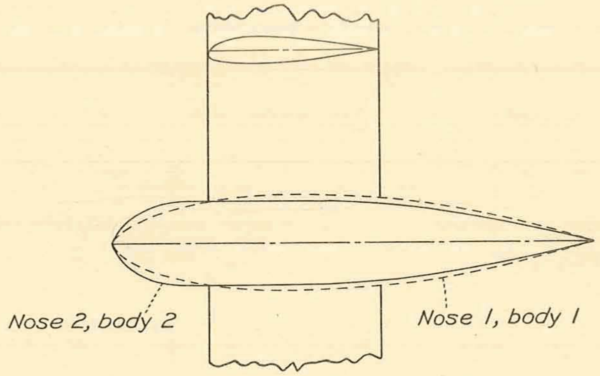


Figure 12.- Effect of compressibility on the drag coefficient. NACA 0012 airfoil.



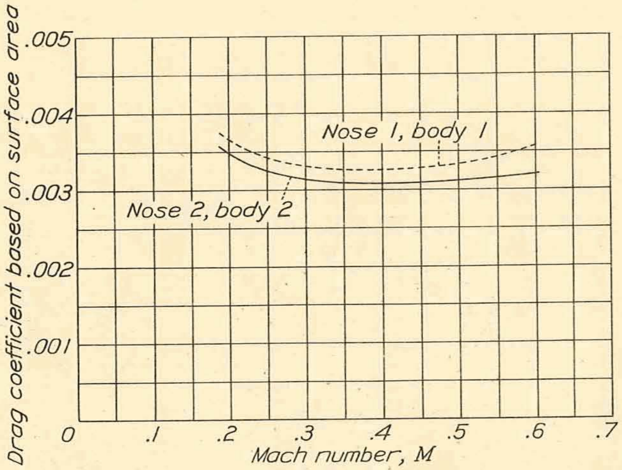


Figure 13.- Effect of Mach number on drag coefficient for two wing-fuselage combinations. Data from reference 15.

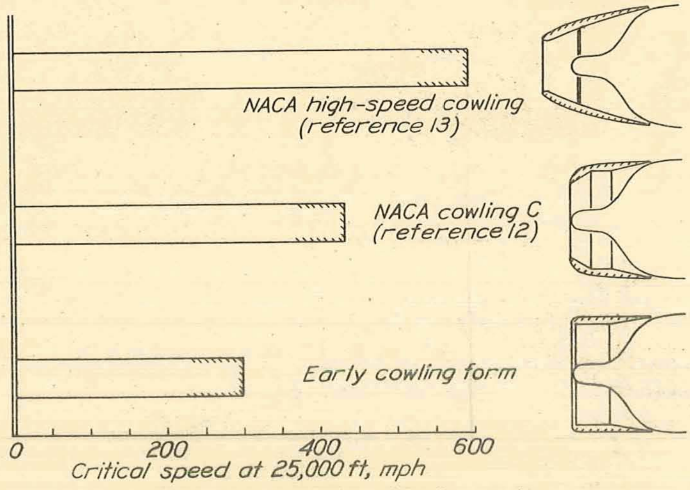


Figure 14.- Cowling development.

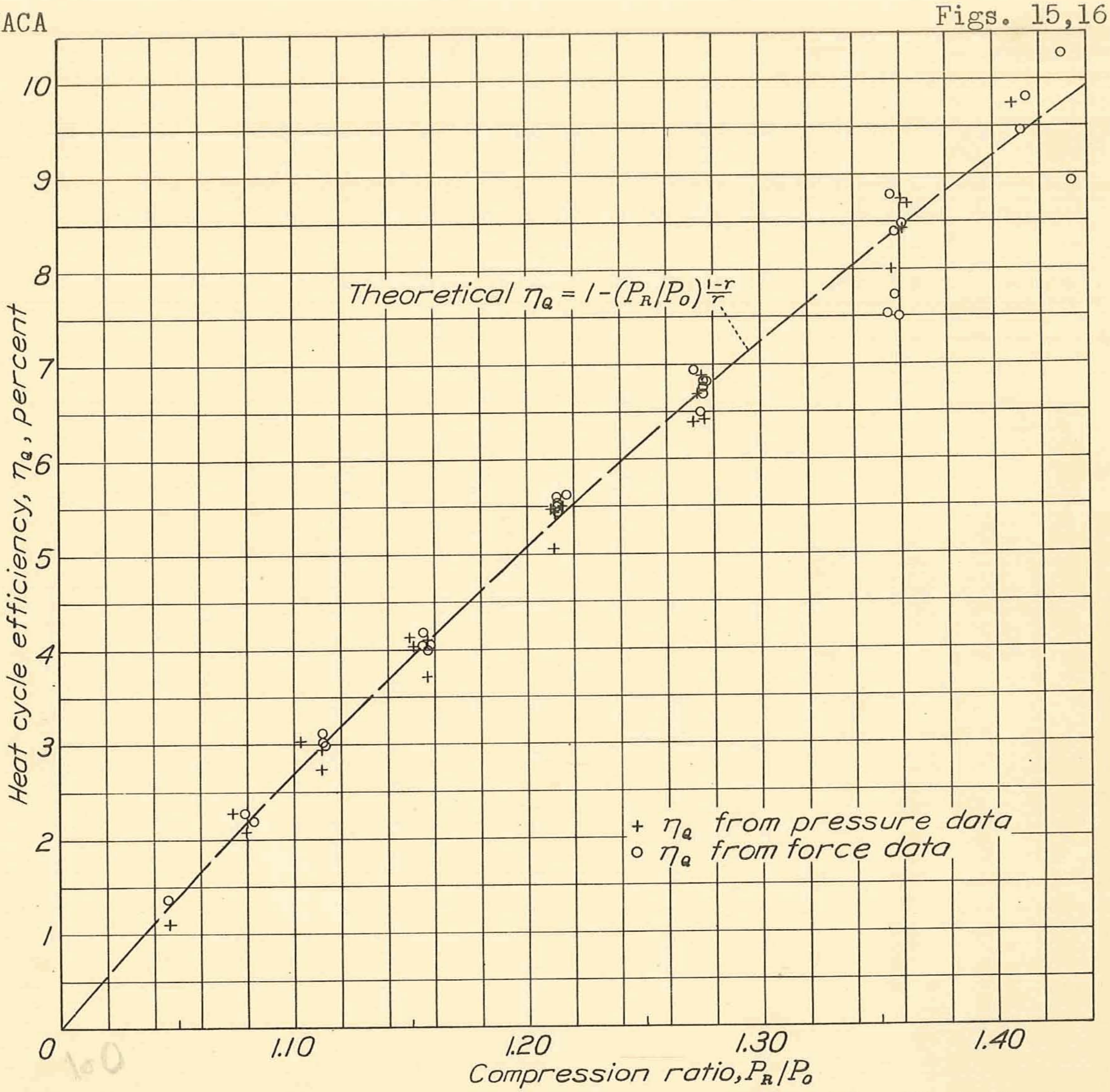


Figure 15.- Waste heat recovery.

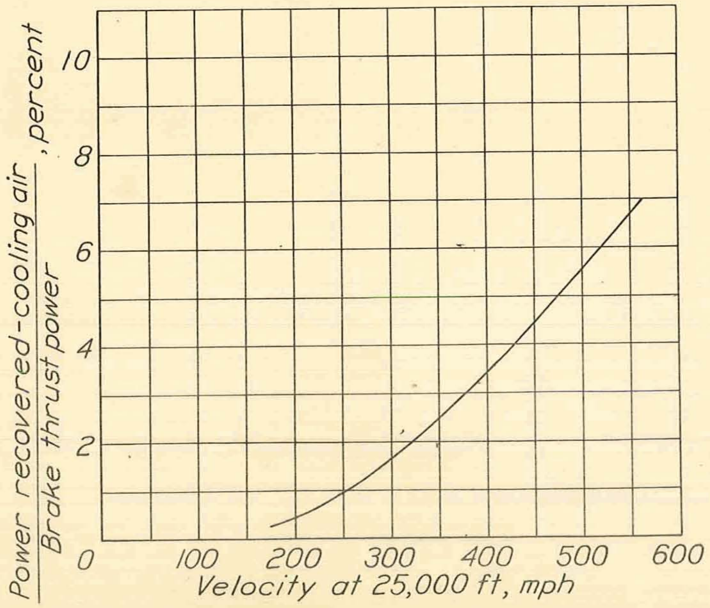


Figure 16.- Meredith effect.

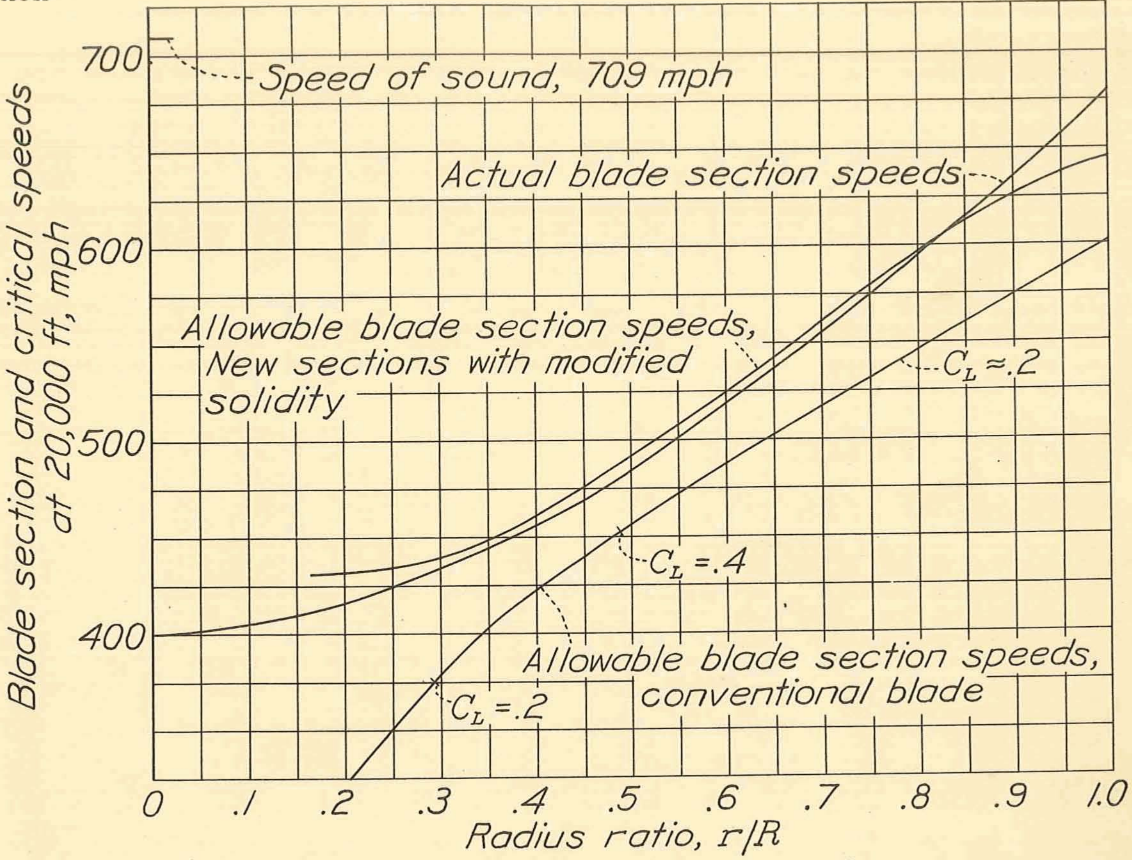


Figure 17.- Critical propeller speeds.

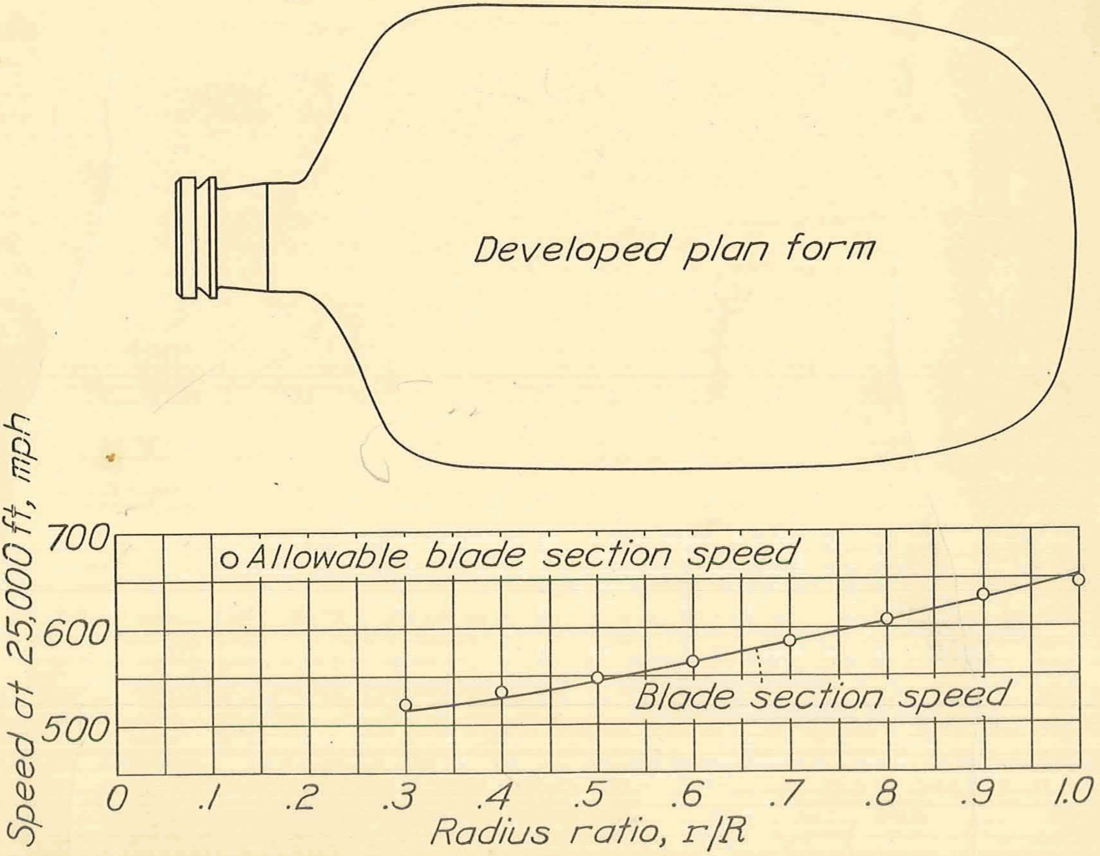
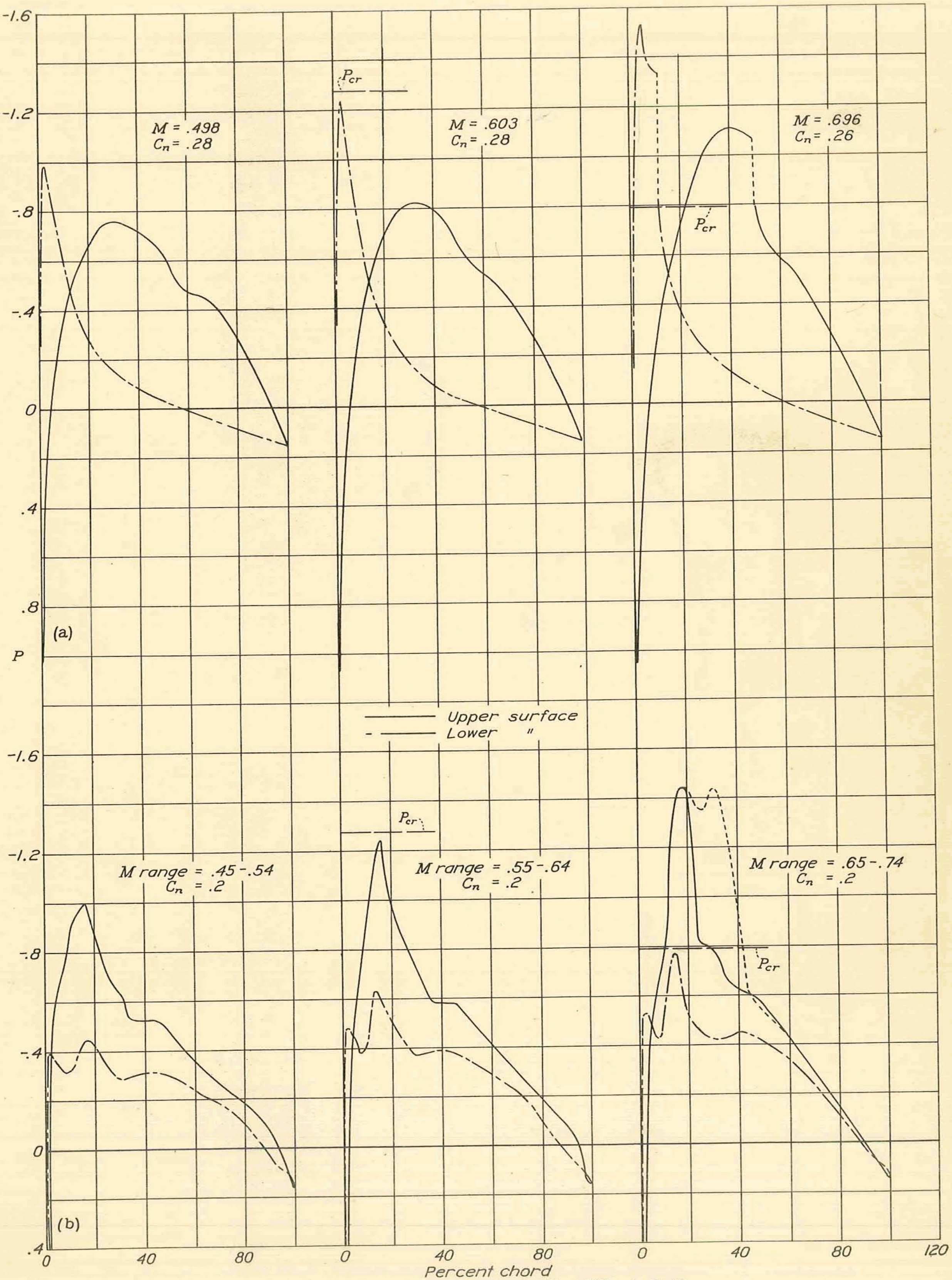


Figure 18.- High-speed propeller.



(a) 24-inch high-speed; NACA 4412 airfoil.
(b) Flight XF2A-2 airplane dive tests; NACA 23014 airfoil.

Figure 19.- Comparison of pressure-distribution diagrams measured in 24-inch high-speed tunnel and flight dive tests at high speeds.