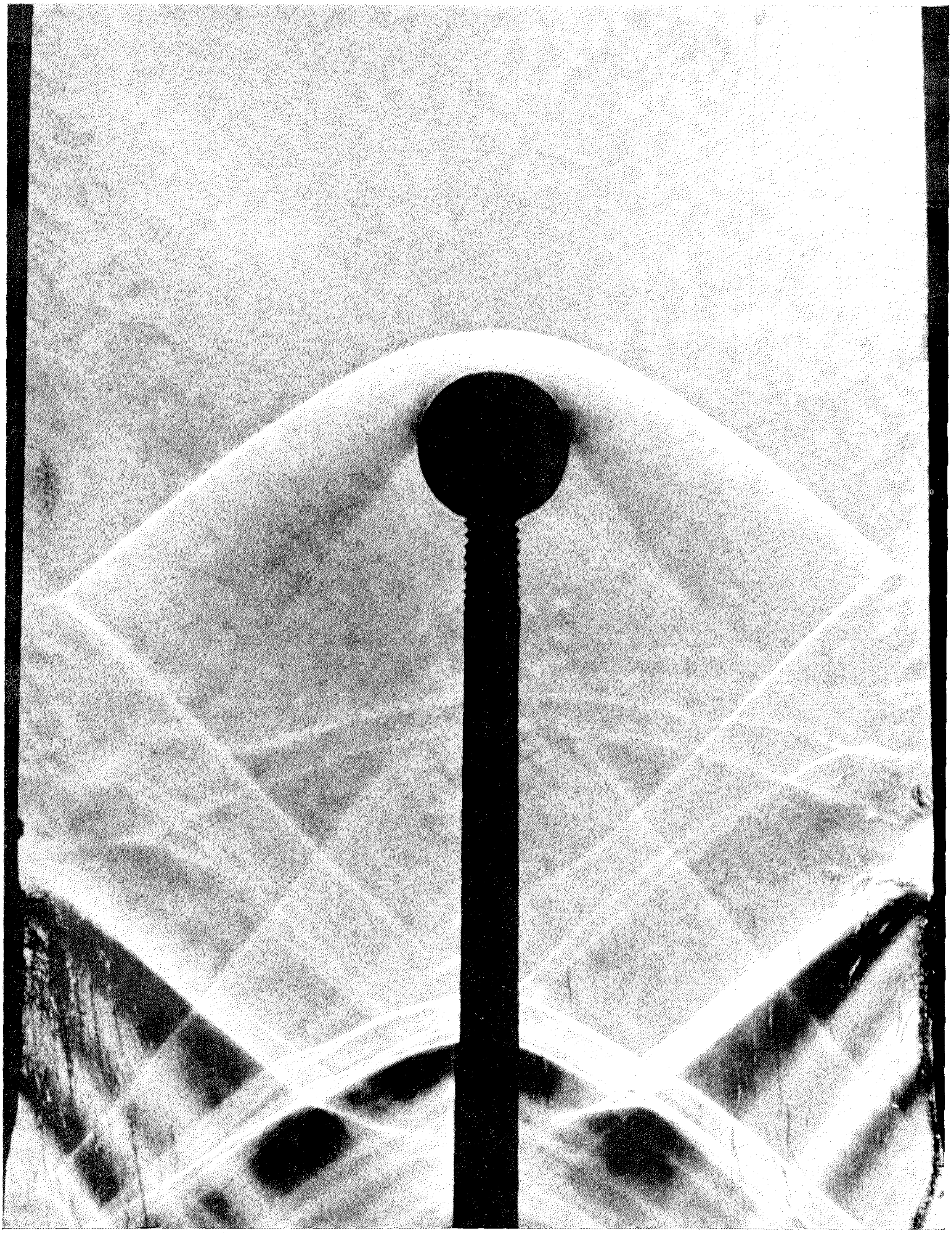

Schlieren photograph of air flowing past a sphere at 1.5 times the speed of sound. This photograph was taken in the Galcit 2.5 inch supersonic tunnel.

Notice the strong headwave produced by the blunt body, similar to a boat's bow wave. A considerable portion of the large drag experienced at supersonic speeds is associated with this phenomena.

High-Speed Aerodynamics*

By ALLEN E. PUCKETT

IN recent years considerable popular attention has been focused on the problem of achieving very high speeds in aircraft. This interest has ben accentuated by the war, which made speed one of the prime requirements for military pursuit aircraft. The advertised top speeds reached by aircraft increased from roughly 400 miles per hour before the war to roughly 600 miles per hour, this last being announced in the press not long ago as the speed attained by a British jet fighter. It has been pointed out in the press that difficulties appear as airplanes approach 750 miles per hour, which is the speed of sound, and many fantastic descriptions have been given of the effects in that region. There are, as a matter of fact, some interesting and even remarkable aerodynamic effects in that vicinity, which we will investigate here in some detail. At the same time, the speed of sound is hardly a magic, unsurpassable speed, as every bullet fired from a gun, not to mention the V-2 and various other rocket missiles, goes several times that fast.

CONCEPT OF SUPERSONICS

The peculiar effects occurring at speeds approaching the speed of sound are associated with the fact that air is compressible, and the study of high speed aerodynamics is almost synonymous with the study of "compressibility effects." We shall examine in detail what this means.

Suppose a small disturbance is made in a room full of air; if the air were truly incompressible, each molecule must press instantaneously on its neighbor, and the effect of the disturbance woud be transmitted instantly to all parts of the room. However, the air is in reality compressible, so that the air molecules cannot transmit a message instantly, but only at some finite speed. A sound wave is an example of such a small disturbance, and the speed of transmission of these small disturbances is called the speed of sound. The speed of sound is a function only of temperature; at sea level it is about 760 miles per hour, and decreases to about 660 miles per hour at an altitude of 35,000 feet. A very strong or large disturbance may travel at speeds above this, but no disturbance will travel at any lower speed.

If a body moves through the air at a very low speed, the disturbance it makes will be propagated to all parts of the air so rapidly, as far as the body is concerned, that the air is effectively incompressible. All classical airplane aerodynamics to date have made this assumption. However, as the speed of the body becomes higher, relative to the speed of sound, it is clear that the rate at which the disturbance is sent through the air may affect the appearance of the flow pattern around the body. Thus the important criterion of speed is apparently the ratio of the speed of the body to the speed of sound. This ratio is given a special name, the "Mach number," after the German scientist who made some fundamental investigations in gas dynamics in the last century. When the Mach number is less than 1, the flow is said to be subsonic; when the Mach number is greater than 1, the flow is said to be supersonic. However, there is a region in the vicinity of Mach number 1 in which the flow is of a mixed type, and this flow is said to be transonic. The aerodynamicist now says little about actual speed in miles per hour, but talks only of Mach number.

If a body moves through the air at a speed greater than the speed of sound, the disturbance it creates will, in general, move at the same speed as the body. This means that some sort of a wave will move in the air just ahead of the body; this wave is very analogous to the wave formed by the nose of a boat on the surface of the water. The wave in air is called a "shock wave." It is interesting to see that a large fraction of the entire mass of air is unaware of the presence of the body—in fact, all the air ahead of the shock wave. Thus the flow patterns and forces produced at a supersonic speed must differ radically from the familiar ones at a low subsonic air speed. On the left is seen a sphere mounted in a supersonic wind tunnel. The strong curved headwave produced by the sphere is clearly visible. Other waves produced by the support apparatus appear behind it.

At low supersonic speeds, we see that the disturbances made by the body will never have an opportunity to pile up into waves stationary with respect to the body. However, the motion of any body through the air will always cause some local acceleration of the air around it, so that there will be local regions over the surface of the body where the relative speed between the body and the air is greater than the "free stream speed," i.e., the speed of the body relative to the air far ahead. Therefore, as the "free stream Mach number" approaches 1, there may be local regions on the body where the air is speeded up to such an extent that it is moving supersonically with relation to the body. A wave could exist in these small local supersonic regions, stationary with respect to the body. An example of this possibility occurs in the flow over an airfoil. It is convenient to think of the airfoil at rest, with air moving in towards it at some free stream Mach number, M, rather than of the airfoil moving into the air at rest; the flow patterns and forces in the two cases are the same of course. If now the free stream Mach number M is of the order of 0.7 to 0.8 or higher, there will be small regions on the surface of the airfoil in which the Mach number (measured in relation to the stationary airfoil) is greater than 1. In these regions, when the Mach number is sufficiently greater than 1, a shock wave may form, stationary with relation to the airfoil. The exact reasons for the formation of a shock wave in a small locally supersonic region are still not clear, and it is not

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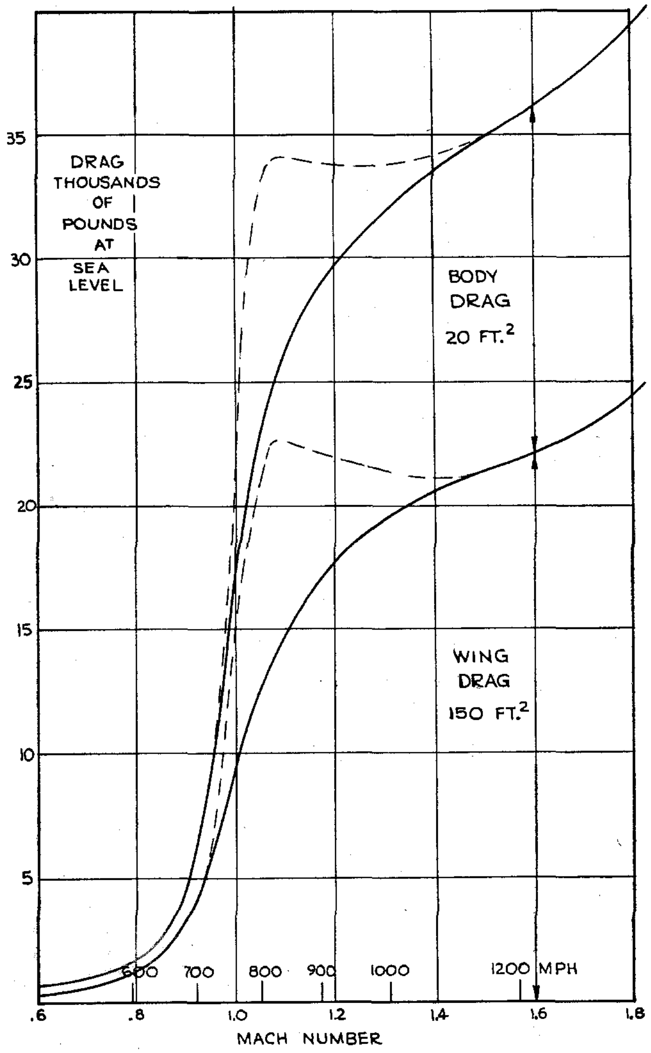

Curves of the estimated body drag and wind drag in the transonic region at sea level.

absolutely certain that it must always occur. However, thus far it has not been possible to avoid it. The effects of this shock wave on performance of the airfoil are, for the most part, very deleterious; they will be discussed in more detail below. On the cover is shown a model of a bomb mounted in the Bomb Tunnel at the Aberdeen Proving Ground, at a subsonic Mach number of approximately 0.9. There is no wave ahead of the model, but the shock waves on either side extend far out.

PERFORMANCE CHANGES WITH SPEED

The effects of the changes in flow pattern mentioned above may be related to the performance of an airplane by examining the forces acting upon it. A forward force, the thrust, is produced by the propeller or jet of the plane. A rearward force, called the drag, is produced by the flow of air over and around the plane. The drag increases, of course, with airspeed, and the plane must accelerate until the drag is equal to the thrust. The top speed of an airplane is thus determined by the available thrust of the plane, and by the speed at which the produced drag is equal to that thrust.

At very low Mach numbers, all forces acting on the plane are roughly proportional to the square of the velocity. As soon as the Mach number has increased sufficiently that the effect of compressibility has become evident, the drag begins to increase somewhat more rapidly than the second power of velocity. However, nothing serious happens until the flow around an airfoil or fuselage becomes locally supersonic, which, as mentioned previously, occurs at free *stream Mach numbers 0.7 and 0.8. Shortly after* this, shock waves form in the locally supersonic regions, and rather violent changes begin to occur in the forces acting on the plane. The shock wave on a wing produces a change in pressure distribution which generally results in diving moments. More seriously, the change in pressure distribution results in a very large drag increase. In the wake of the shock wave a trail of highly turbulent air may follow, since the wave itself is probably very unsteady. This turbulent wake buffets the rear control surfaces of the plane, and may cause complete loss of control.

As the plane speed increases further, the assumption being that thrust is available and control is sufficient, the shock wave moves to the rear. When the free stream speed is exactly equal to the speed of sound, it is at present impossible to say exactly what happens to the flow patterns, and to the forces on the airfoil or the airplane. In fact, there is some indication that no steady state flow pattern is possible at exactly $M=1$, but that the flow must fluctuate rapidly. In this case the particular phenomena and forces at exactly $M=1$ may well depend on the acceleration of the plane as it passes through this speed. There is definitely a range of uncertainty between $M=.95$ and $M=1.05$ in which no one pretends to have made steady-state measurements.

When the Mach number becomes greater than 1, the forces rapidly become steady again, and it is possible to compute and predict the flow patterns. A shock wave now appears, of course, ahead of the body, and with this there is associated, in ordinary cases, a very large drag. But the big jump is over.

The problem of increasing airplane speeds above Mach number 1 can best be appreciated by an actual computation of the drag in a particular case. To provide a very simple example, let us consider an airfoil of conventional design with an area of 150 square feet—which at 66 pounds per square foot would support a gross wegiht of about 10,000 pounds. This is a reasonable wing loading and weight for a pursuit airplane. The average wing thickness has been assumed to be 9 per cent of the chord. Let us consider also a streamlined fuselage or body of roughly 20 square feet cross section area.

Estimates can be made of the drag of these bodies as a function of Mach number. Above are shown curves of the estimated drag of the wing above, and of the combination. It will be seen that the drag increases slowly up to a Mach number of roughly 0.8, corresponding to 600 miles per hour. Shortly after this a very rapid rise occurs. In the range $M=0.9$ to $M=1.3$ the uncertainty of the wing drag has been indicated by drawing a solid curve at a lower, optimistic estimate, and a dotted curve at a higher value which we have reason to believe may be reached or even exceeded under the proper conditions. The effect of this higher estimate of the wing drag has been indicated by a dashed line in the total drag curve.

It will be seen quickly that the rapid rise in these curves of drag at sea level does represent almost a "drag wall" at roughly $M=0.8$, or 600 miles per hour. A power plant suitable for this hypothetical airplane might at present be expected to produce a thrust of the order of 3000 to 4000 pounds, which is ample for the lower speeds, but is stopped short at 650 miles per hour. At high altitudes, however, the situation is not so bad, because of the much lower density of the air. Below, the same curves are plotted for an altitude of 35,000 feet. It will be noted that the same Mach number now represents an air speed considerably lower. But the ordinates of the curve have been reduced to almost one-fourth of the previous values. It is reasonable to speculate about the possibility of pushing an airplane through M=1. The first striking fact is that if the first large drag hump is overcome, there is a region from M=1 to M=1.3 or 1.4 in which the drag rises very little, or may even decrease. Thus, if we build a power plant sufficiently powerful to overcome the first large drag peak, it will take very little more to push the airplane to a Mach number of 1.5. In fact, if the higher drag curve does exist, the pilot would find it difficult if not impossible to fly at a Mach number of 1.1; at this Mach number, a slight decrease in speed produces an excess of drag over thrust, and a further deceleration. Or a slight increase in speed produces a decrease in drag, causing the pilot to accelerate more.

The region in the immediate vicinity of M=1 will almost certainly cause flow oscillations and instabilities, making it advisable to get through it in a hurry. In addition, the possibility that the peak forces themselves may depend on the acceleration through the speed of sound makes it probable that we will want to go as fast as possible through that region. It appears, then, that the next step in increasing the speed of aircraft will be to provide a power plant with thrust sufficient to overcome the drag peak, and to produce a reasonable acceleration through the speed of sound, with the object of reaching steady-state flight somewhere near a Mach number of 1.4 or 1.5, i.e., 900 or 1000 miles per hour. In other words, the top speed of airplanes may be inched up by a few more miles per hour, but will then probably take a large jump from, say, 650 or 700 miles per hour to 1000 miles per hour. This jump will probably be made at fairly high altitudes. And it is

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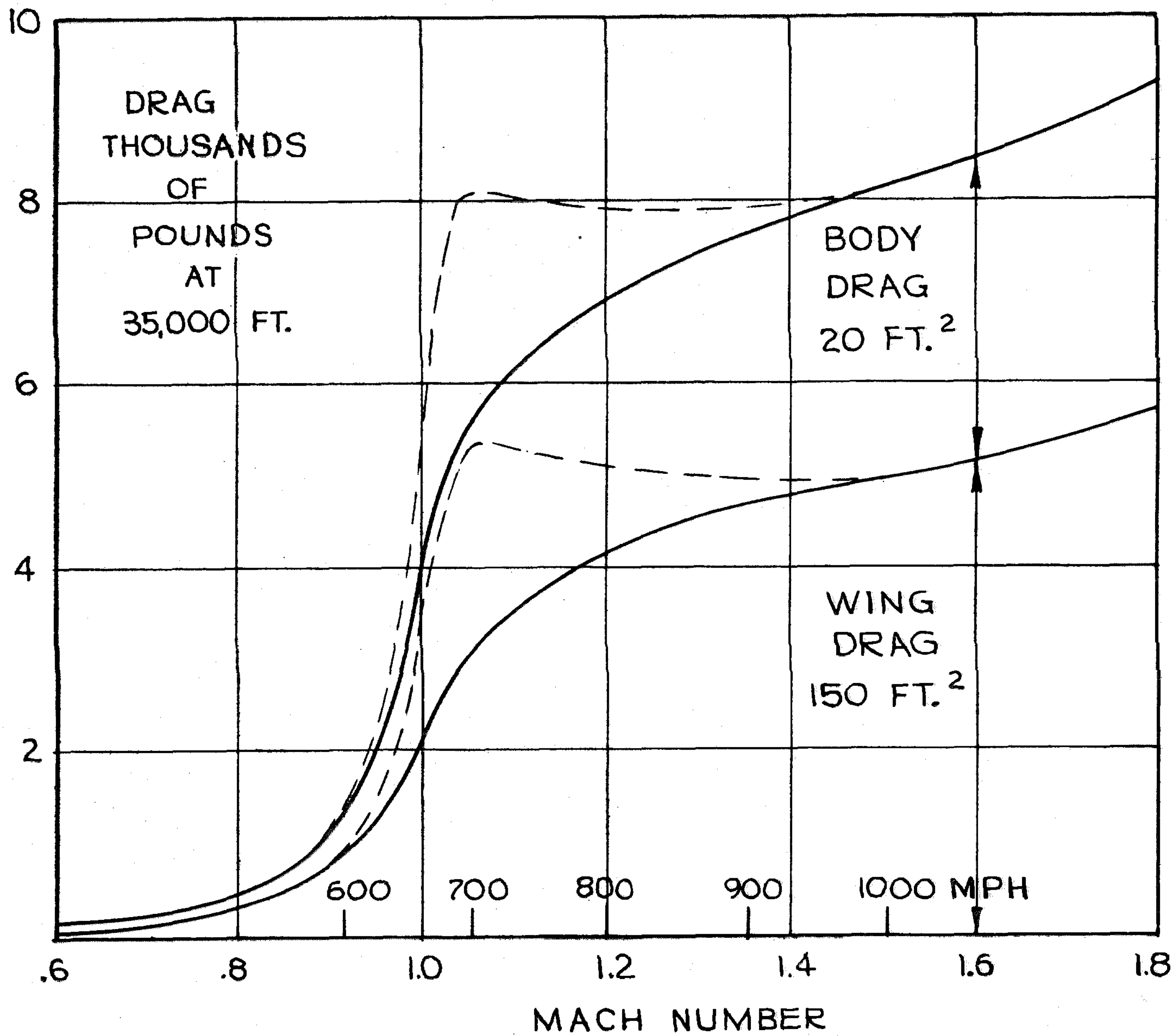

Curves of the estimated body drag and wind drag in the transonic region at 35,000 feet.

High-Speed Aerodynamics

(Continued from page 7)

certain that the power plant will be some jet propulsion device.

AN AERODYNAMICIST'S PROBLEM

The estimates made thus far have referred primarily to a more or less conventional airplane design, in that the performance estimates have been based on tests of such designs. However, the aerodynamicist can resort to a few additional tricks in the battle against drag. One of these is the use of a wing platform with leading edges swept back from the normal to the free stream flow. In an infinite wing, it can be shown that the Mach number which determines the performance characteristics of this swept-back wing is not the free stream Mach number, but the component of it normal to the leading edge. Thus, for a 45 degree sweepback, at a free stream Mach number of 1, the effective normal Mach number will be only 0.7, and we may expect that the appearance of the sudden rise in drag will be at least postponed somewhat. Experimentally this seems to be the case, and the height of the drag peak itself will probably be considerably decreased. This immediately brings the prospect of flight through the speed of of sound much closer. However, there are many practical problems connected with the use of swept-back wings, such as poor stalling characteristics, and increased structural difficulties, which cause the designer to hesitate somewhat before building all airplanes with swept-back wings.

There are many possible variations on the basic idea of a swept-back wing. One of these is a triangular, or "Delta wing." These wings appear to have some considerable advantages for use at supersonic speeds. Their drag for a given lift may be roughly one-fourth of the drag of a conventional airfoil at supersonic speeds. At present almost no idea is too fanciful, no design too radical to be unworthy of attention.

SUPERSONIC TUNNELS

A word about the difficulties involved in making aerodynamic tests at these high speeds is in order. Wind tunnels have been developed for many years to make tests at low speeds on models of airplanes supported in them. These have reached such heights of perfection as the NACA 80 foot x 40 foot tunnel at Moffet Field, in which full-scale airplanes can be tested, or the 8 foot x 12 foot high-speed Southern California Cooperative Wind Tunnel being operated by Caltech. This latter tunnel, powered with 12,000 horsepower, is able to produce Mach numbers approaching very near to 1. But as this range is approached, the wind tunnel meets difficulties not unlike those encountered by the airplane; a very large intererference between model and wind tunnel walls begins to appear. As the Mach number approaches closer to 1, the model must be made smaller and smaller to avoid these interference effects. At exactly $M=1$, the maximum model size is theoretically zero, which is hardly practical. No really reliable wind tunnel tests have been made between Mach numbers of roughly 0.95 and 1.05.

At supersonic speeds, testing in a wind tunnel becomes straightforward again, with the exception that the power required to drive the tunnel has increased in a manner similar to the drag of the airplane. For instance, the Cooperative wind tunnel may use 12,000 horsepower to blow air at $M=0.9$ through an area of roughly 100 square feet, with an air density of one-fourth atmosphere. A supersonic tunnel of the same size, operating at a Mach number of 2.0, at the same density, will require 130,000 horsepower. At the present time much essential test data can be obtained in supersonic tunnels of a much smaller size, but we must be prepared to build large supersonic tunnels in the near future.

It is clear that the problems facing the aerodynamicist at high speeds are now such that the next advances will not be made by building everything a little more powerful, or a little bigger or stronger, as has been the case in the past, but only with the aid of extensive and careful fundamental research. Moreover, the necessary information and design data cannot be provided overnight when the need arises, but must come from a long-range systematic program of research.

The practical impetus for work in this field of high-speed aerodynamics has come from its military applications, but it is certainly to be hoped that the emphasis will shift. Because of the peculiar whims of man, we may be interested in whisking a business-man from breakfast in Los Angeles to lunch in New York two hours later. This is certainly within the range of serious possibility. Fortunately, the aerodynamicist does not ask why, he simply tries to do it.