BASE PRESSURE ON WINGS AND BODIES WITH TURBULENT BOUNDARY LAYERS[1]

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At present there is no satisfactory theory for calculating the pressure which acts at the blunt base of an object traveling at supersonic velocity. In fact, the essential mechanism determining the base pressure is only imperfectly understood. As a result, the existing knowledge of base pressure is based almost entirely on experiments. The main object of this paper is to summarize the principal results of the many wind-tunnel and free-flight measurements of base pressure on both bodies of revolution and blunt-trailing-edge airfoils. A relatively simple method of estimating base pressure is presented, and an indication is given as to how the characteristics of base pressure play an essential role in determining the shape of an aerodynamically efficient object for supersonic flight.

It now is generally accepted that the base pressure depends markedly on the type of boundary-layer flow, that is, whether laminar or turbulent. Although extensive measurements have been made at the Ames Laboratory and in various other laboratories with both types of boundary-layer flow, only the case of turbulent flow will be considered here. Such a choice is made, of course, because turbulent flow at present is of more practical importance to the missile designer than is laminar flow.

The number of variables that affect base pressure are many, since anything that affects the boundary-layer flow can affect the base pressure. It will be convenient, however, to think of each variable that affects base pressure as acting in one or more of three ways: first, by changing the flow field exterior to the boundary layer - such changes affect the base pressure in a manner that can be estimated from considerations of the flow of an inviscid gas; second, by changing the thickness of the boundary layer just upstream of the base - this latter type of change affects base pressure in a manner that can be determined by systematic experiments; and third, by changing the distribution of velocity and density within the boundary layer, or within the mixing layer downstream of the base. This last type of effect is complicated indeed and has thus far proven intractable by theoretical methods.

The chief variable of the first type mentioned is body shape. Even in an inviscid flow, base pressure depends on the body shape because the local pressure and local Mach number approaching the base is different for different bodies. The upper sketch in figure 1 illustrates the flow about a given body; the lower sketch in this figure illustrates a

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[1]This is a reprint of the paper by the same author which was presented at the NACA Conference on Aerodynamic Design Problems of Supersonic Guided Missiles at the Ames Aeronautical Laboratory on Oct. 2-3, 1951.

fictitious inviscid flow from which the pertinent Mach number and static pressure of the disturbance field can be calculated. The notation is as follows: M_∞ and p_∞ designate the free-stream Mach number and static pressure, respectively; whereas, M' and p' designate the Mach number and static pressure induced in the vicinity of the base by the presence of the body. As is illustrated, M' and p' represent conditions along a hypothetical extension, averaged over a region occupying the same relative streamwise position as the dead-air region in the real flow. The surface of the hypothetical extension is parallel to the free-stream direction. The significance of M' and p' evaluated in this particular manner, is that they form reference quantities to which the base pressure can be referred and be nearly independent of profile shape in an inviscid flow. In a real flow, therefore, the quantities M' and p' can be thought of as the Mach number and static pressure corrected for the effect of body shape on the flow field exterior to the boundary layer. The method illustrated is valid for small boattail angles only.

Since M' and p' are used extensively in subsequent figures, it may be of some help in clarifying the basic idea by mentioning an analogy, namely, the theory of subsonic wind-tunnel-wall corrections. There, the free-stream Mach number and pressure are corrected for the disturbance induced in the vicinity of the model by the presence of the tunnel walls. Here, the same quantities are corrected for the disturbance induced in the vicinity of the base by the presence of the body. In both cases, the correction is accurate only if the disturbance field is small and is nearly uniform over the region in question.

In general, numerical calculations of M' and p' show that as far as base pressure is concerned this correction is significant at all supersonic Mach numbers for bodies of revolution with boattailing. For bodies without boattailing, the correction is less important. For airfoils the correction is important at low-supersonic Mach numbers where the bow wave is detached, but is negligible at moderate Mach numbers where the bow wave is attached. In most cases the static-pressure correction is larger than the Mach number correction.

In the examples presented later, the quantities M' and p' for cone-cylinder bodies of revolution have been determined from the characteristics solutions of reference 1. For bodies of revolution with curved sides, M' and p' have been calculated from the second-order theory of Van Dyke (reference 2). The corresponding quantities for airfoils in the region of bow wave detachment have been determined from the results of Guderley and Yoshihara (reference 3) and of Vincenti and Wagoner (reference 4).

The principal use to be made of the quantities M' and p' is in estimating the base pressure of a boattailed profile from a knowledge of the base pressure on a profile without boattailing. The essential concept involved is that the base pressure, when referred to M' and p', is independent of body shape. This concept neglects changes in the boundary-layer flow. Figure 2 illustrates the accuracy of estimating base pressure in this manner. Afterbodies converging toward the base are designated by positive boattail angles and are plotted on the right of the ordinate axis. Cones are designated by negative boattail angles and are plotted on the left. The line composed of short dashes represents the estimated values from calculations of M' and p'. The line composed of long dashes represents a method of estimation recently given by Cortright and Schroeder (reference 5). In this and most subsequent figures, the base pressure ratio is plotted as the ordinate; hence, it is to be remembered that the base drag per unit base area is proportional to one minus the ordinate, and that the base drag is reduced if the base pressure is increased. In figure 2, for example, it is seen that at a Mach number of 1.5 the observed increase in base pressure is such that the base drag is reduced almost to zero at boattail angles of about 15°. It is seen further that, in the range shown, negative boattail angles on bodies of revolution lower the base pressure, thus increasing the base drag considerably, whereas positive boattail angles have the opposite effect.

Figure 3 shows the effect of boattail angle on the base pressure of airfoils. It is evident that there is little effect of boattail angle in this latter case. This is in accordance with the estimate based on the calculated values of M' and p', as indicated by the short dashes. In view of the reasonable agreement between these experiments and the estimated values, it is believed that for turbulent boundary-layer flow the effect of boattailing on base pressure is due principally to changes in the outer flow field rather than to changes in boundary-layer flow brought about by the boattailing.

When employing the above method of estimating base pressure it is necessary, as already mentioned, to have experimental data on a profile without boattailing. The compiling of such data is greatly simplified by the fact that the effect of Reynolds number on base pressure is small for turbulent boundary-layer flow and often can be neglected. This is illustrated by figure 4 showing base pressure measurements as a function of Reynolds number for various profile shapes, with and without boattailing, and for several different Mach numbers.

For airfoils with turbulent boundary-layer flow, the effect of Reynolds number also is small, as indicated in figure 5. From a comparison of figures 4 and 5, it can be concluded that, in general, moderate differences in Reynolds number will have only a small effect on base pressure if the boundary layer is turbulent. Therefore, the many experimental measurements of base pressure for which the test Mach numbers and Reynolds numbers both varied can be plotted as a function only of the Mach number. Such a plot for a number of bodies of revolution without boattailing is shown in figure 6. Also shown in this figure are data for several cones since these latter data (unpublished data from Ames supersonic free-flight wind tunnel) are the only data available which are representative of turbulent flow at Mach numbers near 6. These data for cones can be compared directly with the other data since M' and p' are used as reference quantities in this figure. It is to be noted that data from a number of different laboratories (references 6 to 11, plus unpublished data of the Ames 10- by 14-inch supersonic wind tunnel) are included here; the free-flight measurements are designated by filled symbols and wind-tunnel measurements, which were taken with rear sting supports, are designated by open symbols. Considering the wide variety of experimental techniques employed in obtaining these data, the degree of mutual agreement is regarded as satisfactory. The mean curve passed through these data can be used either to estimate the base pressure of a boattailed body according to the method described earlier, or, if a body has no boattailing and a cylinder three or four diameters long preceding the base, then this mean curve can be used directly to give the base pressure. The equation used in estimating the base pressure of a given body, for which M' and p' have been calculated, is

$$\frac{p_b}{p_\infty} = \left(\frac{p_b}{p'}\right)_{M'} \frac{p'}{p_\infty}$$

where the quantity $\left(p_b/p'\right)_{M'}$ is the experimental value of p_b/p' picked from the curve of figure 6 at the Mach number M'.

Of course, a plot similar to the one shown can also be made for airfoils. Such a plot is presented in figure 7, where again free-flight data (reference 12) are represented by filled symbols and wind-tunnel data (reference 13 and unpublished data from the Langley 9- by 12-inch supersonic blowdown tunnel, the Langley 9-inch supersonic tunnel, and the Ames 1- by 3-foot wind tunnels) are represented by open symbols. Most of these data represent measurements on finite-span wings on which considerable spanwise variations in base pressure can exist. In such cases, the values shown represent an average over the span of the trailing edge. The filled point situated at the extreme left in this figure actually was taken at a flight Mach number of 1.0, but, on this graph, it plots in the position shown because of the large effect of profile shape on base pressure in the region of bow wave detachment. All these data for airfoils were obtained with the trailing edge normal to the stream direction. Rectangular plan forms were used for most measurements, although one set, indicated by the tagged symbols, was obtained with a triangular wing. The base pressure for the two different plan forms is nearly the same. Some base pressure measurements recently have been obtained at the Langley Laboratory on a constant-chord wing with trailing edge swept back 45°. These latter measurements are not shown in figure 7 because of the difficulty in calculating the average value of p' for a sweptback wing. The actual measured values of the base pressure, however, were nearly the same as for unswept wings at 1.62 Mach number, but were about 20- to 50-percent higher at Mach numbers of 1.41 and 1.96.

A comparison of figures 6 and 7 shows that, at high-supersonic Mach numbers, the base pressure on bodies and airfoils is almost the same, with the base pressure in each case approaching a vacuum as the Mach number is increased. On the other hand, it can be seen also that at low-supersonic Mach numbers the base pressure is much lower for airfoils than bodies. In fact, at a Mach number of 1.2, the observed difference is such that the base drag per unit base area of an airfoil is over two times that of a body of revolution. The characteristics just noted, namely, the essential difference in base pressure between bodies and airfoils at low-supersonic Mach numbers, and the essential similarity at high-supersonic Mach numbers where the base pressure approaches zero, would exist in an inviscid flow (reference 8), and hence these characteristics are believed to be associated to a large degree with the behavior of the flow exterior to the boundary layer.

All data in figures 6 and 7 represent conditions where the turbulent boundary layer is thin relative to the base dimension. If the boundary layer is thick compared to the base height, then the base pressure will be somewhat higher, and the base drag correspondingly lower. A general trend of increasing base pressure with increasing boundary-layer thickness has been found in the experiments on bodies (reference 8) and airfoils (unpublished) conducted at the Ames Laboratory. Another general trend, of increasing base pressure with increasing surface temperature, has been observed by Kurzweg at the Naval Ordnance Laboratory (reference 7). Since an increase in surface temperature also increases the boundary-layer thickness, both trends can be shown together by plotting base pressure against a parameter proportional to the ratio of turbulent boundary-layer thickness to base thickness. Such a parameter, as indicated in figure 8, involves the ratio of body length to base diameter, the Reynolds number, and the ratio $\delta/(\delta \text{ no heat})$. This latter factor represents the ratio of boundary-layer thickness of a heated body to that of an unheated body at the same Reynolds number and has been determined from the analysis of the turbulent boundary layer with heat transfer as given by Van Driest (reference 14). The open symbols, which represent the experiments at the Ames Laboratory on bodies without heat transfer, show a slow rise in base pressure as the boundary-layer thickness increases.

The filled symbols, which represent the experiments at the Naval Ordnance Laboratory on heated bodies, show a much more rapid rise in base pressure. It is evident, then, that the transfer of heat affects the base pressure principally through the changes it brings about in the distribution of density and velocity within the boundary layer, rather than through the changes it brings about in boundary-layer thickness.

For airfoils, the ratios of boundary layer to base thickness that are of practical interest extend to considerably higher values than for bodies of revolution. As a result, the boundary-layer thickness has to be considered more carefully in estimating base pressure. This is illustrated in figure 9 where the base pressure (unpublished data from Ames 1- by 3-foot supersonic wind tunnels) is plotted as a function of the parameter which is approximately proportional to the ratio of turbulent boundary-layer thickness to trailing-edge thickness. The airfoil thickness ratio t/c and the trailing-edge bluntness ratio h/t were systematically varied in these experiments. The results shown represent twelve different profiles and correlate reasonably well on this plot. From this it can be seen, for example, that a thin airfoil with a thin trailing edge will have a significantly higher base pressure than a thick airfoil with a fully blunt trailing edge. It should be mentioned that although only a small effect of Reynolds number was noted earlier, a significant effect of boundary-layer thickness is noted in figure 9 because the fifth root of the Reynolds number is involved in this latter figure.

The extent to which the characteristics of base pressure influence the total afterbody drag of bodies of revolution is illustrated in figure 10. Here the afterbody length is held constant and the base diameter varied. In these examples the side drag has been calculated on the assumption of inviscid flow, and the base drag has been estimated by the method described earlier. A few experimental points also are shown in figure 10. It can be seen that at a Mach number of 1.5, the afterbody drag in this particular example is reduced about 30 percent by boattailing to a base diameter of about two-thirds of the body diameter. The minimum afterbody drag occurs when the base drag is about one-fifth of the total afterbody drag. At a Mach number of 3 the situation is about the same; but at a Mach number of 8 there is seen to be no significant effect of afterbody shape on the total afterbody drag. Hence, at very high supersonic Mach numbers, there is little to gain by boattailing.

The characteristics of base pressure also have an important effect on the drag of airfoils. This is illustrated in figure 11, where the calculated pressure drag of a family of airfoils, all having the same cross-section area, is plotted as a function of the ratio of trailing-edge thickness to maximum airfoil thickness. For each value of the trailing-edge thickness, the profile ahead of the base was determined by the condition that the foredrag calculated from shock-expansion theory be a minimum. The base drag was determined from the correlated measurements presented earlier except in the case of a Mach number of 8 for which the base pressure was assumed to be zero. It is apparent that, at Mach numbers of 1.5 and 3, the minimum total pressure drag occurs for airfoils with a slightly blunt trailing edge. Also, at these Mach numbers a substantial drag penalty will occur if a fully blunt trailing edge is employed instead of the optimum. At a Mach number of 8, however, the drag penalty compared to the optimum is small even with a vacuum at the base; the minimum pressure drag at this Mach number occurs when the trailing-edge thickness is about two-thirds of the maximum airfoil thickness. The main practical significance of these results lies in the structural advantages of a thick trailing edge, particularly when a control surface is employed, since the thickness of the airfoil at the hinge line and the torsional stiffness of the control surface are greatly increased.

From the viewpoint of increasing missile performance, it naturally is desirable to be able to reduce the base drag. One method of doing this has been indicated by Cortright and Schroeder of the Lewis Laboratory (reference 15). They found that by permitting small quantities of air to flow out of the base of bodies of revolution the base pressure could be increased a substantial amount. Some of their results are presented in figure 12 where the measured base pressure is plotted as a function of the ratio of jet chamber pressure (p_j) to free-stream static pressure. One curve is for a body without boattailing, and the other is for a body with a 9.3° boattail angle. The observed maximum increase in base pressure, as indicated in figure 12, corresponds to a decrease in base drag of about 30 and 60 percent, respectively. The quantity of bleed air required at the optimum value of jet pressure for the body without boattailing corresponds to a mass flow of bleed air equal to about 4 percent of the mass flow that would flow through the base if the free stream passed through the base undisturbed.

Figure 13 shows that the base drag of airfoils also can be reduced considerably by bleeding air out of the base. (These latter unpublished data for airfoils were obtained in the Ames 1- by 3-foot wind tunnels.) At Mach numbers of 1.45 to 2, the observed maximum increases in base pressure correspond to base drag reductions of about 36 and 35 percent, respectively. In these two cases the jet exit area is 18 percent of the total base area, and the optimum values of jet pressure correspond to a mass flow of bleed air between about 3 and 5 percent of the mass flow that would flow through the base if the free stream passed through the base undisturbed. Also, in these two cases the optimum jet pressures correspond to jet-exit Mach numbers in the high-subsonic region.

In a comparison of figures 12 and 13, it is significant to note that the optimum jet pressure in all cases is less than the free-stream static pressure since this greatly minimizes the problem of supplying bleed air.

All preceding results are for bodies of revolution and blunt trailing-edge airfoils set at zero angle of attack. In figure 14 some typical data for bodies of revolution (references 10, 16, and unpublished data from the Lewis 1- by 1-foot and Ames 1- by 3-foot wind tunnels) are collected which illustrate the effect of angle of attack on base pressure. In each case the base pressure decreases considerably as the angle of attack is increased. To what extent this decrease is due to changes in the exterior flow in the vicinity of the base and to what extent it is due to the changes in boundary-layer flow approaching the base is not known as yet. The situation is considerably clearer for airfoils, since the characteristics of the exterior flow at angle of attack can be calculated easily. The calculated values of M' and p' for airfoils do not change with small changes in angle of attack. It is not surprising, therefore, that over the Mach number region shown the base pressure on airfoils, as indicated in figure 15, does not change significantly with a change in angle of attack. This result is seen to apply at Mach numbers ranging from 1.5 to 4.0, and for a variety of airfoil sections. Comparing these two figures, we see that the situation is quite similar to that noted earlier when considering the effect of boattail angle on base pressure. The observed effect is large for bodies of revolution but small for airfoils.

Some measurements at angle of attack have been made on a 45° sweptback blunt trailing edge (unpublished data from Langley 9- by 12-inch supersonic blowdown tunnel) which indicate that up to about 10° the effect of angle of attack on base pressure is small at 1.96 Mach number, but is sizable at 1.62 and 1.41 Mach number at which the bow wave is detached.

The results of this paper can be summarized in three general statements: First, base drag of bodies of revolution and airfoils can be estimated with reasonable accuracy from the correlation of experiments and from the method of calculation described at the beginning of this paper; second, a body of revolution or an airfoil that is designed to have minimum drag at supersonic speeds generally will not be pointed at the rear, but will have a finite base, the thickness of which generally increases as the Mach number increases; and third, some recent experiments have indicated that the base drag of bodies of revolution and airfoils can be significantly reduced by bleeding relatively small quantities of air out of the base.

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DISTURBANCE INDUCED NEAR BASE BY PRESENCE OF BODY

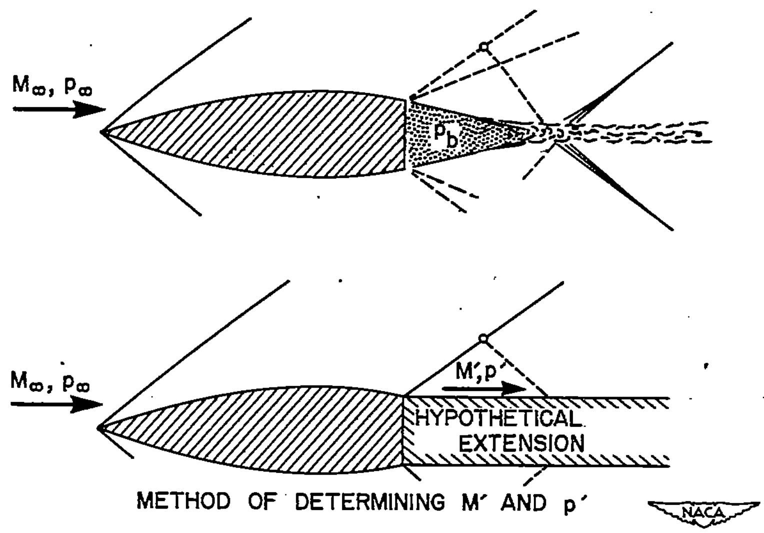

Figure 1

BODIES

EFFECT OF BOATTAIL ANGLE ON BASE PRESSURE

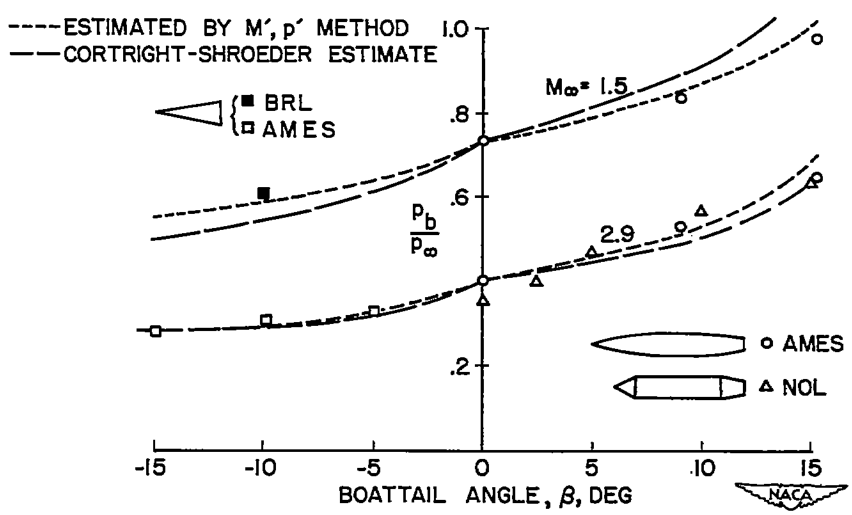

Figure 2

AIRFOILS

EFFECT OF BOATTAIL ANGLE ON BASE PRESSURE

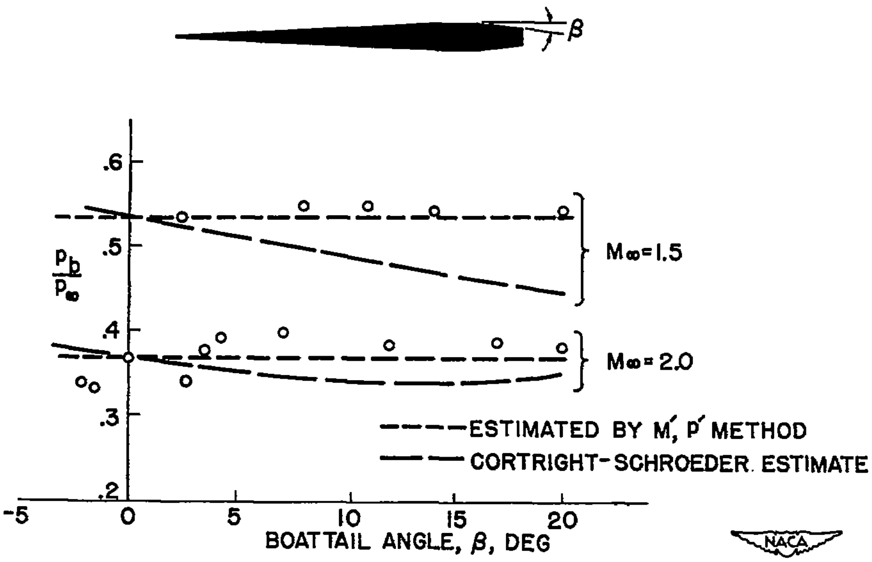

Figure 3

BODIES

REYNOLDS NUMBER EFFECT ON BASE PRESSURE

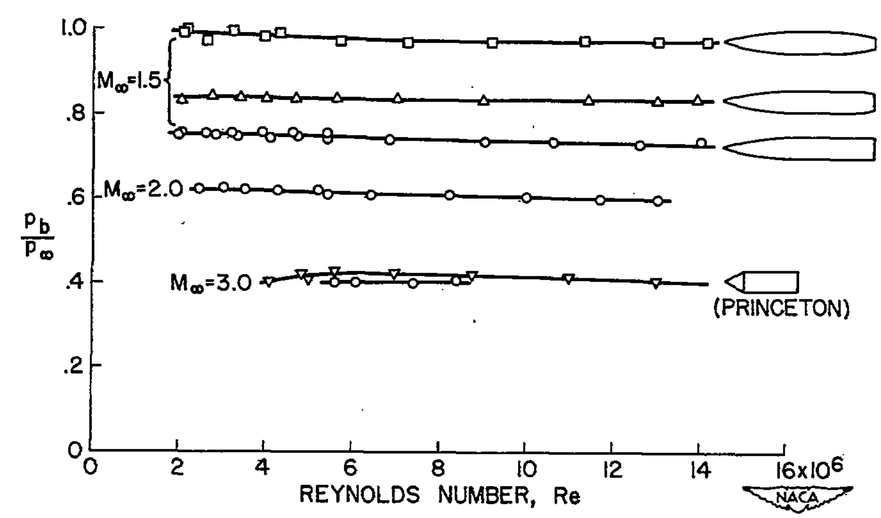

Figure 4

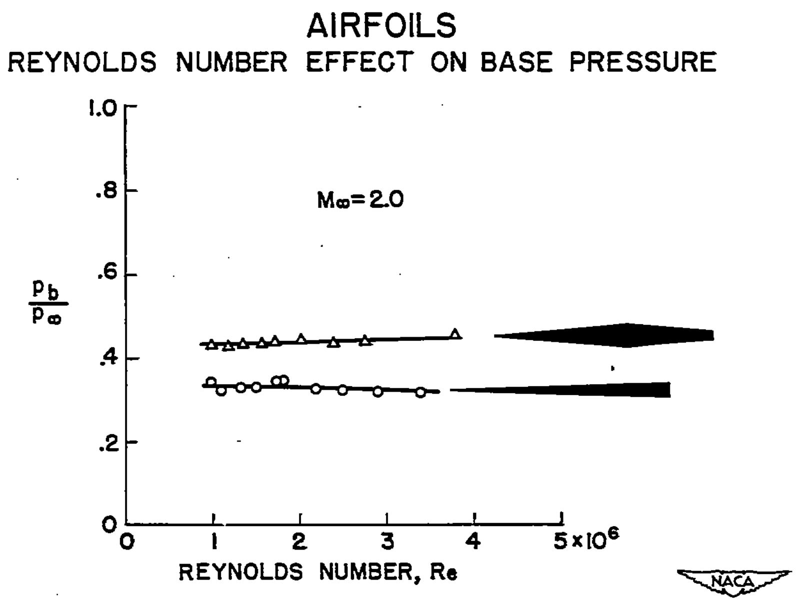

Figure 5

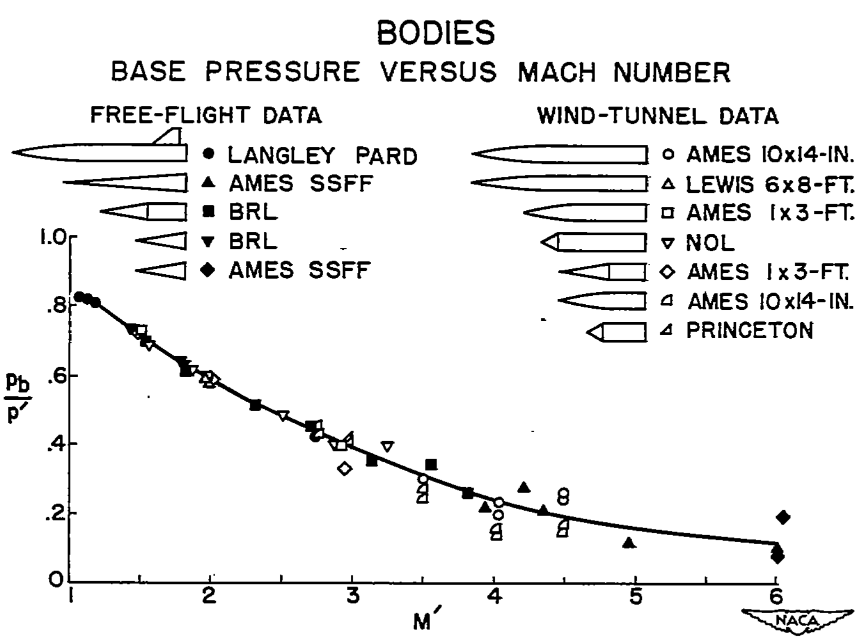

Figure 6

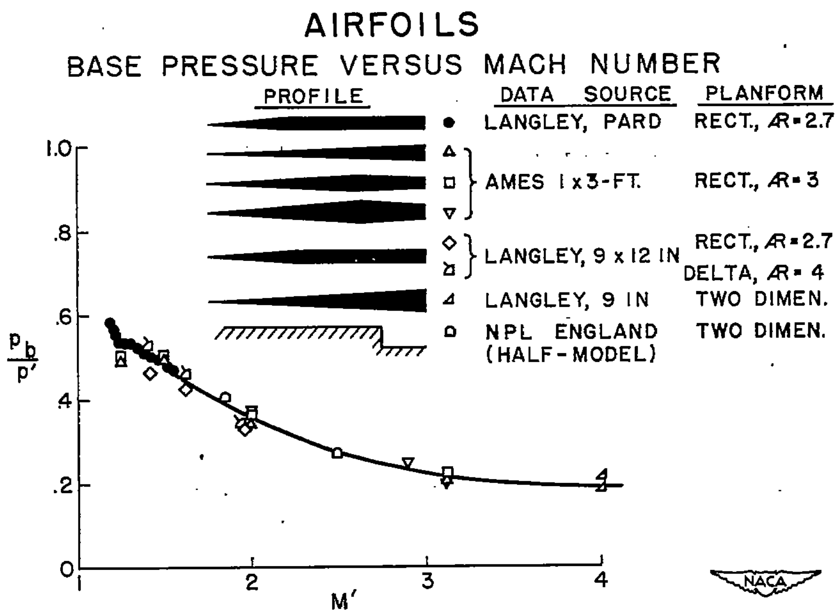

Figure 7

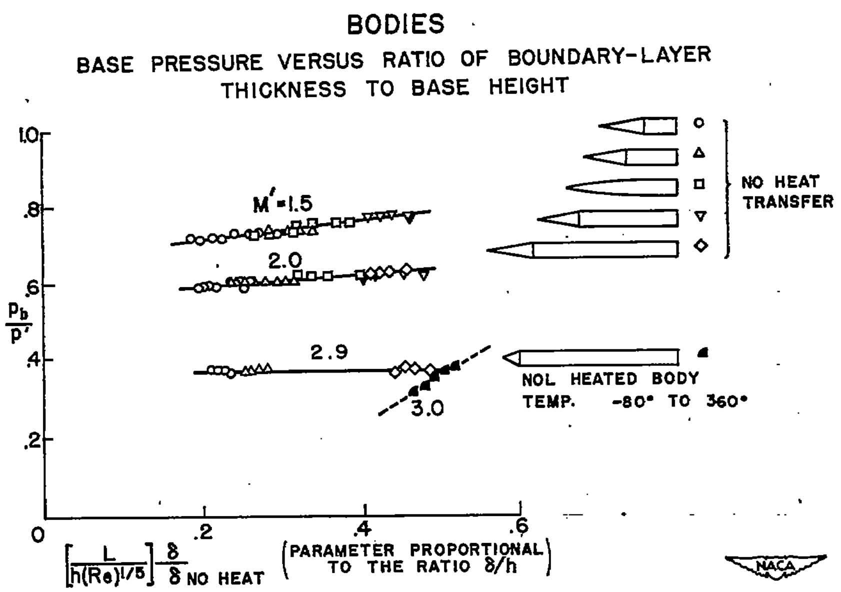

Figure 8

AIRFOILS

BASE PRESSURE VERSUS RATIO OF BOUNDARY-LAYER THICKNESS TO BASE HEIGHT

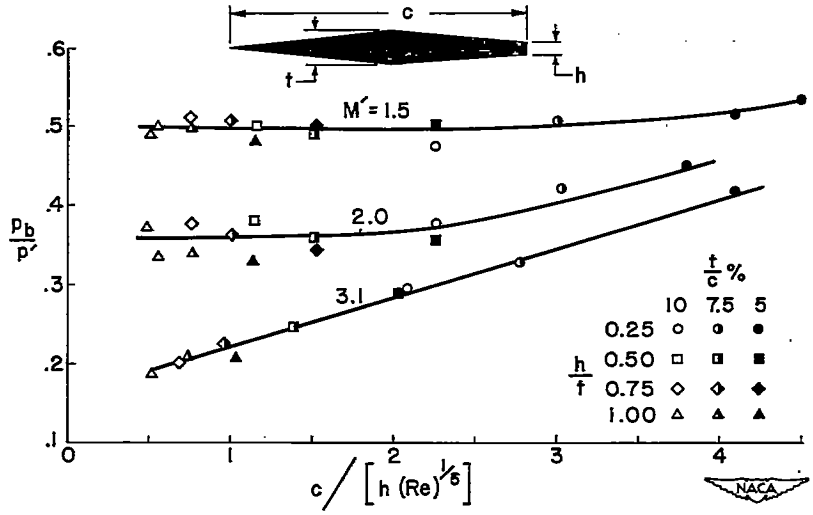

Figure 9

BODIES

AFTERBODY DRAG FOR CONSTANT AFTERBODY LENGTH

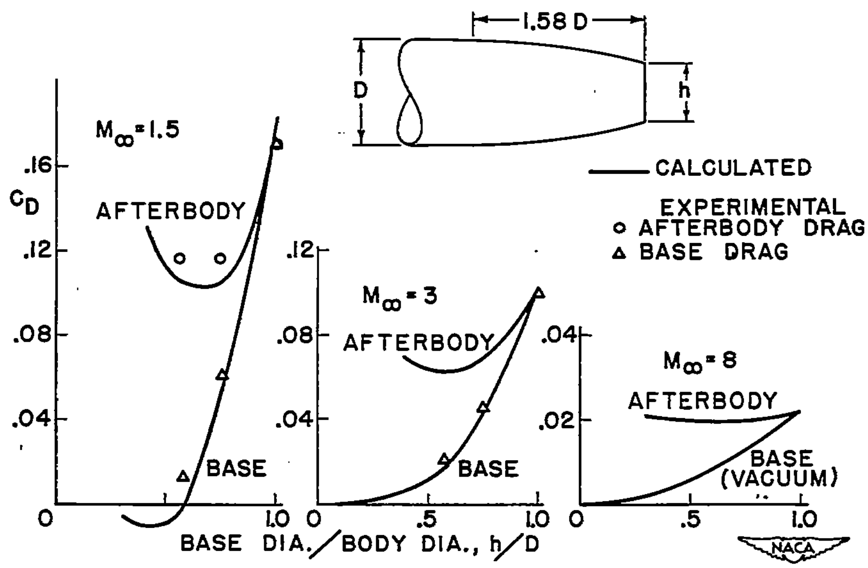

Figure 10

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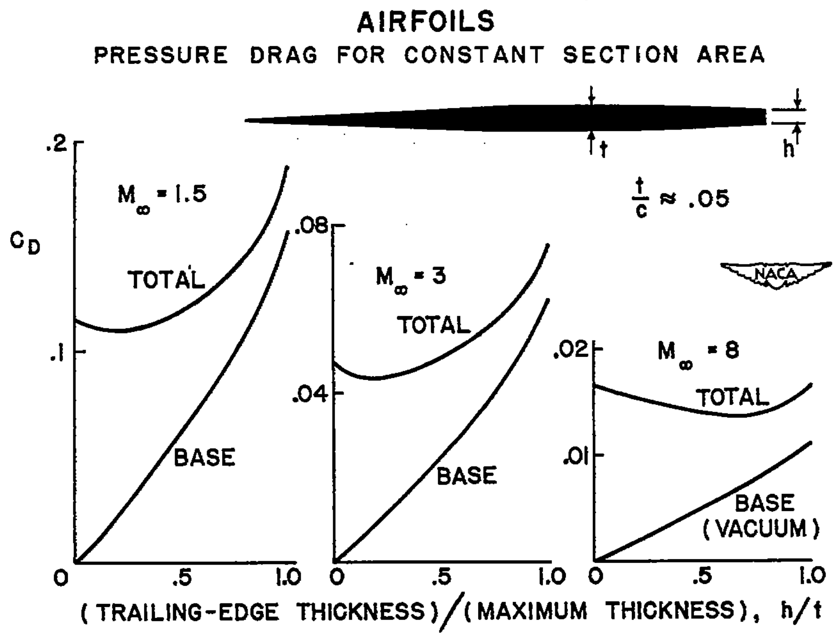

Figure 11

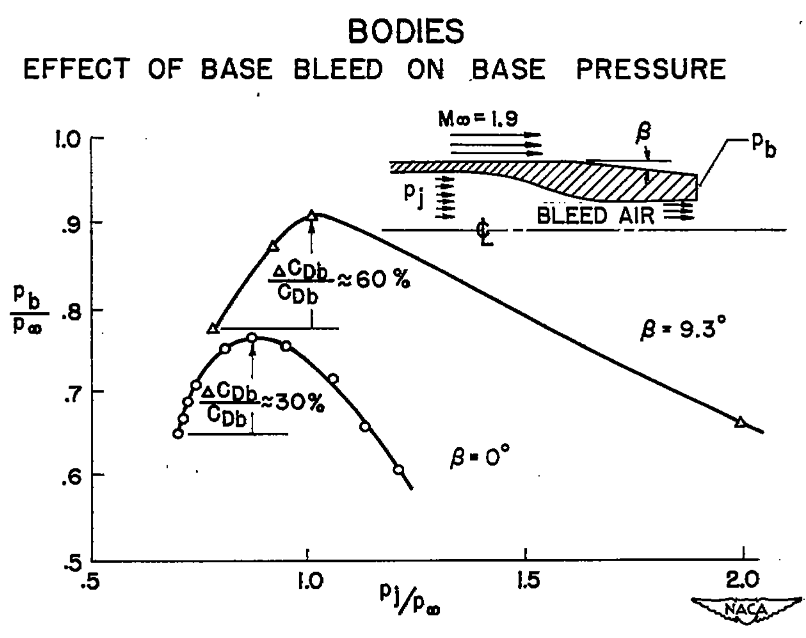

Figure 12

AIRFOILS

EFFECT OF BASE BLEED ON BASE PRESSURE

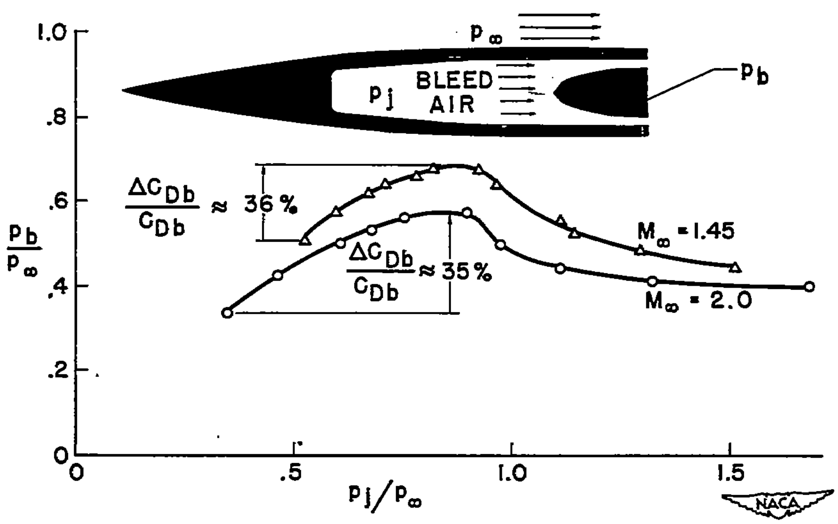

Figure 13

BODIES

EFFECT OF ANGLE OF ATTACK

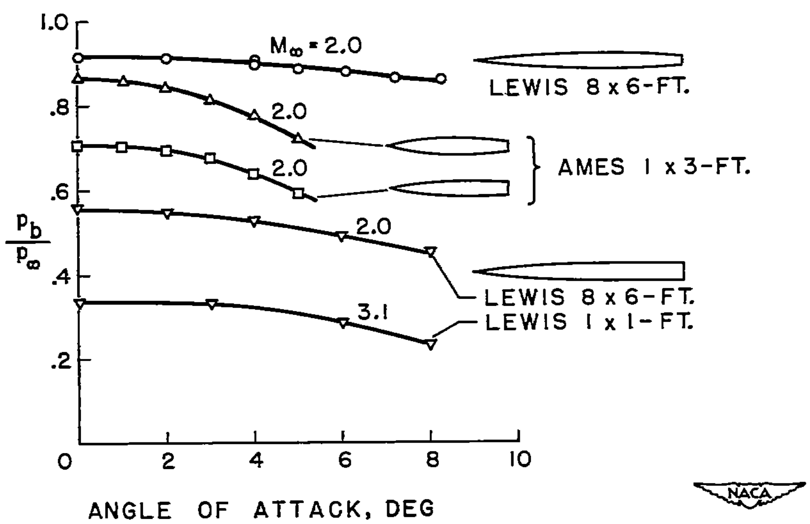

Figure 14

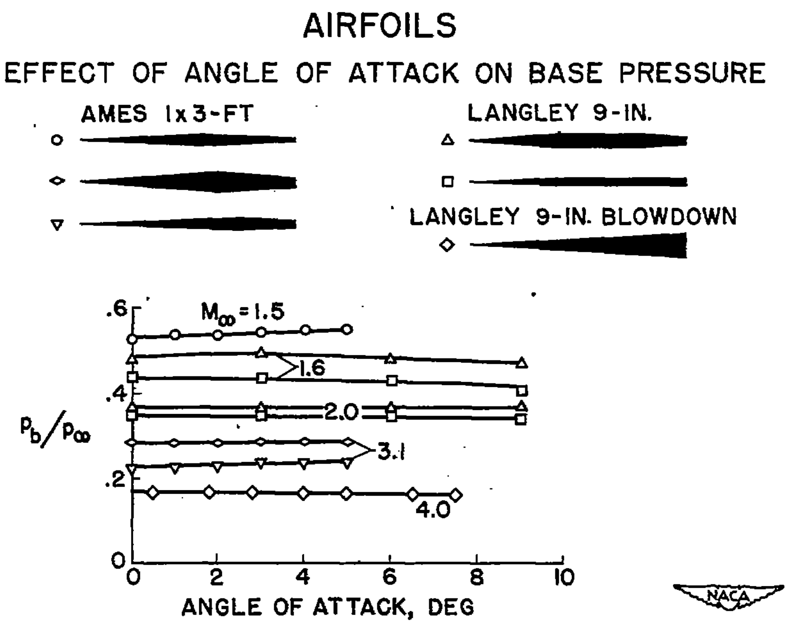
AIRFOILS
EFFECT OF ANGLE OF ATTACK ON BASE PRESSURE
AMES 1x3-FT
LANGLEY 9-IN.
LANGLEY 9-IN. BLOWDOWN
M∞=1.5
1.6
2.0
3.1
4.0
pb/p∞
ANGLE OF ATTACK, DEG
0
2
4
6
8
10
.2
.4
.6
NACA

Figure 15