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REPORT NO. 1337

# REVIEW OF BASE DRAG

by

R. Sedney

October 1966



U. S. ARMY MATERIEL COMMAND
BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

BALLISTIC RESEARCH LABORATORIES

REPORT NO. 1337

OCTOBER 1966



# REVIEW OF BASE DRAG

R. Sedney

Exterior Ballistics Laboratory

RDT&E Project No. 1P222901A201

ABERDEEN PROVING GROUND, MARYLAND

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

REPORT NO. 1337

RSedney/cr
Aberdeen Proving Ground, Md.
October 1966

# REVIEW OF BASE DRAG

## ABSTRACT

A review of the present state of knowledge of axisymmetric base drag is given. With application to ballistics in mind, this review is especially concerned with supersonic flight and turbulent boundary layers. Correlations of base pressure are discussed as well as some analytical methods for attacking the problem; no satisfactory analytic theory exists. Experimental methods for determining base pressure in wind tunnels and ballistic ranges are discussed. The effect of a boattail on total drag and base pressure is discussed and one other method for reducing base drag is considered briefly.

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| | |
|---|---|
| $C_D$ | Total drag coefficient |
| $C_{DH}$ | Head drag coefficient |
| d | Diameter of rod (Figure 1) |
| h | Diameter of cylinder (Figure 1) |
| $K_D$ | $= \pi C_D/8$ |
| L | Length of projectile |
| M | Mach number |
| $P_b$ | $= (p_b - p_\infty)/q_\infty$ |
| $P_{bi}$ | $= -\frac{2}{\gamma M_a^2}(1 - \frac{p_b}{p_a})$ |
| p | Pressure |
| q | Dynamic pressure |
| R | Reynolds number |
| U | Velocity |
| $u_*$ | Nondimensional velocity on dividing streamline |
| x | Axial distance from nose of projectile |
| $\beta$ | Body inclination angle at the base |
| $\gamma$ | Ratio of specific heats |
| $\delta$ | Boundary layer thickness |
| $\theta_{ae}$ | Effective two-dimensional expansion angle |
| $\mu$ | Coefficient of viscosity |
| $\rho$ | Density |

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LIST OF SYMBOLS (Contd)

Subscripts

| | |
|---|---|
| a | Approach value at the base |
| b | Value on base |
| c | Value before boattail |
| t | Stagnation (total) condition |
| $\infty$ | Free stream value |
| $(\ )_{a}'$ | "Effective" approach value |

## 1. INTRODUCTION

### 1.1 Historical Remarks

The "base drag problem" is essentially the same as the "base pressure problem" because the first is solved by integration of the result of the second. In current terminology the base pressure problem is also referred to as the "near wake problem." Thus the base drag problem is a particular example of a separated flow. This area of fluid dynamics, viz. separated flows, is one of the oldest yet one of the most popular. It probably appeared first in the mid-eighteenth century works of d'Alembert and Borda.

The recent AGARD Specialist Meeting on "Separated Flows" and the popularity of the near wake problem attest to recent interest. An historical account of work on both internal and external separated flows is given by Korst,[1*] for the period 1930 - 1955. Research cited there on the base pressure problem in supersonic flow is of special interest here.

To achieve proper historical perspective of the base drag problem one would also have to trace the contributions of studies in ballistics; for some of these, see Charters.[2]

It may, perhaps, be not without profit to emphasize these contributions to our present understanding of the flow in the neighborhood of the base. The work of Chapman[3] and Kurzweg,[4] showing the dominant role of viscosity in this flow, relied heavily on the results from ballistic range firings undertaken in the interest of improving ballistic technology.

Obviously base drag, or more generally afterbody drag, is of importance to a broader field of technology, not just ballistics. Also, one would expect that this topic would be reviewed periodically in the literature and appear in textbooks. This is not the case, to the author's knowledge.

Two-dimensional base flow has been reviewed by Nash[5] in 1962 and more recently in 1965;[6] these reviews were limited to consideration of turbulent flows. There have been reviews of the wake problem and some

* *Superscript numbers denote references which may be found on page 43.*

of this work is pertinent to the base flow region. Some limited information, theoretical and experimental, is given by Cope in a readily available book.[7] A concise statement of Chapman's model of reattachment of a laminar, separated flow is given by Moore;[8] this model is an important element of a theory of two-dimensional base flow.

The above remarks attempt to justify the need for a review of the axisymmetric base drag/pressure problem.

1.2 Scope of this Review

Limitations of space, time, and material preclude making this review all inclusive. The scope will be limited by the following constraints.

a. In some broad sense, the chosen subject matter should be pertinent to ballistics. In that application, turbulent base flow is the rule; thus the exceptional case of laminar flow will not be considered in detail nor will the effects of transition be emphasized.

b. Most of this review will be concerned with the case of supersonic approach flow. One can say, depending on his point of view, that there is too much or too little known about the subsonic case to enable substantive statements to be made in a short review. References 5 and 6 do give an outline of what is known concerning the subsonic flow situation, albeit with emphasis on two-dimensional flow. Some limited information will be given on subsonic projectiles.

c. The problem of the effect on base pressure of a jet exhausting into the near wake will not be considered. This is an interesting case for which there are a number of established results; it is a significant area considering the applications to artillery rockets, rocket assisted projectiles, and, of course, first-stage boosters for ballistic missile and satellite launchers.

Actually the scope of this review will be broadened to include boattail effects on base drag and boattail drag. Boattailing is the one practical means of reducing total drag that is used in ballistics and there is an intimate relationship between boattail pressure and base pressure.

In outline, the following topics will be covered. First, theoretical attempts at solving the base pressure problem will be outlined; these will include semi-empirical correlations. Second, boattail effects will be discussed. Third, experimental methods of determining base pressure will be considered. Finally, some techniques for reducing base drag will be briefly reviewed.

Before proceeding in this program, some statements of design practice, as I understand them will be given.*

## 2. DESIGN PRACTICE

The main interest in shell design is, of course, in the total drag. The designer, ever desirous of increasing the range and/or terminal velocity of projectiles, is eager to decrease the drag at almost any cost. But this price cannot include deterioration of the stability of the vehicle.

In subsonic aerodynamics it is conventional to divide the drag into two components: form (pressure) drag and viscous (skin friction) drag. Since the latter is usually small, if a streamline shape is employed (to avoid separation of the flow) the drag can be reduced to very small values, approaching the perfect fluid result of zero drag. Unfortunately such shapes have undesirable stability characteristics. Thus, relatively high drag shapes are used.

For rational design of supersonic vehicles, the drag is divided into the following components: head (pressure)(wave) drag, viscous (skin friction) drag, boattail (pressure) drag, and base drag. There are cases where such a division is ambiguous, but the division into pressure and viscous components is still reasonable. Apparently the design practice is to decrease the head drag and skin friction drag as much as feasible and then accept, more or less, the remaining base drag.

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*The author would like to acknowledge the help of Dr. B. G. Karpov and Mr. L. C. MacAllister in this and some other aspects of this review.*

It would seem, then, that the theoretical and semi-empirical attempts to "solve" the base pressure problem are not of much interest in design practice.

One indication of this is the lack of information on the relative magnitude of base drag compared to total drag, for some typical shell. For the low drag class of body shapes, base drag contributes from 40 to 50 percent of the total drag, for Mach numbers between 2 and 3. For shapes with high drag, the contribution can range from 0 to 20 percent. For a sphere at M = 5, the base drag is slightly negative. For some artillery rocket type bodies, it has been reported that base drag can contribute as much as 70 percent of the total drag.

Again, the practical techniques for reducing base drag usually have an adverse effect on stability. A number of studies have been made to examine the reduction in total drag due to a boattail. Although this device is effective in reducing the drag, only a portion of this reduction can be used because of the concomitant effect on the gyroscopic and dynamic stability. For example, for a 7-caliber long body, Karpov[9] has reported a 20 percent reduction in total drag for a boattail length of 2 calibers. The nutation damping rate is negative, viz. -1.0, indicating instability. Further drag reduction is possible by increasing the boattail length but the models become progressively less stable. The instability is traced to an increase in Magnus torque with boattail length. A rational explanation of the afterbody effects on Magnus force and moment would be very desirable.

Other methods of reducing base drag are conceivable and some of these will be discussed on the following page; however, these have not been studied seriously in ballistics. Thus, base drag is accepted and other methods of increasing range are sought.

## 3. THEORY OF BASE PRESSURE

In view of the previous statements, one can ask: could design practice benefit from the large amount of research that has been done on base pressure? The answer to this is surely, yes. The theory of base pressure can be helpful to the designer in determining, at least, what to avoid so that base drag is not increased. For example, even the inviscid theory shows the relative magnitudes of base pressures for two-dimensional and axisymmetric flows; this can lead to qualitative estimates of the effect on base drag of a fin at the base.

Of course, the key to an understanding of the base flow came from a realization of the importance of viscous effects, i.e., dependence of the base pressure upon Reynolds number. To the author's knowledge, the first papers in the open literature which showed this effect are those of Hankins[10] and Cope.[11] These results are discussed in Reference 7. On the basis of detailed measurements of the near wake region in a supersonic wind tunnel, Sternberg[12] deduced many of the important features of the flow model generally accepted today. In particular, he found

a. that the fluid in the "dead air" region actually has significant velocities (estimated at $M \cong 0.2$ or 0.3) due to the mixing along the free shear layer and the reversal of the flow at the convergence point; and

b. that changes in base pressure with Reynolds number are small until transition occurs in the near wake.

(Reference 12 is an abstract; the complete manuscript was available to the author.) The work of Chapman,[3] originally a part of a thesis submitted to California Institute of Technology in 1948, confirmed and established the model of base flow in use today. The work of Chapman and Perkins[13] and Kurzweg[14] added some vital information for this formulation.

### 3.1 Results from Inviscid Theory

The inadequacy of an inviscid theory for base pressure was shown by Chapman.[3] (For an outline of previous work on this approach, see Korst.[1]) An infinite number of solutions is obtained for two-dimensional flows and for axisymmetric flows with a rod extending from the base. (Without such a rod only zero base drag is obtained.) From the single-infinity of solutions, where the parameter is base pressure or "wake shock" angle, a limiting case can be defined for each approach Mach number, $M_a$. This is done by choosing the largest possible oblique shock angle (of the "weak" family) which will deflect the flow back to its original (free stream) direction. The corresponding base pressure coefficient is called $P_{bi}$ and it gives the maximum base drag. Chapman attempts to make use of this limiting value and is partially successful.

Such a calculation for two-dimensional flows is quite simple and requires using a set of compressible flow tables. The axisymmetric case must be computed by the method of characteristics. Aside from this, there are important differences between the two types of flows. For axisymmetric flow the expansion fan is not made up of straight characteristics (a non-similar solution), the constant pressure free streamline is curved, and the flow cannot be continued to the axis, so the insertion of the rod is necessary. Thus an additional parameter, d/h, must be introduced, the ratio of rod to body diameter.

The results of Chapman's calculation are reproduced in Figure 1. A discussion of various features of the calculation is given in Reference 3; in particular, it is shown that, as $d/h \to 1$, the two-dimensional result for $P_{bi}$ is obtained. Thus, the inviscid theory predicts lower base pressures - or high base drag - for the two-dimensional case compared to the axisymmetric case. This qualitative result is borne out in experimental results. It also explains, qualitatively, the fact that a body with fins attached near the base has considerably high base drag,[15] since there would be "leakage" of flow from the higher pressure of the body to the lower pressure of the fins.

Results of calculations of the flow fields at the base of a semi-infinite cylinder are given in graphical form by Sims.[16] These are more detailed than those given by Chapman and cover the range $1.2 \leq M_a \leq 7.0$, but the maximum base drag solution is not singled out.

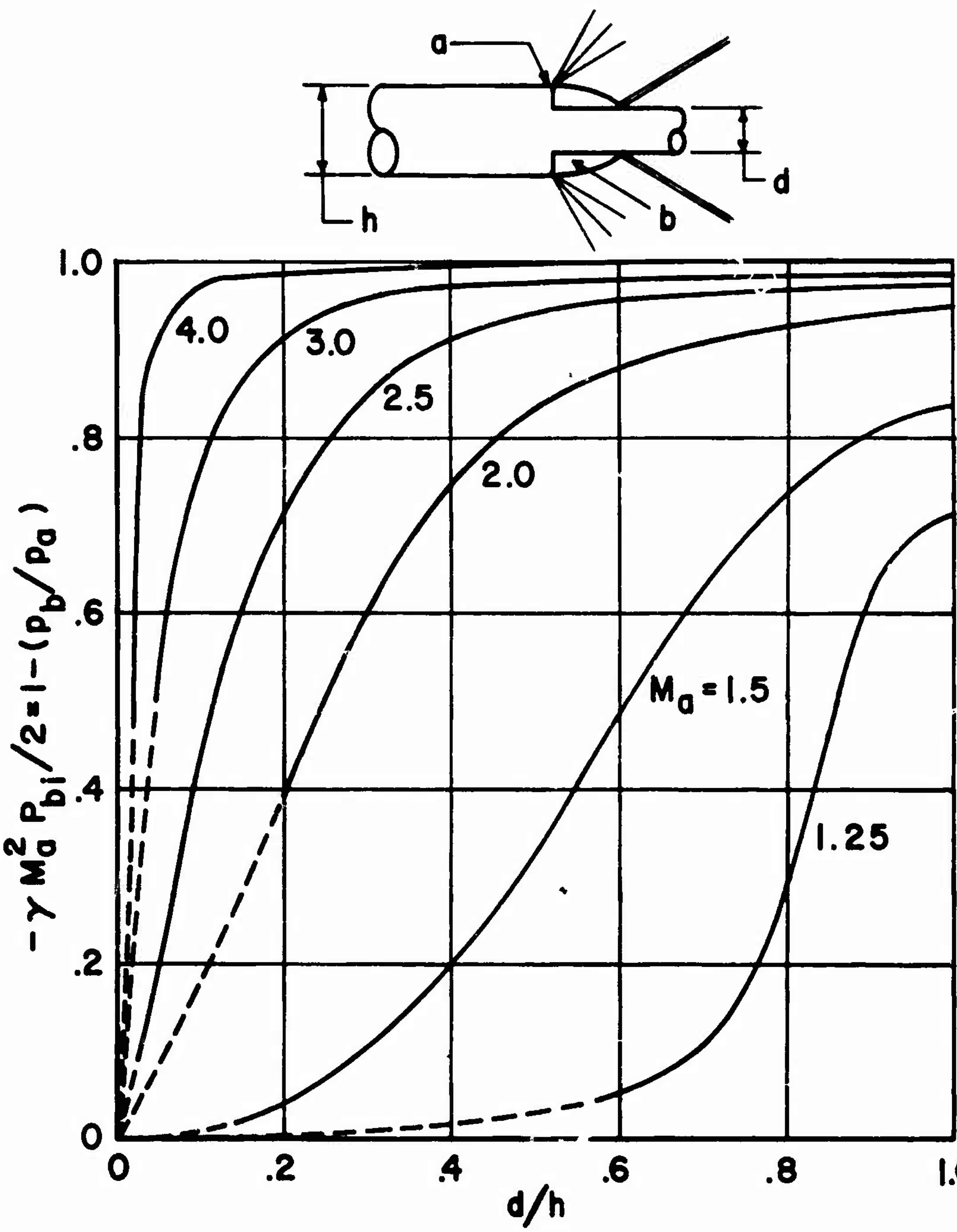


Figure 1. Parameter proportional to the maximum base drag possible in an inviscid axially symmetric flow; d/h = 1 gives two-dimensional results. Data are from Reference 3.

It is tempting to draw an analogy between the rod and the "wake diameter" in a real flow. Chapman has done this with only limited success. In the two-dimensional case, the presence of a plate extending from the base would have no effect on the inviscid base pressure; for one airfoil shape at M = 2.0 and a laminar boundary layer the analogy yields a base pressure coefficient within 10 percent of the experimental result. In Chapman's analogy, the experimental result is that obtained by extrapolation to infinite Reynolds number. In the axisymmetric case, the wake is not always steady for Mach numbers close to one; but from examination of range shadowgraphs a wake thickness ratio t/h (analogous to d/h) of 0.55 and 0.49, for M = 1.5 and 2.0 respectively, is deduced. For these two cases, $P_{bi}$ = -0.25 and -0.29 are obtained whereas the extrapolated results are -0.24 and -0.20. As Chapman states: "The good agreement obtained in two of the three cases may be entirely fortuitous. Additional experiments are needed to clarify the point." To the author's knowledge no further work on this matter has been done.

Although an inviscid theory cannot yield the correct solution to the base pressure problem, it is still possible that further work along this line might yield a method for estimating the base pressure that would be satisfactory for design calculations. This should be feasible if one includes some results from the viscous, mixing theories to determine a unique solution.

## 3.2 Effects of Profile Shape

The above discussion of inviscid theory applies only for a semi-infinite cylinder. Even the inviscid theory for flow over some profile shape would have to take account of the history of the flow and the effect of reflected waves (characteristics) from the bow shock on the base flow region. Another contribution of Chapman[3] was to offer a simple means of calculating "corrected" approach Mach number and pressure, $M_a$ and $p_a$. Chapman states that the correction is "accurate only when the induced disturbance field (due to profile shape) is small and approximately uniform over the region in question." Thus it is not surprising that the corrected values lose their validity for some extreme profile changes.

As an approximation to the correction, Chapman suggests the following rule: extend the afterbody one caliber and take the average Mach number and pressure along this extension as the corrected $M_a$ and $p_a$. A different, more complicated, rule is necessary for a body with a flare or boattail. He proceeds to use these corrected values - together with a dimensional argument to account for boundary layer thickness (see below) - to correlate measured base pressure on a variety of shapes at $M_\infty = 1.5$ and 2.0 for laminar and turbulent flow. The correlation for laminar flow and $M_\infty = 2.0$ is particularly impressive; the body shapes range from a cone, fineness ratio, $L/h = 0.9$, to an ogive-cylinder, $L/h = 7.3$.

The validity of the correlation depends on both the profile correction and the dimensional argument; the latter will be discussed below. To correlate results for blunted 9 degree half-angle cones for $2 \leq M_\infty \leq 5$, bluntness ratio, 0.3, and turbulent boundary layers, Whitfield and Potter[17] give an "interim proposal" different from Chapman's correction for calculating the approach Mach number and pressure. Predictions from this are not confirmed for $M_\infty > 5$ by the experimental data of Zarin.[18] The usefulness of any correction for profile shape is disputed by Love.[15]

Since high-speed computing machines and characteristics programs are so readily available today, it does not seem very profitable to pursue this tack. The essential point is that the base pressure is determined by (among other things) the values of $M_a$ and $p_a$ and to some extent, depending on the domain of dependence of the base flow region, by the profile shape.

## 3.3 Correlations

Because predicting the base pressure is such a formidable theoretical problem, many correlations have been attempted as an aid to understanding or as a practical means of estimating base drag. Only some of the most commonly used correlations will be discussed here.

Again, it is instructive to follow the reasoning of Chapman.[3] The base pressure, according to his model, depends on the approach Mach number and pressure, boundary layer thickness $\delta$, body diameter, h, and body angle, $\beta$, at the base. The profile correction gives an effective approach Mach number, $M_a'$, and pressure, $p_a'$. Then dimensional analysis yields

$$P_b' = f(M_a', \delta/h, \beta)$$

where $P_b' = (p_b - p_a')/q_a'$, $p_b$ is the base pressure, q is dynamic pressure.

The profile correction can relate $M_a'$ to $M_\infty$. The Reynolds number $R = \rho_\infty U_\infty L/\mu_\infty$ is based on body length and free stream conditions. For a laminar boundary layer $\delta \sim R^{-1/2}$ whereas for the turbulent layer $\delta \sim R^{-1/5}$ is assumed. For $\beta = 0$ and a fixed Mach number, the final results of the dimensional analysis are

$$P_b' = f(L/hR^{1/2})$$

for laminar flow and

$$P_b' = f(L/hR^{1/5})$$

for turbulent flow.

Using the above reasoning, Chapman arrives at a "reasonably good correlation" for both laminar and turbulent flows at $M_\infty = 1.5$ and 2.0. Unfortunately, experimental results of Reller and Hamaker[19] show that the correlation is poor for $M_\infty \geq 3$. Love[15] contends, and supports this with a different type of correlation, that Chapman's correlation with $L/hR^{1/5}$ is successful only because the range of R variation is small and that "it is obvious that L/h is by far the predominant factor in determining base pressure for such bodies" viz. those with "appreciable variation in $M_a$ and $p_a$ with L/h".

For bodies of somewhat similar shapes (e.g., slender, pointed bodies), fixed L/h, and with turbulent boundary layers, experimental results show that the variation of $P_b$ with R is slight. Thus a correlation of $P_b$ with $M_\infty$ might be possible. Chapman[3] showed such a correlation for cone-cylinder models with L/h = 5 and 6 and $2 \leq R \times 10^{-6} \leq 7.5$. This correlation, quoted as Chapman's semi-empirical method, is often used to estimate base pressure, even beyond the originally restricted range of parameters. Love[15] has given a slightly different correlation for $L/h > 5$ and $2 \leq R \times 10^{-6} \leq 22$. This is sometimes called Love's semi-empirical method.

The data used by Chapman were taken from wind tunnel and free flight tests; actually a majority of points were from the latter. Those used by Love were mainly from wind tunnel tests. There is no significant difference between results from the two facilities.

Reller and Hamaker[19] performed wind tunnel tests on ogive-cylinder and power law bodies with $L/h = 3.12$ and $10.00$. Reynolds number effects on base pressure for the two fineness ratios were detectable.

Kahl[20] performed free flight tests in a ballistic range on 35 degree half-angle cone-cylinders with $L/h = 2.0$. This set of data is very extensive, covering the range $R = .5 \times 10^6$ at $M_\infty = 1.5$ to $R = 4.8 \times 10^6$ at $M_\infty = 7.5$. The higher $M_\infty$ results were obtained in atmospheres of air and $N_2$ at low ambient temperatures ($\sim 100^oK$) so that no significant real gas effects are present; thus the results are comparable to high Mach number wind tunnel results. The accuracy (to be discussed below) is greater than or equal to wind tunnel test accuracy. Only about half of this data is used in the following discussion.

The above four sets of data are presented in Figure 2. Kahl's data are shown only for $M_\infty > 3$; for $M_\infty = 3$, $R = 1.06 \times 10^6$ in his data. Thus, for all these data, the Reynolds number range is $1 < R \times 10^{-6} \leq 22$ and the boundary layers are presumably turbulent. For the detailed conditions at the various Mach numbers, the reader must consult the original references. As mentioned before, at the lower Mach numbers there is no systematic difference between the wind tunnel and free flight test results. In Figure 2, especially for $M_\infty > 4$ there does seem to be a significant difference* between the results of References 19 and 20.

---

**The high value of* $-P_b$ *at* $M_\infty = 3.8$ *is not representative of scatter in Kahl's data. It is traceable to a "bulge" in the total drag curve for his model; this "bulge" is reproducible even for tests in a gas of* $\gamma = 1.174$.

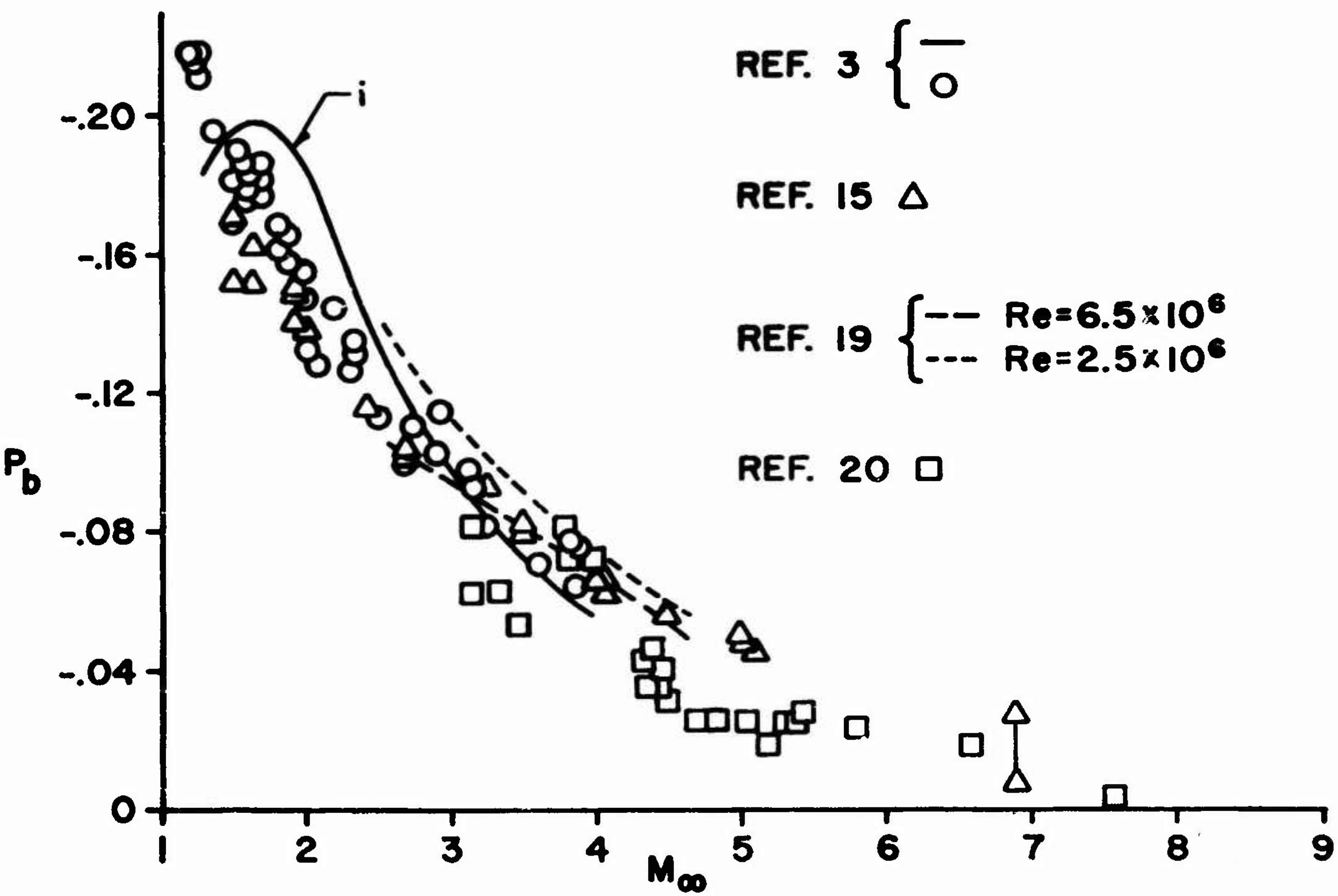


Figure 2. Base pressure coeffi :ient versus Mach number for turbulent boundary layer. See references for experimental conditions.

The values at $M_\infty = 5$ from Reference 15, which are high compared to those of Reference 20, come from work dated 1949 at the Johns Hopkins University Applied Physics Laboratory. The original references were not available to the author, but it is suspected that the data were obtained by telemetry from a full scale model.

The details of the experimental methods and accuracy of wind tunnel and free flight tests will be discussed later. Suffice it to say that both techniques suffer in accuracy at the higher $M_\infty$.

The results presented in Figure 2 are representative of the vast amount of data available from which such a correlation could be attempted. Any correlation of this sort may be valuable for making base pressure estimates but not for achieving an understanding of the basic problem.

The curve "i" shown in Figure 2 is taken from Reference 3; it comes from application of information from Figure 1, a measurement of the "wake thickness", and the analogy described in Section 3.1.

Love[15] devised semi-empirical method based on correlating measurements of the wake angle. He deduces an "effective two-dimensional expansion angle", taken as 0.85 of the wake angle. This effective angle $\theta_{ae}$ ($\delta_e$ in Love's notation) is shown in Figure 3 as a function of $M_a$. For $M_a > 4$, the wake angle measurements were not available; a curve fitting technique was then used.

Love's method is to take the known values of $M_a$ and $p_a$ and calculate $p_b$ assuming a Prandtl-Meyer expansion through the angle $\theta_{ae}$. The calculation is trivial once $M_a$ and $p_a$ are known, e.g., from characteristic calculations. Application of this method to some representative cases yields results shown in Table 1. Some of the measured wake angles on which this method is based were taken from Reference 21; therefore the first three predicted values are more of a check on the internal consistency of the method. Evidently the method works better for lower Mach numbers and higher L/h.

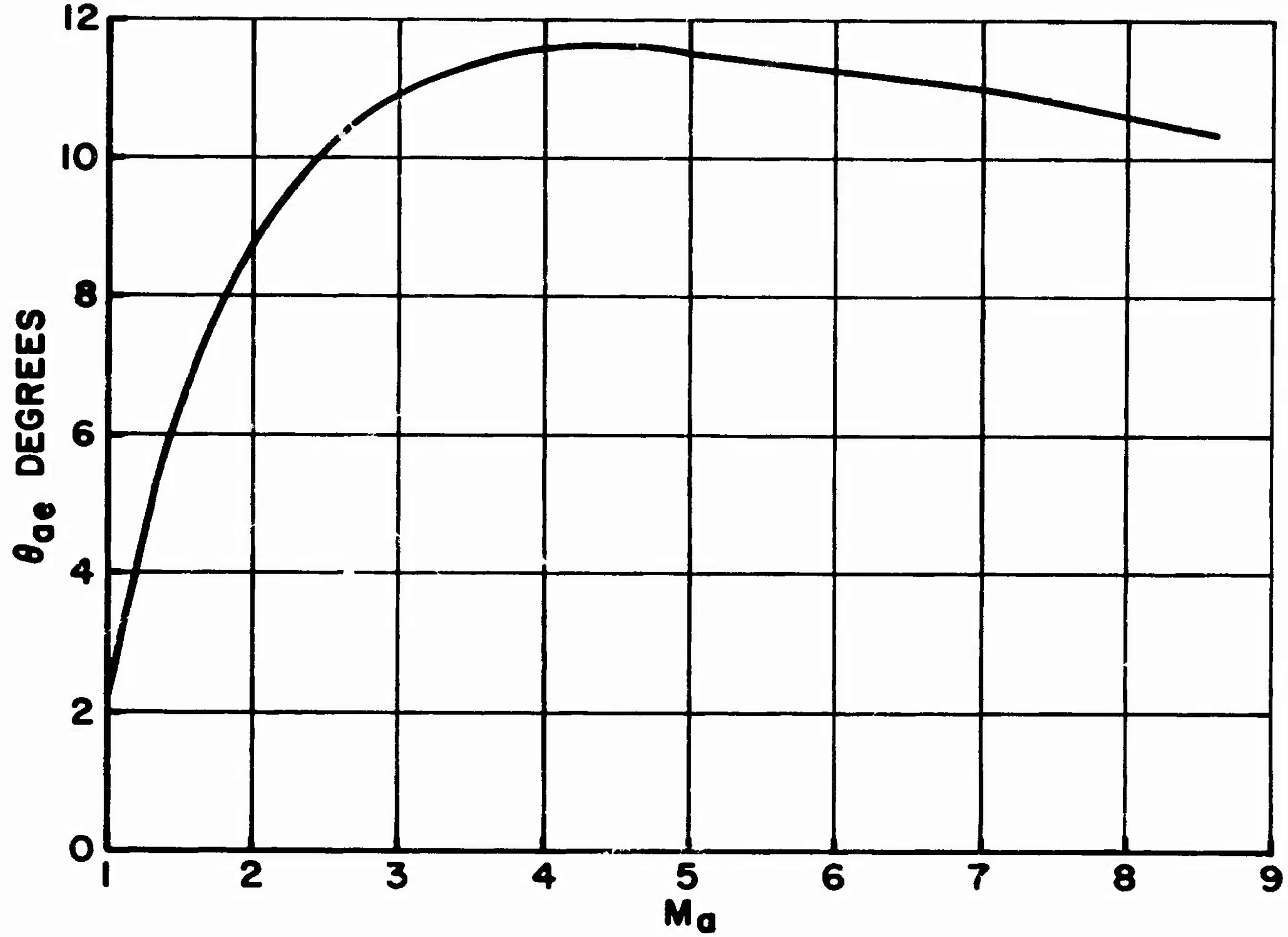


Figure 3. "Effective two-dimensional convergence angle" versus Mach number ahead of base as given in Reference 15.

TABLE I

APPLICATION OF LOVE'S "TWO-DIMENSIONAL EXPANSION ANGLE" METHOD

| $M_\infty$ | $p_b/p_\infty$ measured | $p_b/p_\infty$ predicted | % diff. | L/h | Ref. |
|---|---|---|---|---|---|
| 2 | .588 | .543 | 8* | 5.0 | 21 |
| 3 | .400 | .345 | 14* | 5.0 | 21 |
| 4 | .258 | .226 | 12* | 5.0 | 21 |
| 3 | .471 | .371 | 21 | 2.0 | 20 |
| 4 | .406 | .335 | 23 | 2.0 | 20 |
| 7 | .588 | .317 | 46 | 2.0 | 20 |
| 1.7 | .670 | .660 | 1.5 | 7.0 | 9 |

*See Text

The results obtained by Lehnert and Schermerhorn[22] for base pressure on sharp and blunted cones, with the same cone angle, can be considered as a type of correlation. Actually the main conclusion drawn there is that if $M_\infty$ is chosen for the sharp and blunt cones so that $M_a$ is the same then $p_b/p_a$ is a function of Reynolds number based on momentum thickness at the base. This correlation holds for laminar, transitional, and turbulent flows.

Also for cones, Cassanto[23] claims to have a correlation of $p_b/p_a$ with $M_a$; he presents no data to support this, only a curve.

Progress in understanding the base flow problem, so that accurate estimates of base drag may be made, must come from some rational theory of the flow. A cursory review of some of these theories is presented in the next section.

## 3.4 Rational Theories of Base Flow

There has been considerable progress in developing a rational theory of the base flow. Almost all of the theoretical work has been specifically for the two-dimensional case, however. Thus, for ballistic applications, i.e., for axisymmetric flow and for turbulent boundary layers, it is safe to say that no completely satisfactory theory exists and this justifies giving only a resumé of the status of the theoretical work. Another reason for including this description is that some of the details of the older theories are now being questioned - and hopefully being improved. In fact, there is at least one controversy in the literature, see, e.g., References 24 and 25 and references cited there.

For a more detailed review of the two-dimensional problem, see References 5 and 6. An elegant survey of separated flows, including items pertinent to the base flow, was given by Carrière to the AGARD Fluid Dynamics Panel in September 1965; to the author's knowledge this has not been published. A recent survey by Lykoudis[26] on hypersonic wake studies mentions items of interest to the base flow problem; this survey contains approximately 190 references. One would think that, with the vast amount of work that has been done on wakes in the past five years, some real progress would have been made in the near wake problem. This does not seem to be the case.

The theories can be divided into two classes. The first is a detailed one in which differential equations are set up and solved after the problem has been suitably simplified. This class is typified by and probably originated with the work of Crocco and Lees.[27] An integral method is used to solve the boundary layer equations; it is not established that the boundary layer approximation is valid for the separated flows considered. More recent work on this class of theory, by Reeves and Lees,[28] seems to give promising results. For two-dimensional laminar flow, the trends predicted by the theory are in agreement with some experimental results. These authors report that work is in progress on the axisymmetric case.

An attempt to apply the Crocco-Lees method to axisymmetric, turbulent flow was made by Davis.[29] Since the report is not generally available it is best to quote from the conclusions of Davis: "On the basis of the one calculation little can be said concerning the quantitative results of the method. In fact, one could not expect much from the theory in its present crude form as far as quantitative results are concerned. However, it is believed that a few refinements based on experimental data for the main parameters could lead to a method for calculating the wake flow (and base pressure) of a body of revolution which could give a good quantitative, as well as qualitative, evaluation of the flow."

The second class of theories is a global one. It constructs a model of the flow in which there are three main elements: (a) the starting profile for the free shear layer, (b) a solution for the free shear layer giving the mass entrained from the "dead air" region, and (c) a convergence (reattachment) criterion that governs the mass returned so that mass is conserved in the dead air region. The development of this type of theory is due to Korst[1,30] and Chapman.[3,31] Korst[30] considered the turbulent case and Chapman et al.[31] the laminar case.

Each of the above three elements is considered separately and, when joined together, provide a solution for the base pressure. In the original work, approximate solutions for each element were given. These will be outlined and some recent attempts to improve the solutions will be mentioned.

(a) In References 30 and 31 explicit solutions were given only for approach boundary layer thickness, $\delta_a = 0$. This approximation obviates the difficult problem: what effect does the sudden expansion at the base have on the boundary layer? Weinbaum[32] has considered the expansion effect on the boundary layer; this effect is similar to that which arises in predicting pressures on boattails considered in the next section. The effect of the expansion on the thick turbulent boundary layers prevalent in ballistics can be considerable even at moderate Mach numbers.

One can simply assume a starting profile of finite thickness (Denison and Baum[33] assumed the Blasius profile) and then proceed to solve (b) numerically. If the free shear layer is long enough, the solution should approach Chapman's similarity solution[34] for laminar flow.

(b) One of the most important parts of this element is to determine the "dividing streamline" and the conditions existing on it. This determination is crucial for the next step in (c). Calculation of the laminar free shear layer is relatively straightforward. For turbulent flow only gross approximations can be made. More details can be found in Reference 6. Extended treatments and literature surveys of free turbulent mixing are available for incompressible,[35] subsonic,[36] and supersonic[37] flows.

(c) The two shear layers (two-dimensional) or annular shear layer (axisymmetric) converge to form the neck of the wake. In this region, the "dividing streamline" delineates the flow that is sent downstream and that which is returned to the base region. The Korst-Chapman convergence criterion states that the total pressure, $p_t$, on the dividing streamline is equal to the static pressure, $p_d$, downstream of the convergence. This static pressure is provided either by an isentropic compression or a shock wave.

This criterion was advanced as a first approximation to the complicated flow in the convergence region. It has recently come under scrutiny by Carrière and Sirieix[38] and Nash.[6] Nash contends that a fortuitous compensation of errors accounts for the success of Korst's theory - the error due to finite initial boundary layer thickness and the error in the convergence criterion. He introduces an empirical factor to modify the criterion. It is the author's opinion that only a more fundamental approach to this complicated flow region will give significant improvements on the Korst-Chapman theory.

Roshko and Thomke[39] have reported some interesting experiments undertaken to explore this convergence region. They tested axisymmetric models with a step; this avoids the difficulties encountered in trying to realize two-dimensional flow. By varying the step height they show how the axisymmetric effect developes.*

Reference 39 also summarizes clearly the computation of the base pressure according to the Korst-Chapman theory and provides a convenient graph. This is reproduced in Figure 4; it can be used to obtain a rough estimate for axisymmetric base pressure, at least for higher Mach numbers. Korst[30] presented a method of handling different approach angles, e.g., because of the presence of a flare or boattail. This method, together with Figure 4, sometimes yields a good approximation to the base pressure, see for example Reference 22.

Remarkable agreement with experiment was shown in References 30 and 31 for the Korst-Chapman theory for two-dimensional flows. In Reference 31 it was shown that the result reduces, for incompressible flow, to

$$P_b = \frac{p_b - p_\infty}{q_\infty} = - \frac{u_*^2}{1 - u_*^2}$$

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*Professor Roshko has informed the author that some of the interpretations of the data have been changed and will be reported in a forthcoming publication.*

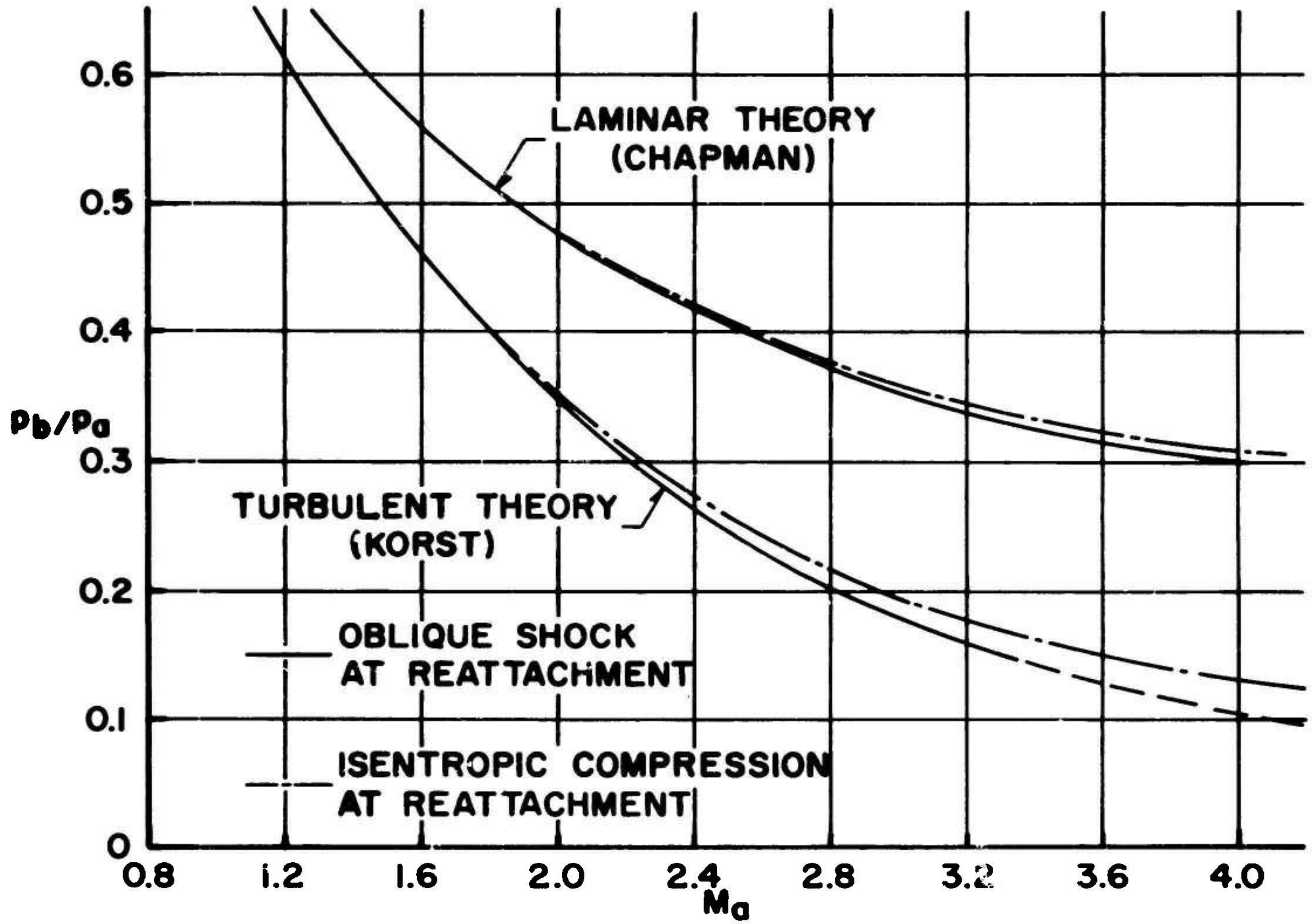


Figure 4. Ratio of base pressure to pressure ahead of base versus Mach number ahead of base for two-dimensional flow. Data are from Reference 39.

where $u_*$, the non-dimensional velocity on the dividing streamline, can be taken as 0.587 for laminar flow and 0.62 for turbulent flow. This result agrees well with experimental results of Roshko[40] for steady, incompressible base flow.

The base pressure determined from the Korst-Chapman theory is independent of Reynolds number. In a test[31] in which the initial boundary layer thickness was negligible this independence was verified experimentally.

The application of the Korst-Chapman theory to axisymmetric flow, at present, involves additional approximations. Reference 33 considered the laminar case and indicated agreement with extrapolated experimental results[22] for cones at $M_\infty = 2.75$; the dividing streamline was assumed to be straight, the inviscid flow at the edge of the shear layer assumed constant, and the transverse curvature effect neglected. Again the base pressure is independent of Reynolds number. An extensive computer program employing axisymmetric inviscid flow and Korst's two-dimensional mixing solution is reported by Street;[41] this includes the presence of a jet exhaust at the base.

It may be that large scale computer simulations of the base flow will some day shed some new light on this complicated problem.

## 4. BOATTAIL EFFECTS

The one effective means of modifying the base pressure that has been found practical in ballistics is the use of a boattail. Although the boattail itself contributes additional drag, the base drag decreases enough to conteract this increase; for small enough boattail angles the total drag is reduced. This effect is illustrated for a typical shell in Figure 5 for subsonic and supersonic flow; a significant reduction in drag is obtained. Note $K_D = (\pi/8)C_D$. This effect has been investigated often in the past fifteen years.[4,9,15,19,42,43,44]

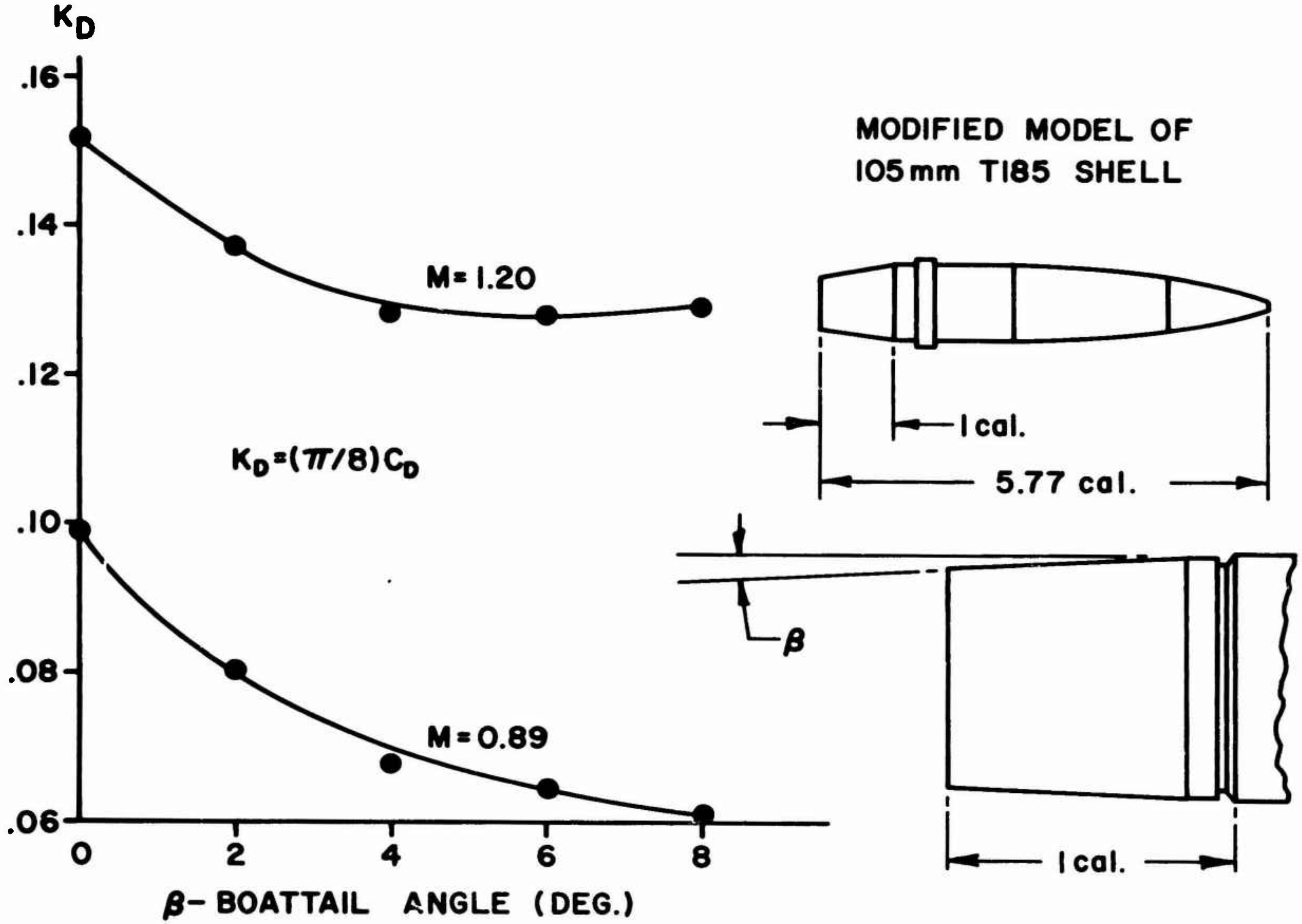


Figure 5. Drag coefficient versus boattail angle for a typical shell.

Results from an extensive set of tests are given by Karpov[9] for conical, ogival, and concave boattails. Total drag as a function of boattail length (fixed base diameter) and conical boattail angle (fixed boattail length) is shown in Figure 6. Note the slight increase in drag for short boattails. The conical boattail is superior to the others. A typical shadowgraph from these tests is shown in Figure 7.

Base pressures were determined in these tests by using the free flight subtraction method to be described below. These are consistent with the correlation of boattail effects on base pressure given by Staylor and Goldberg.[44]

Karpov[9] used a semi-empirical method devised by Sternberg (in 1948 but only published as an appendix to Reference 9) to predict the increment of base pressure due to the boattail. He found good agreement with experimental results. Similar, semi-empirical methods have been suggested by Chapman[3] and Cortright and Schroeder.[42]

Staylor and Goldberg[44] have collected data from several sources, for $1.5 \leq M_c \leq 5.8$, where $M_c$ is the Mach number before the boattail, $0^\circ \leq \beta \leq 21^\circ$, and various boattail lengths. This set is shown in Figure 8 which includes Karpov's data. They state that the methods of References 3 and 42 were found to be only in qualitative agreement with this set of data. Applying Sternberg's method to the case for $M_c = 5.8$ does not yield agreement with the data.

This is not surprising in view of the large effect, shown in Reference 44, of the relatively thick turbulent boundary layer on boattail pressures. Measured pressures are almost a factor of two greater than those computed by characteristics. This type of discrepancy has been known for many years, e.g., see Reference 42; it has, however, been largely ignored. Results from some recent wind tunnel tests at the Ballistic Research Laboratories (BRL) for two of Karpov's models are shown in Figure 9. The boattail length was 1.4 calibers. The conical boattail angle was $6^\circ$, the final angle of the ogival boattail was $12^\circ$. Also, results of characteristic calculations are shown for comparison. The increasing discrepancy with Mach number is quite noticeable.

Such discrepancies can be important when the subtraction method of determining base drag/pressure is used. Staylor and Goldberg give a "sonic expansion" method for determining the average boattail pressure. In this method, Prandtl-Meyer expansion through the boattail angle starting at M = 1 is used, regardless of the Mach number at the edge of the boundary layer. For their results the sonic expansion method gives reasonably good agreement. From the conical boattail data presented in Figure 9 it would also give a much better approximation than the characteristic results for $M_\infty = 4.5$ but not for the lower Mach numbers.

## 5. EXPERIMENTAL METHODS FOR DETERMINING BASE PRESSURE

Space does not permit a complete description of experimental techniques for determining base pressure. The most common method is to measure the pressure in a wind tunnel. The free flight subtraction method is somewhat less common. Both of these have their drawbacks. Perhaps the free flight-wind tunnel techniques being developed will give the most reliable results.

One of the major problems in the wind tunnel method is, of course, the ever present support effect. For development tests which require limited accuracy there is no problem. The rules of thumb that have been developed over the years will suffice unless the model has some unusual features. In that case, or if greater accuracy is needed, a systematic study of support effects is necessary. At higher Mach numbers possible effects of condensation must be considered; a method of correcting for these is proposed in Reference 19. In that reference a systematic effect due to the transition promoting device was also noticed; no method of correcting for this was found even though the effect on $P_b$ was estimated to be as much as 10 percent. At higher Mach numbers care must be exercised because the measured pressure can be quite small. Also it is necessary to know the type of boundary layer; this is sometimes difficult to determine at high Mach numbers.

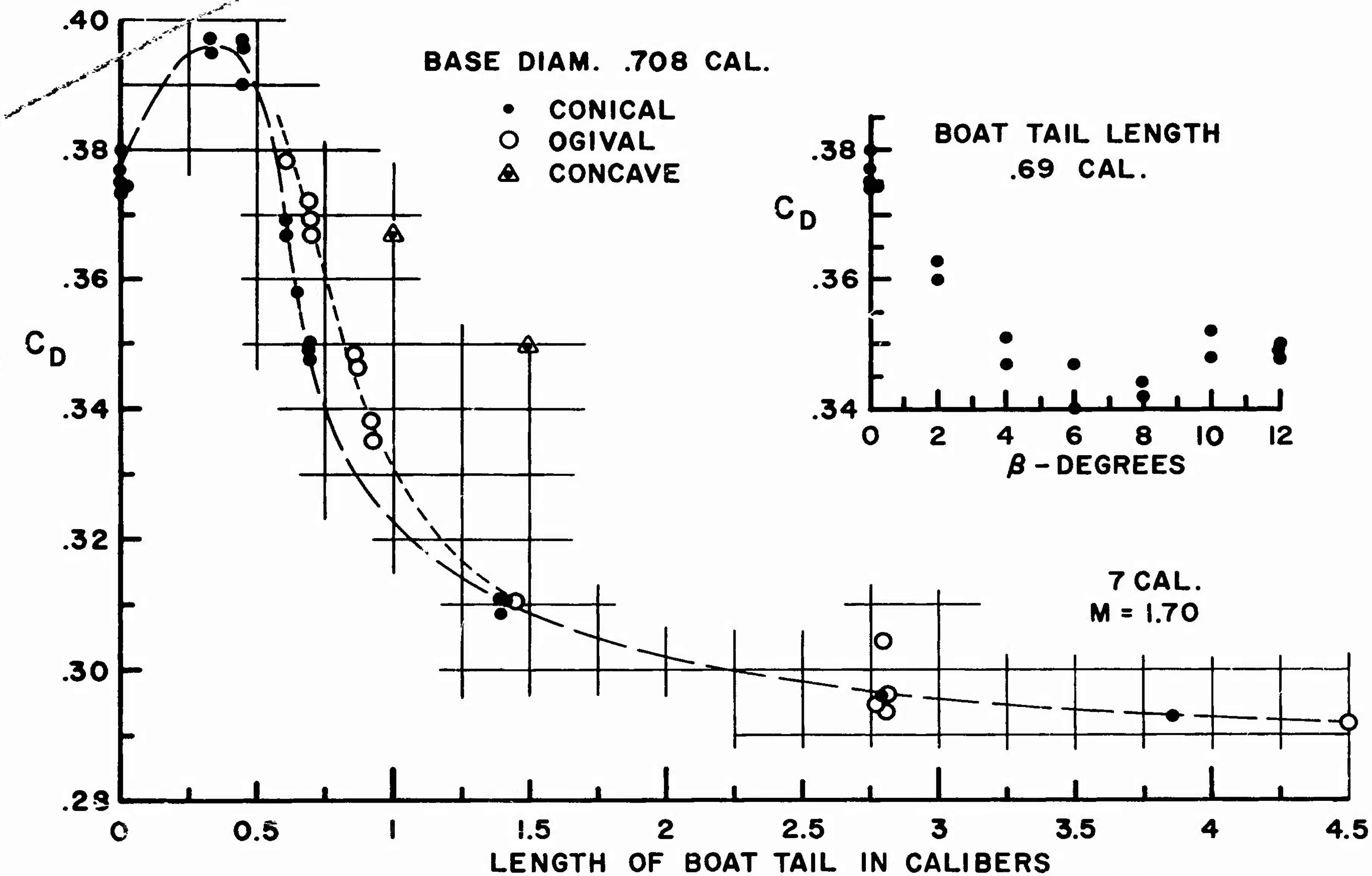


Figure 6. Drag coefficient versus boattail length and conical boattail angle for body shown in Figure 7. Data are from Reference 9.

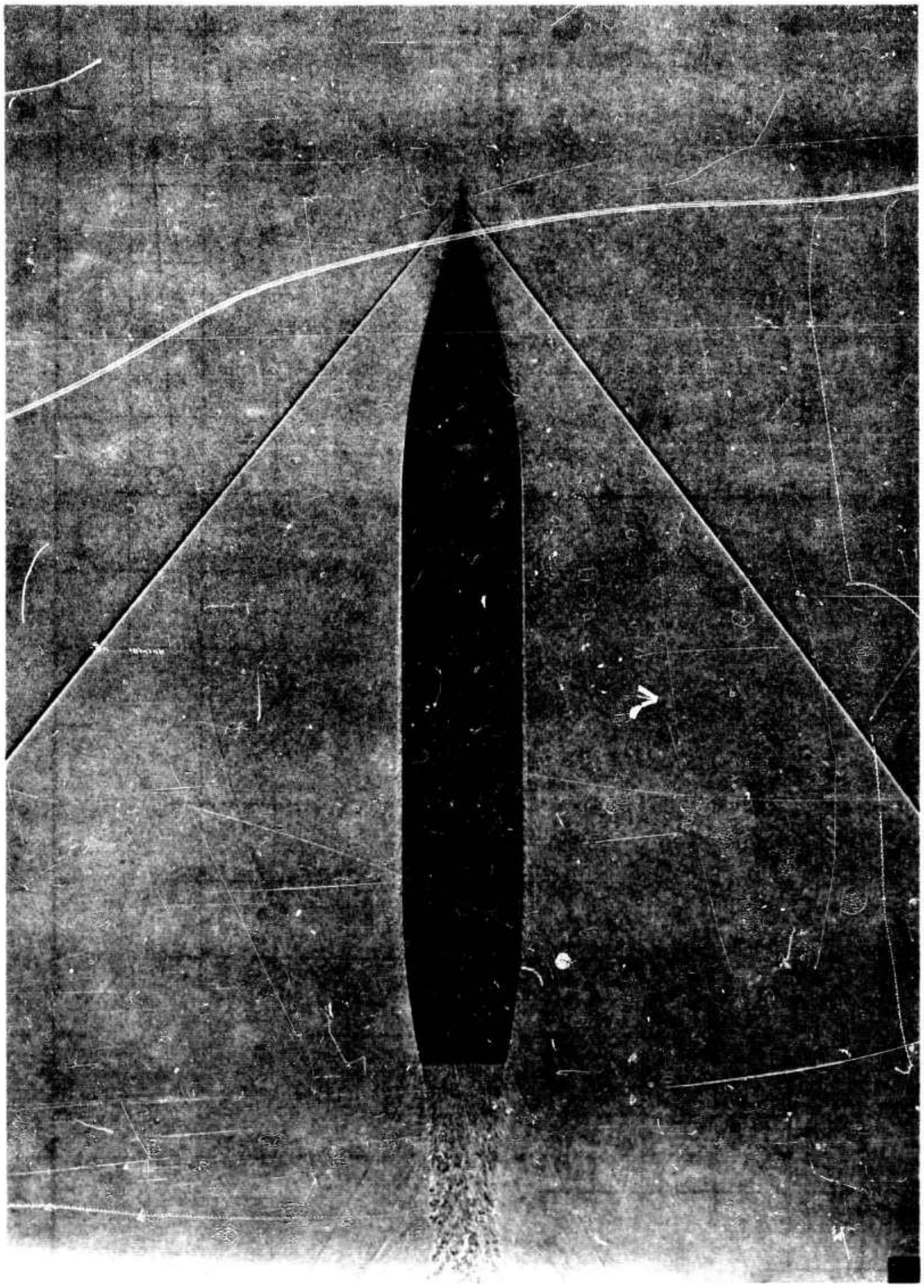

Figure 7. Shadowgraph of a typical model fired in the ballistic range tests of Karpov, Reference 9; nose angle 16.075°, $M_\infty = 1.72$, atmospheric pressure.

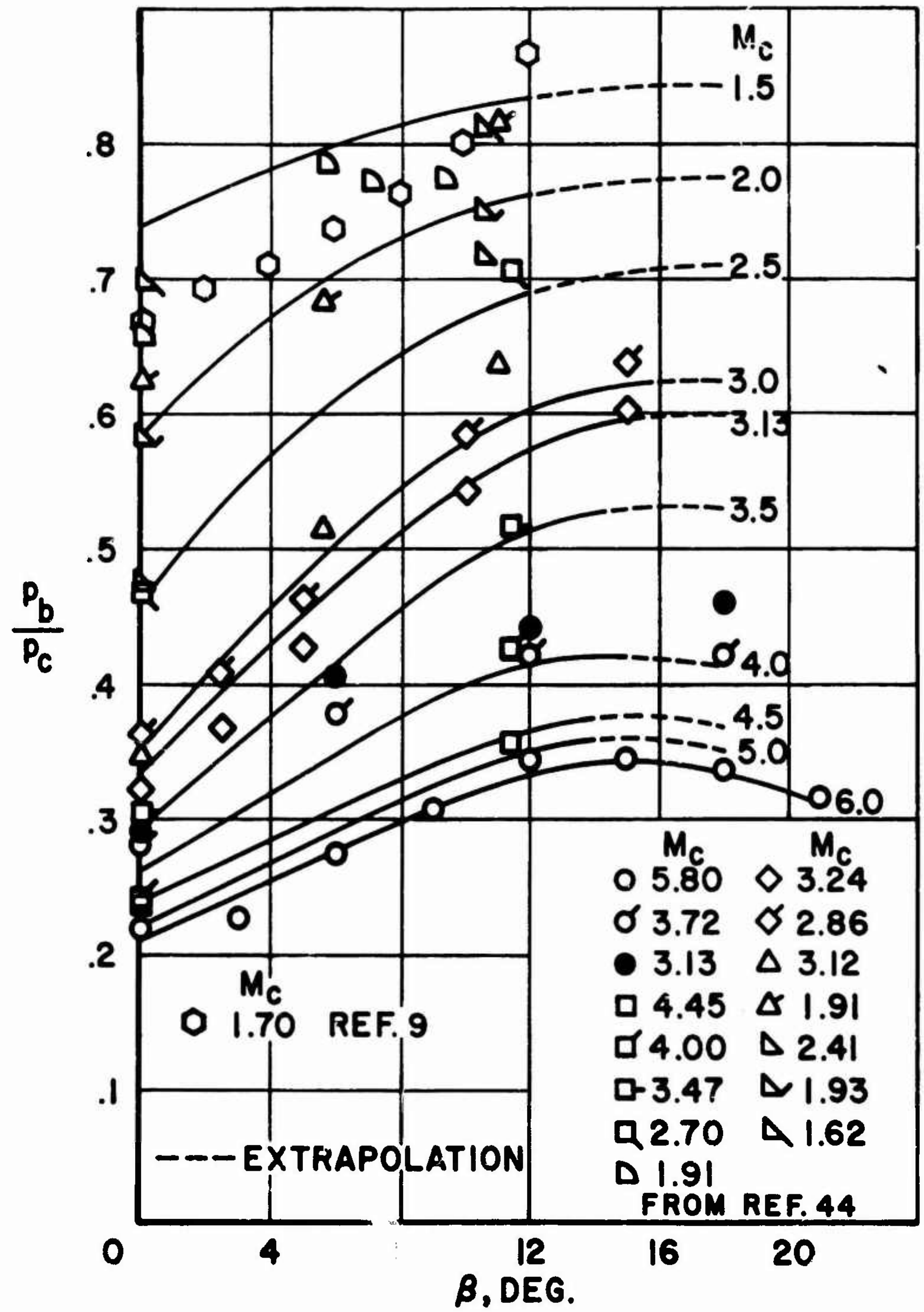


Figure 8. Ratio of base pressure to pressure ahead of boattail versus boattail angle for various Mach numbers ahead of boattail. From Reference 44 (except for Reference 9 data). All bodies with pointed noses, except ● $M_c$ = 3.13 hemispherical nose.

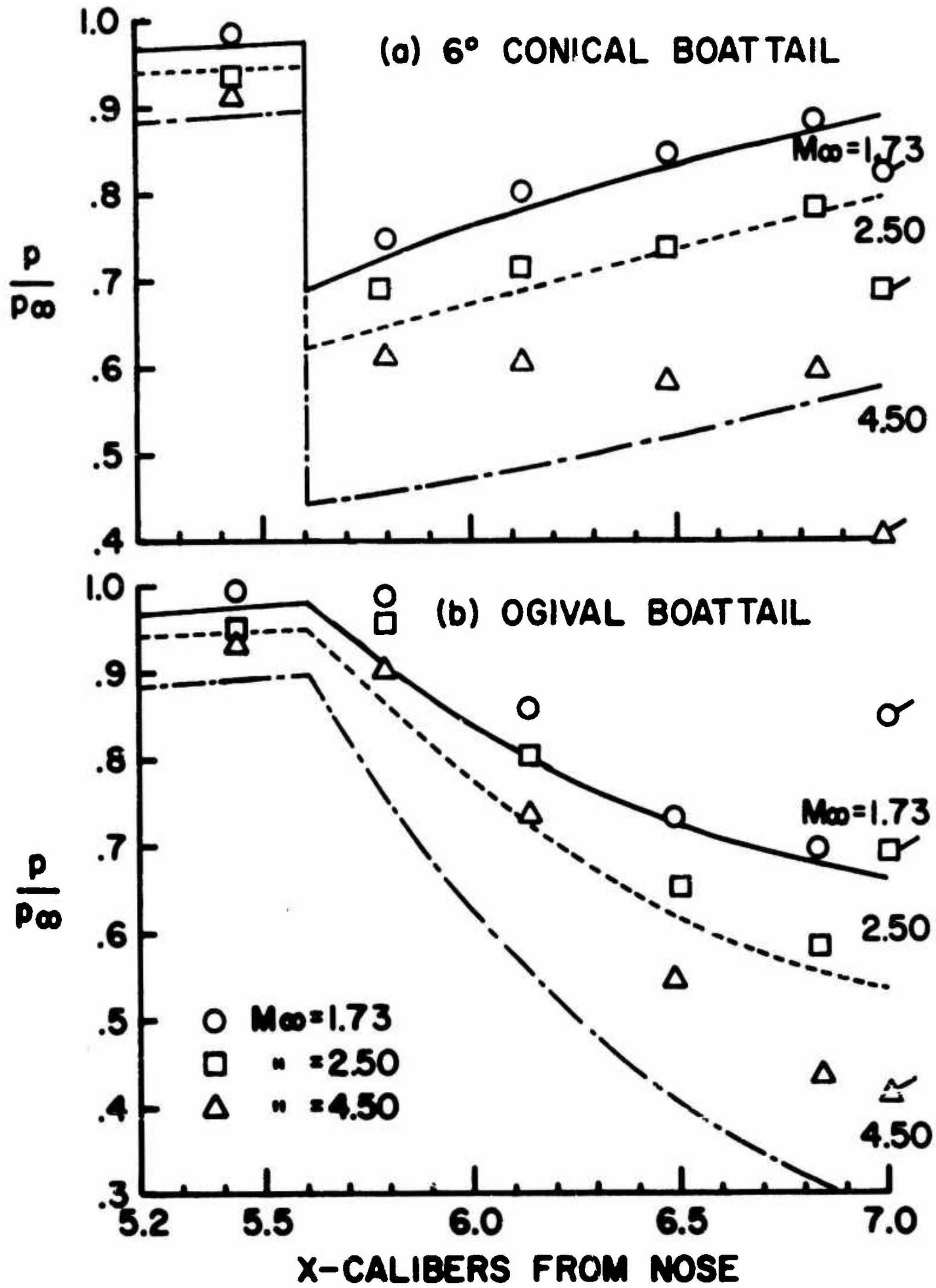


Figure 9. Comparison of calculated (characteristics) and measured (wind tunnel) pressures on two boattailed bodies (type used in Reference 9). Flagged symbols give base pressure. Angle at base is 12° for (b).

The subtraction method is the most commonly used technique applied to results from ballistic range tests. The total drag is measured; head, boattail, and skin friction drags are calculated and the sum subtracted from the total drag. From the resultant base drag, assuming pressure on the base is constant, the base pressure is determined. The total drag must be measured accurately; one percent accuracy is possible in modern ballistic ranges. Head drag can be computed accurately, especially for pointed shapes. Friction drag, being a small part of the total, need not be computed as accurately; however, with our present state of knowledge of compressible turbulent skin friction, one can do better than apply the Prandtl-Schlichting formula which was necessary twenty years ago.[21] (See Reference 9 for some comment on this.) At higher Mach numbers the boattail drag may be quite inaccurate if characteristic calculations are used.

An illustration of the relative magnitudes of total drag and head drag is given in Figure 10 where $(C_D - C_{DH})/C_D$ is plotted vs. $M_\infty$, $C_{DH}$ being head drag. Thus the numerator is also the sum of skin friction, boattail, and base drags. The upper set of points is for slender bodies, mainly $10^\circ$ cone-cylinders, the lower set for blunt bodies, mainly $35^\circ$ cone-cylinders, plus two points for a sphere. ($C_{DH}$ for the sphere was determined from interferometric data.) The accuracy of the $p_b$ determination is greater for larger values of the ordinate in Figure 10; for small values finer precision is required in measuring $C_D$ and estimating skin friction to obtain comparable accuracy in $p_b$.

The scatter in the data is not representative of what is possible in a modern ballistic range. The upper set of points comes from measurements made twenty years ago, the lower set from measurements in a pressure controlled range with a rather short base line, approximately 35 feet.

In Reference 21, a determination of base pressure from measurements of the wake angle was made and found to agree with results of the subtraction method. This is, in fact, the basis of Love's semi-empirical method. The flow variables at the base must be known.

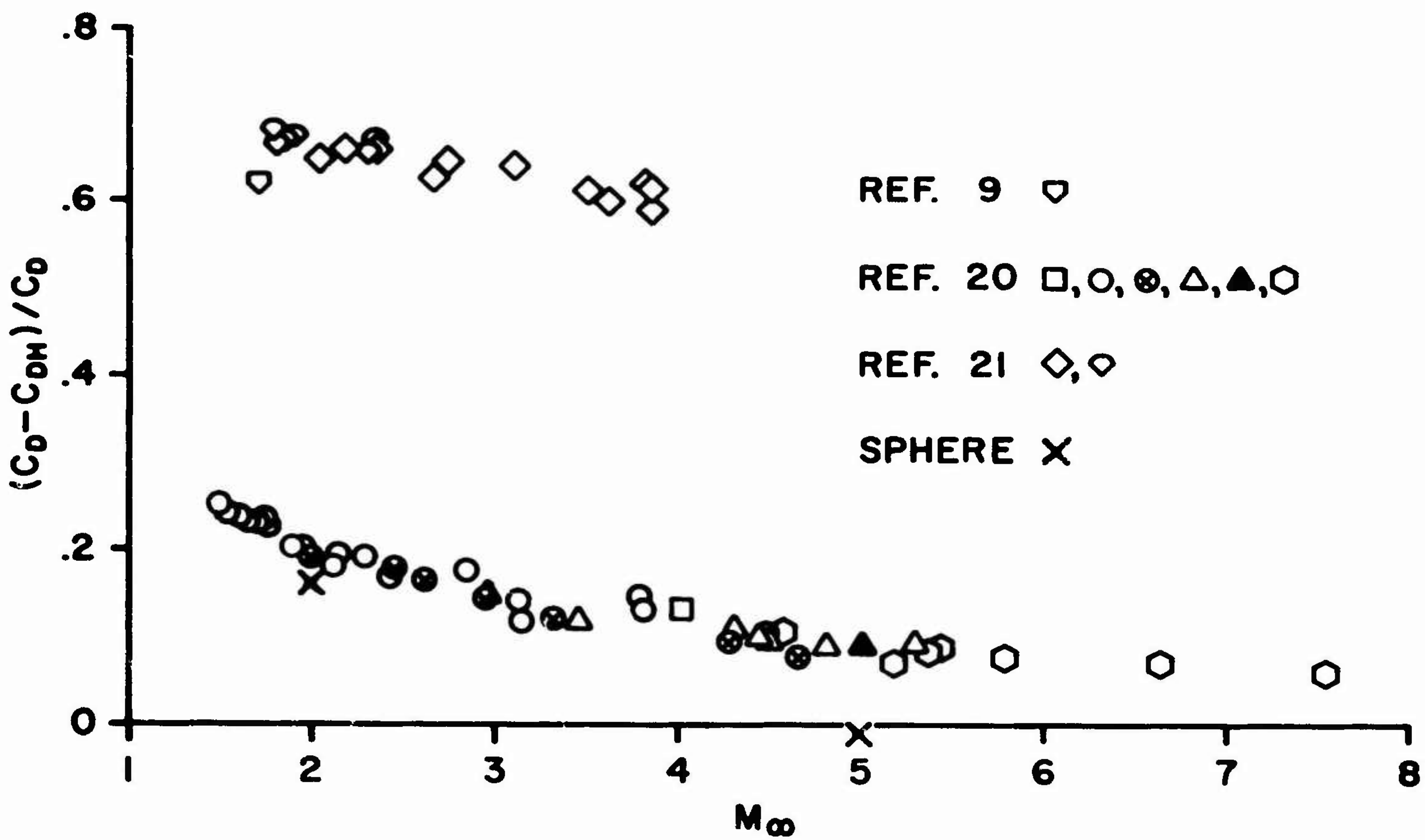


Figure 10. Relative magnitudes of total drag and head drag for slender bodies (upper points) and blunt bodies (lower points).

Recently developed techniques seem very promising for gaining new detailed information about the base flow region. The author knows of some preliminary work, which may be published now*, at the NASA Ames Laboratory on a transducer-telemetry unit to measure base pressure on a free flight model in a wind tunnel. Results from sphere wake measurements have been reported[45] in which the sphere was magnetically supported in a wind tunnel so that there is no question of support interference.

## 6. METHODS FOR REDUCING BASE DRAG

One effective means of increasing base pressure- thereby reducing base drag - is that of "base bleed". The author knows of no systematic attempt to study this for ballistic applications. One limited study was made at BRL and the results were reported by Dickinson.[46] In this study, the idea was to bleed air from the boattail to the base; the tests were made on an existing shell with a cavity at the base. No detectable change in drag resulted.

Another possibility for bleeding into the base region is to use a combustible material at the base. Whether or not this has been studied is not known to the author. However, this type of base bleed is accomplished with a tracer in the base of a shell.

In one study by MacAllister[47] of a 90mm shell with and without tracer, the following results were obtained. At supersonic speeds the drag was 14 percent lower and at subsonic speeds the drag was 6 percent lower with the tracer than without. Somewhat analogous to the boattail case, some adverse effect on stability was measured. In a private communication from C. Briercliffe it was indicated that some results at CARDE also have shown that the presence of a tracer material reduces measured drag.

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## 7. CONCLUSIONS

The essential conclusions of this review are:

a. much work has been done on the axisymmetric base drag/ pressure problem

b. the physical processes which determine the base pressure are fairly well understood except for the convergence (reattachment) zone

c. no satisfactory analytical theory exists

d. there is need for additional work.

Unfortunately much of the previous work is not always useful; with our present understanding of the problem the parameters which need to be measured and controlled are known.

One important effect which was not given attention was that of transition. Though turbulent boundary layers are the rule in ballistics, one should be cognizant of the possibility of transition in or near the base region.

This review was completed before Proceedings of the AGARD Specialist Meeting on "Separated Flows" became available. These papers will no doubt shed light on the base pressure problem but it is noted that very few were devoted to the axisymmetric case, which is certainly a fruitful area of research.

RAYMOND SEDNEY

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13. ABSTRACT

A review of the present state of knowledge of axisymmetric base drag is given. With application to ballistics in mind, this review is especially concerned with supersonic flight and turbulent boundary layers. Correlations of base pressure are discussed as well as some analytical methods for attacking the problem; no satisfactory analytic theory exists. Experimental methods for determining base pressure in wind tunnels and ballistic ranges are discussed. The effect of a boattail on total drag and base pressure is discussed and one other method for reducing base drag is considered briefly.

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