

THE WAVE DRAG COEFFICIENT OF SPHERICALLY BLUNTED SECANT OGIVE FOREBODIES OF FINENESS RATIO 1.0, 1.5 AND 2.0 AT ZERO INCIDENCE IN TRANSONIC FLOW

SUMMARY

This Data Item presents charts of forebody volume coefficient and wave drag coefficient for spherically blunted secant ogive forebodies (including the blunted cone) of fineness ratio, 1.0, 1.5 and 2.0, in the Mach number range 0.70 to 1.05.

The wave drag charts were derived by use of a computer program developed at the Aircraft Research Association and based on a modified version of the South-Jameson finite-difference method which calculates the inviscid transonic potential flow around non-ducted axisymmetric bodies. It is assumed that, for axisymmetric forebodies, viscous effects are small and it is permissible to equate wave drag to pressure drag and to derive the latter from integration of the surface pressure.

Examples are provided which compare forebody pressure distribution and wave drag coefficient calculated by the computer program with wind-tunnel data, whilst other evaluations which compare calculated results with experimental data are referenced.

NOTE

In the case of blunted cone forebodies (which are included in the family of secant ogive forebodies and are considered in this Data Item) results for fineness ratio 2.0 are also available in T.D. Memo. 89033¹². These later results have been derived from finite difference solutions to the Euler equations. As explained in T.D. Memo. 89033, solutions to the Euler equations in principle represent improvements over the corresponding solutions obtained from potential flow methods for flows where shock waves occur. It is therefore recommended that, where available, results based on solutions to the Euler equations should be used in preference to results, such as those in this Data Item, which are based on potential flow methods.

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1. INTRODUCTION

This Data Item presents charts of forebody volume coefficient and wave drag coefficient for spherically blunted secant ogive forebodies of fineness ratio 1.0, 1.5 and 2.0 over a Mach number range from 0.70 to 1.05. Charts of axial distribution of forebody pressure coefficient for the same family of forebody shapes are presented in T.D. Memo. 83018¹. This present Item supplements T.D. Memo. 79004² by extending to a wider range of forebody shapes the data available on the exchange rates between volume coefficient and wave drag for axisymmetric bodies. The importance, applications and limitations of such data are discussed in the Introduction to T.D. Memo. 79004.

In T.D. Memo. 79004 the families considered were the spherically blunted tangent ogive, spherically blunted paraboloid and modified ellipsoid. The tangent ogive is a member of the family of secant ogives; another member of the family that is frequently encountered is the blunted cone, which is one of three forebody shapes considered here. The other two forebodies considered are both blunted secant ogives intermediate in curvature of the ogival portion between the tangent ogive and the cone. An important distinction between the tangent ogive and the bodies considered here is the existence in the latter of a discontinuity in slope at the forebody/afterbody junction (shoulder), this discontinuity being greatest for the conical forebodies.

The wave drag charts were derived by use of a computer program³ developed at the Aircraft Research Association and based on a modified version of the South-Jameson finite-difference method⁴ which calculates the inviscid transonic potential flow around non-ducted axisymmetric bodies[†]. The modifications were introduced to enable the method to cope with bodies possessing discontinuities in slope or curvature. In deriving the charts it was assumed that viscous effects were small and it was permissible to equate wave drag to pressure drag and to derive the latter from integration of the surface pressure. In Section 6 examples are provided which compare forebody pressure distribution and wave drag coefficient calculated by the computer program with experimental wind-tunnel data, whilst other evaluations which compare calculated results with experimental data are referenced.

In the calculations the forebodies were followed by a cylindrical afterbody stretching downstream to infinity. It should be noted that in the ARA computer program no account is taken of the increase in entropy that occurs through a shock. Thus for real configurations such as missiles or aircraft fuselages, which are of finite length and usually close in a boat-tail, the change in entropy that occurs due to a shock may have an adverse effect on the flow conditions downstream of the shock resulting in higher values of pressure drag coefficient for the boat-tail. It is difficult to estimate the magnitude of this effect and thus, in using this Item, a degree of caution should be exercised.

The data in the charts may be applied to bodies with the given forebody shape followed by a cylindrical midbody and (usually) afterbody where the midbody is sufficiently long for there to be no interference effects between the forebody and afterbody. Where there are interference effects the wave drag of the complete body must be evaluated as an entity and Reference 3 can be used for this purpose. However, when doing so, the comment regarding the absence in Reference 3 of any account of entropy changes must be borne in mind.

[†] See the NOTE following the SUMMARY concerning the use of potential flow solutions for flows where shock waves occur.

2. NOTATION

In using this Item a consistent unit of linear dimension must be used. Symbols in square brackets are those used in the computer program listed in Appendix A.

$b[B]$	nose blunting ratio ($= d/D$)
C_D	drag coefficient (based on cylindrical afterbody cross-sectional area)
C_{Dw}	wave drag coefficient (based on cylindrical afterbody cross-sectional area)
C_p	pressure coefficient
C_V	forebody volume coefficient, ratio of forebody volume to volume of enclosing cylinder (see Sketch 3.2)
d	diameter of spherical nose blunting ($= 2r$)
$D[D]$	diameter of cylindrical afterbody ($= 2R$)
$D'[XD]$	diameter of cylindrical afterbody of blunted tangent ogive forebody of length L' (see Sketch 3.1)
$f[F]$	forebody fineness ratio ($= L/D$) (see Sketch 3.1)
$L[L]$	forebody length
$L'[XL]$	length of a blunted tangent ogive forebody having the same value of ogive radius, R_0 , as the equivalent blunted secant ogive forebody of length L (see Sketch 3.1)
L_0	virtual length of an unblunted ogive forebody having the same value of ogive radius, R_0 , as a blunted ogive forebody of Length L (see Sketch 3.1)
M_0	freestream Mach number
$r[R]$	radius of spherical nose blunting
$R[AR]$	radius of cylindrical afterbody
$R_0[RO]$	secant ogive radius (see Sketch 3.1)
$R'_0[CURT]$	radius of a blunted tangent ogive having the same value of fineness ratio, f , as the equivalent blunted secant ogive of ogive radius R_0 (see Sketch 3.1)
$\bar{R}[R\bar{B}AR]$	curvature ratio ($= R'_0/R_0$)
$x[X]$	axial distance (see, for example, Sketch 3.1)
$y[Y]$	radial distance (see, for example, Sketch 3.1)

Subscripts

j	denotes match point between spherical blunting and ogive part of secant ogive forebody (see Sketch 3.1)
t	denotes match point between spherical blunting and ogive part of tangent ogive forebody (see Sketch 3.1)

3. GEOMETRIC CHARACTERISTICS OF THE BLUNTED SECANT OGIVE FOREBODY

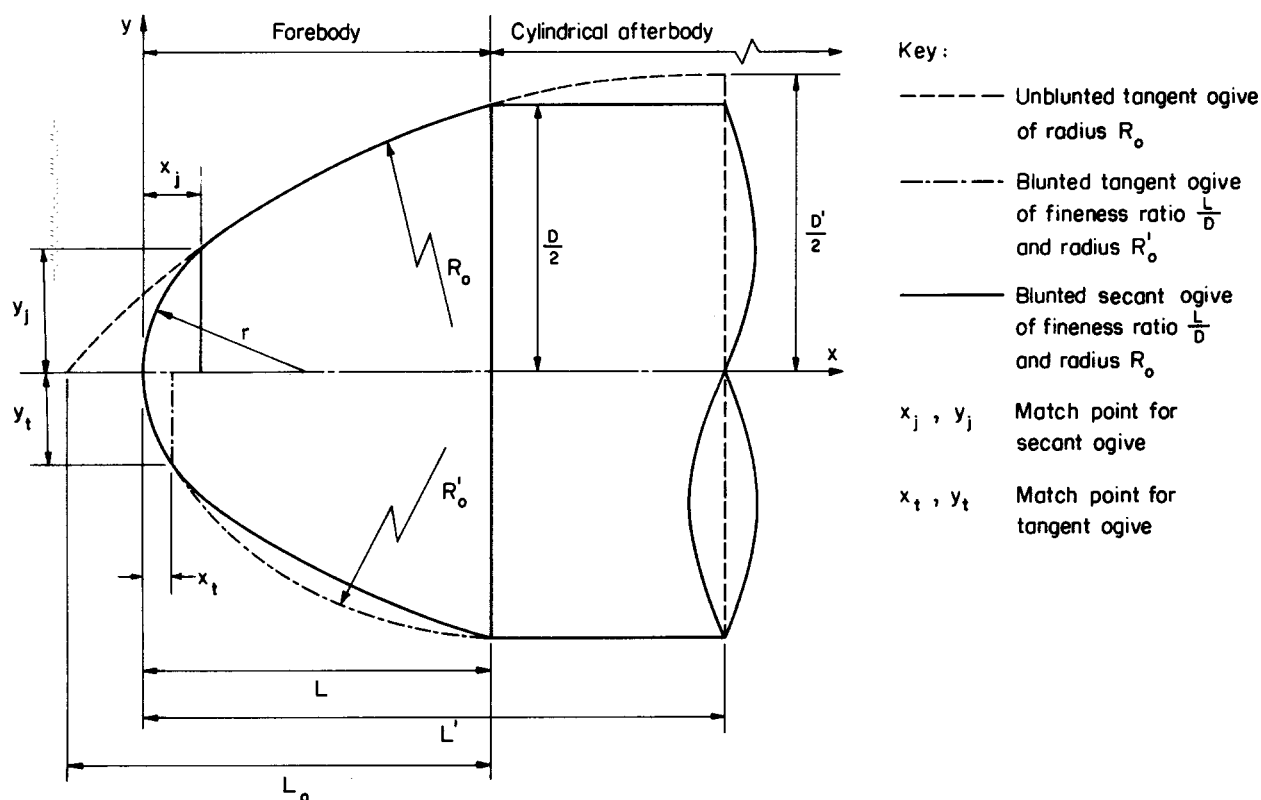
Sketch 3.1 shows the notation used here to describe the spherically blunted secant ogive geometry.

For a given afterbody diameter, D , an unblunted secant ogive is defined by its radius, R_0 , and the distance, $(L' - L)$, of its centre of arc aft of the base of the ogive, fineness ratio then being implicit. For an unblunted tangent ogive L' equals L and (for given D) the radius R_0 completely defines it.

At a given fineness ratio (L/D) a convenient parameter to describe a family of secant ogives is the ratio $\bar{R} = R'_0/R_0$ (here designated the curvature ratio), where R_0 is the radius of curvature of the secant ogive of given fineness ratio and R'_0 is the radius of curvature of the tangent ogive of the same fineness ratio. Thus the two limiting secant ogive forebodies are the tangent ogive and the inscribed cone for which $\bar{R}$ equals 1.0 and 0.0 respectively.

For the secant ogive forebodies considered in this Item the spherical nose blunting is such that there is no discontinuity in slope at the match point between the nose blunting and ogival portions of the forebody, but curvature is discontinuous at this point. The limiting values of nose blunting ratio are zero (corresponding to a pointed forebody) and unity (corresponding to a hemispherical-headed forebody).

Figure 1 illustrates the effect on geometry of varying curvature ratio for nose blunting ratios of 0.0, 0.5 and 1.0 at a fineness ratio of 2.0. The effects on geometry of varying spherical nose blunting ratio through 1.0 (hemisphere), 0.8, 0.5, 0.3 and 0.0 (pointed forebody), for the range of fineness and curvature ratios considered here, are shown in Figures 3, 7 and 11, each of which is immediately followed by the relevant wave drag charts. These figures also show the match points between the spherical nose blunting and the ogival portions of the forebodies.



Sketch 3.1 Forebody geometry notation for spherically blunted secant ogives

3.1 Forebody Surface Coordinate Generating Equations

The equation of the generator defining the spherical nose blunting is

$$y = [x(bD - x)]^{0.5}, \quad (3.1)$$

where $bD = 2r$.

The equation of the generator defining the ogive portion is

$$y = (D'/2) - R_0 + [R_0^2 - (x - L')^2]^{0.5}, \quad (3.2)$$

where

$$R_0 = \frac{L'^2 - bDL' + (D'^2/4)}{D' - bD}. \quad (3.3)$$

The coordinates of the match point between the spherical nose blunting and the ogive part of the forebody, (x_j, y_j) , are given by

$$x_j = bD \left[\frac{R_0 - L'}{2R_0 - bD} \right] \quad (3.4)$$

and

$$y_j = \frac{bD}{2} \left[\frac{2R_0 - D'}{2R_0 - bD} \right]. \quad (3.5)$$

Equations (3.1) to (3.5) may be derived from the equivalent equations for the blunted tangent ogive (Equations (4.1) to (4.5) of T.D. Memo. 79004), by putting (in that Document) f equal to L'/D' , putting D equal to D' and scaling b by D/D' .

The dashed symbols may then be derived in terms of the undashed symbols by imposing the conditions on Equation (3.2) of this Memorandum that at $x = L$, $y = D/2$, and at $x = L'$, $dy/dx = 0$. This leads to:

$$L'^2 = bDL' - bDR_0 + R_0^2 - [(R_0^2 - (L - L')^2)^{0.5} - D/2]^2 \quad (3.6)$$

and

$$D' = D + 2R_0 - 2[R_0^2 - (L - L')^2]^{0.5}. \quad (3.7)$$

Equation (3.6) can conveniently be solved by iteration.

For the special case of the blunted cone the equation of the generator defining the "ogive" portion is

$$y = \left[\frac{(D/2) - y_j}{L - x_j} \right] (x - x_j) + y_j. \quad (3.8)$$

The coordinates of the match point between the spherical nose blunting and the ogive part of the forebody, (x_j, y_j) , are given by

$$x_j = \frac{bD}{2} \left[1 - \frac{(DA) - (2L - bD)bD}{D^2 + (2L - bD)^2} \right] \quad (3.9)$$

and

$$y_j = \frac{bD}{2} \left[\frac{bD^2 + (2L - bD)A}{D^2 + (2L - bD)^2} \right], \quad (3.10)$$

where

$$A = (D^2 + 4L^2 - 4bDL)^{0.5}. \quad (3.11)$$

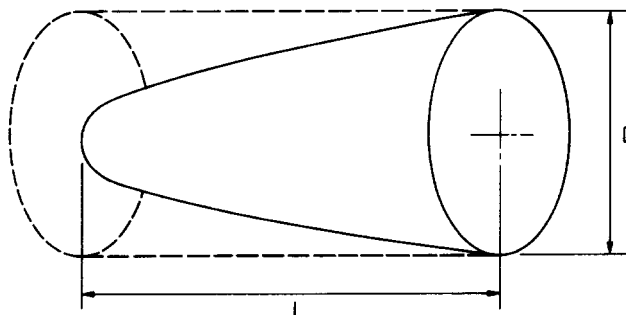
Appendix A presents the listing of a computer program written in FORTRAN which generates the surface coordinates of the blunted secant ogive family of forebodies from a knowledge of f , $\bar{R}$ and b . These coordinates may be used to construct the forebody graphically or as part of the input to the ARA solid body computer program. Also generated are the values of the parameters L' , D' , R_0 , x_j and y_j . Values of these parameters for most of the forebodies considered in this Item are given, non-dimensionalised by R , in Appendix B. Thus by substitution of L' , D' and R_0 into Equation (3.2) and use of appropriate values of b and D in Equation (3.1), the surface coordinates for the forebodies in Appendix B may be generated directly.

3.2 Volume Coefficient

The forebody volume coefficient, C_V , is defined as the ratio of the volume of the forebody to the volume of the enclosing cylinder (see Sketch 3.2).

The variation of volume coefficient with spherical nose blunting ratio and forebody fineness ratio is presented in Figure 2 for spherically blunted secant ogive forebodies of curvature ratio 0.7, 0.4 and 0.0 (*i.e.* the blunted cone).

It can be seen from Figure 2 that, for fixed fineness ratio, volume coefficient increases as both curvature ratio and nose blunting ratio increase.



Sketch 3.2 Typical forebody shape in enclosing cylinder for the calculation of forebody volume coefficient

4. CHARTS OF WAVE DRAG COEFFICIENT

4.1 Presentation of the Charts

Figures 4–6 present wave drag coefficient as a function of spherical nose blunting ratio and freestream Mach number for blunted secant ogive forebodies of curvature ratio, $\bar{R} = 0.7, 0.4$ and 0.0 , in the freestream Mach number range $M_0 = 0.70$ to 1.05 , at a fineness ratio of 1.0 . Figures 8–10 present wave drag coefficient for the same range of $\bar{R}$ and M_0 at a fineness ratio of 1.5 , and Figures 12–14 at a fineness ratio of 2.0 .

Two further figures are presented to demonstrate particular features of the wave drag charts. Figures 15 show the variation of wave drag coefficient with curvature ratio at a Mach number of 1.00 for forebodies of fineness ratio $1.0, 1.5$ and 2.0 . Figures 16 show the variation of wave drag coefficient with fineness ratio at a Mach number of 1.00 for forebodies of curvature ratio 0.0 (*i.e.* the blunted cone), 0.4 and 0.7 .

In deriving the charts, calculations were performed for spherical nose blunting ratios of $0.0, 0.3, 0.5, 0.6, 0.7, 0.8, 0.9$ and 1.0 , but not for $0.1, 0.2$, or 0.4 . For these latter three geometries results have been obtained by interpolation, and thus have been shown by broken lines in the wave drag charts.

At a Mach number of 1.05 , which is near the limit of the validity of the method, in some instances improbable results were obtained. In these cases the results which are presented have been estimated by interpolation from other nose blunting ratios and by extrapolation from lower Mach numbers, and are shown by a chain dotted line in the appropriate figures.

4.2 Variation of Wave Drag Coefficient with Freestream Mach Number

The increase in wave drag coefficient associated with increasing freestream Mach number is shown by the wave drag carpet plots in Figures 4–6, 8–10, and 12–14.

At a Mach number of 0.70 there is generally only a negligible amount of wave drag, except for forebodies of fineness ratio 1.0 at low nose blunting and curvature ratios (see, for example, Figure 6).

The shape of the curve of wave drag coefficient with increasing freestream Mach number falls roughly into three categories. In the limiting case of the hemisphere ($d/D = 1.0$ in all the curves) the wave drag coefficient increases very rapidly once $M_0 = 0.70$ has been exceeded.

The other two categories are most readily appreciated by reference to Figure 12. At low values of d/D no wave drag is evident until M_0 exceeds 0.85 but by $M_0 = 0.95$ C_{Dw} is growing quite rapidly. At $d/D = 0.7$, however, wave drag is evident at $M_0 = 0.75$ but grows only slowly (drag creep) until M_0 has exceeded 0.95 .

T.D. Memo. 80008⁵ observes that a relatively slow drag creep occurs where a shock wave forms ahead of the shoulder and that the rapid drag rise only occurs when the shock wave reaches, or first forms at, the shoulder. Further discussion of the origin of this drag creep will be found in Reference 6.

4.3 Variation of Wave Drag Coefficient with Nose Blunting Ratio

One significant feature of the wave drag charts is that some degree of nose blunting can delay the rapid drag-rise to a higher Mach number and reduce forebody wave drag coefficient throughout the curvature ratio and fineness ratio range considered. This feature has already been observed for the tangent ogive in both theoretical² and experimental work^{7–10}. For a given fineness ratio it is possible to determine a nose blunting ratio that is near-optimum for the transonic regime, as the optimum is only weakly dependent on

Mach number and curvature ratio. This optimum blunting tends to be near 0.8 for forebodies of fineness ratio 1.0, near 0.7 for those of fineness ratio 1.5, and near 0.6 for those of fineness ratio 2.0 as illustrated for $M_0 = 1.00$ in Figures 15.

The wave drag minimum associated with optimum blunting is more pronounced at the lower curvature and fineness ratios (see Figures 15c and 16c). It is clear that there is some disadvantage in choosing the unblunted cone as opposed to unblunted forebodies of higher curvature ratio, in terms both of wave drag and also of volume coefficient. For instance, the pointed cone of fineness ratio 1.0 yields roughly the same amount of wave drag as the hemisphere cylinder (Figure 6) but clearly has less volume. However, the disadvantages of the cone are somewhat ameliorated at high bluntings where there is a well defined wave drag minimum.

T.D. Memo. 80008 explains the mechanism whereby a moderate amount of nose blunting can reduce wave drag on a tangent ogive, and this explanation is also valid for secant ogives of lower curvature ratio. For forebodies in subsonic, supersonic flow a shock will exist for low blunting ratios near the forebody shoulder, and for high blunting ratios near the forebody match point. For forebodies of moderate blunting ratio there may be a shock in one or other, or both, of these locations but any shock is relatively weak and thus makes a smaller contribution to wave drag coefficient. An example of this for the blunted cone of fineness ratio 2.0 at a freestream Mach number of 0.90 is provided in Figure 25 of T.D. Memo. 83018.

4.4 Variation of Wave Drag Coefficient with Curvature Ratio

For all Mach numbers in the transonic regime, the minimum wave drag occurs at an intermediate value of curvature ratio (between 0.7 and 1.0 for forebodies of fineness ratio 2.0, decreasing slightly as fineness ratio decreases). This is apparent from Figures 15 which show the variation of wave drag coefficient with blunting ratio for all four curvature ratios and all three fineness ratios at a freestream Mach number of 1.00.

For the unblunted cases the wave drag values for the tangent ogive and secant ogive of curvature ratio 0.7 virtually coincide. At low blunting ratios a hump develops in the curve for the tangent ogive while the other three curves show a decrease in wave drag. For a fineness ratio of 2.0 all the curves reach a minimum at a nose blunting ratio between 0.6 and 0.7, there being little difference between the tangent ogive and the secant ogive of curvature ratio 0.7. For a fineness ratio of 1.5 the minimum occurs at a blunting ratio of 0.7, with the least wave drag yielded by the secant ogive of curvature ratio 0.7. For a fineness ratio of 1.0 the minimum occurs at a blunting ratio of 0.8, there being little or no difference between the secant ogives of curvature ratio 0.7 and 0.4; the tangent ogive has a somewhat higher value of wave drag. At yet higher bluntings all the forebodies begin to have very similar and rapidly increasing wave drag coefficients as their shapes become more similar until, in the limiting case of the hemisphere, all the results coincide.

Thus the greatest difference between results for different curvature ratios occurs at low bluntings. The difference between blunted secant ogives of different curvature ratios is generally accentuated both by increasing Mach number and decreasing fineness ratio. This means in particular that the difference between the tangent ogive results and those for the optimum curvature ratio secant ogive is usually more marked at lower fineness ratios and higher Mach numbers.

The variation of curvature ratio produces subtle geometric changes in the forebody which are reflected in the small effect that all but the most extreme changes of curvature ratio have on wave drag coefficient. Decreasing curvature ratio, with fineness ratio and nose blunting ratio kept constant, moves the match point rearwards, decreases the curvature of the ogival portion of the forebody, increases the curvature discontinuity at the match point and increases the slope discontinuity at the forebody shoulder. These geometric changes affect not only the pressure coefficient distribution around the forebody but also the manner in which the cross-sectional area distribution varies in the streamwise direction. Since wave drag coefficient is derived from the integral of the product of pressure coefficient and cross-sectional area² there can be no simple generalization of the manner in which wave drag varies with curvature ratio. However, it

is clear that the increase, with decreasing curvature ratio, in the axial distance from the nose of the match point, and the curvature discontinuity there, is an important feature because it leads to an increase in shock strength near the match point (see, for example, Figures 27 and 28 in T.D. Memo. 83018). At low curvature ratios the strength of this shock can be quite substantial and this may contribute significantly to the high wave drag coefficient associated with, for instance, the blunted cone.

4.5 Variation of Wave Drag Coefficient with Fineness Ratio

Figures 16 illustrate the effects of varying fineness ratio. For all but high nose blunting ratios, a reduction in fineness ratio causes a large increase in wave drag coefficient. However, at high bluntings (about 0.85 and above) the higher fineness ratio forebodies actually generate more wave drag than the lower fineness ratio forebodies. This feature has previously been noted by Partington and Baker⁶ and is attributable to the fact that forebodies of lower fineness ratio have a wave drag minimum for the transonic regime at higher values of nose blunting ratio. This, in turn, is associated with the drag creep that occurs at high nose blunting ratios and delays the onset of the rapid drag-rise. Since drag creep is most prominent at the lower fineness ratios it follows that the lower fineness ratios yield the lower wave drag at high nose bluntings.

5. DERIVATION OF THE CHARTS

The charts were derived by use of a computer program³ developed by Baker at the Aircraft Research Association and based on a modified version of the South-Jameson finite-difference method⁴ which calculates the inviscid transonic potential flow around axisymmetric bodies at zero incidence. This program is described more fully in Section 6 of T.D. Memo. 79004.

In general, spherically blunted secant ogive forebodies have a discontinuity of surface slope at the shoulder. For such cases, convergence of the solution proved more difficult to obtain at the higher freestream Mach numbers than it was for the forebodies considered in T.D. Memo. 79004, which did not have slope discontinuities. It was necessary to reduce the relaxation factor and use a stabilizing factor as recommended in Reference 3. Even then, the difficult cases required in excess of one thousand iterations on the fine grid (61×20 points) to obtain satisfactory convergence.

At freestream Mach numbers of 1.00 and 1.05, where the largest number of iterations was required, a convergence criterion different from that recommended³ was used. Convergence of the solution was considered satisfactory if a difference of less than 0.0004 in computed pressure drag coefficient between the last two sets of 100 iterations on a computer run was obtained. This level of convergence was attained for all the results presented in this Document for Mach numbers of 1.00 or 1.05, except for some of the results represented in the charts by a chain dotted line and referred to in Section 4.1.

In the charts, computed wave drag coefficient, C_{Dw} , has been adjusted such that $C_{Dw} = 0.0$ at a low subsonic Mach number, typically $M_0 = 0.40$ or 0.60 , so as to eliminate the residual errors that occur in the numerical integration of the calculated pressure coefficients. Usually these residual errors are small, typically being within ± 0.0100 , but in particular cases with large discontinuities of slope at the shoulder larger errors have occurred, in one case an error of 0.0500 being recorded.

6. EXPERIMENTAL VERIFICATION OF THE METHOD

It was demonstrated in T.D. Memo. 79004 and by Baker himself^{3, 11} that computed pressure distributions for forebodies without surface slope discontinuities compare favourably with experimental data¹¹ from wind-tunnel tests. For forebodies with surface slope discontinuities, a comparison between theory and experiment is provided by Figure 17 which compares the calculated pressure distribution with experimental results obtained by Ward⁹ for a conical forebody of fineness ratio, $f = 2.0$, with a nose blunting ratio, $d/D = 0.3$, at a freestream Mach number, $M_0 = 0.970$.

Computed wave drag coefficients for typical forebody shapes have been compared with experimental results in Reference 7 whilst Figure 15 of T.D. Memo. 79004 compares the measured and calculated values of wave drag coefficient for a tangent ogive forebody of fineness ratio, $f = 2.0$, with a nose blunting ratio, $d/D = 0.6$, in the Mach number range, $M_0 = 0.40$ to 1.05 . Figure 18 of this Memorandum presents wave drag results for a conical forebody of fineness ratio, $f = 2.0$, with a nose blunting ratio, $d/D = 0.3$, in the same Mach number range. For both comparisons the experimental and computed results have been adjusted to agree at a Mach number of 0.70 . Within the Mach number range considered wave drag coefficient, and, in particular, drag-rise Mach number are well predicted by the theoretical calculations.

As far as it is known, no experimental measurements of pressure distribution or forebody wave drag coefficient have been made for spherically blunted secant ogive forebodies with curvature ratios intermediate between those for the cone and the tangent ogive.