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THE EFFECT OF NOSE SHAPE ON THE DRAG OF BODIES OF REVOLUTION AT ZERO ANGLE OF ATTACK[1]

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The subject of this paper is the drag of the nose section of bodies of revolution at zero angle of attack. The magnitude of the nose drag in relation to the total drag is very distinctly a function of the body design and the Mach number. It can range from a very small fraction of the total drag of the order of 10 percent to a very large fraction as high as 80 percent. The natural objective of nose design is to minimize the drag, but this objective is not always the primary one. Sometimes other factors overshadow the desire for minimum drag. The most conspicuous example of this is the proposal of guidance engineers that large-diameter spheres and other very blunt shapes be used at the nose tip. This paper will attempt to discuss both phases of the problem, noses for minimum drag and noses with very blunt tips. The state of the theory will also be reviewed and recent theoretical developments described, since the theory still remains a very valuable tool for assaying the effects of compromises in design and departure from shapes for which experimental data are available.

The three best-known theories for computing pressure distributions and pressure drag for pointed shapes are the Taylor and Maccoll theory for cones and the method of characteristics and linearized theory for other shapes. The first two of these methods are the exact inviscid theories and both have been experimentally verified over a wide range of conditions. Both are limited, however, the first to a single class of bodies and the second by the large amount of painstaking labor required to obtain a single solution. The linearized theory suffers from neither of these limitations but is restricted to slender shapes at low supersonic Mach numbers because of assumptions in its development. Therefore, none of the three best-known methods can be considered a satisfactory design tool for the full range of Mach numbers and fineness ratios now being proposed. Two more recent theories represent an improvement in that, used to supplement each other, they allow more complete coverage of the working range of Mach numbers and fineness ratios than is provided by linearized theory and require far less effort to apply than the method of characteristics. They are the second-order theory of Van Dyke (reference 1) and the shock-expansion theory of Eggers and Savin (reference 2). The second-order theory extends the range of accurate application of the linearized theory essentially up to its fundamental limit, the Mach number at

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which the tip Mach cone is tangent to the nose vertex. Fortunately, the shock-expansion theory is most accurate where second-order theory does not apply. Examples of the application of each of these theories will be shown. Then, a summary chart showing their ranges of application will be presented.

The left-hand part of figure 1 shows an application of second-order theory to a tangent ogive with a nose fineness ratio $(l/d)_n$ of 3.5 at a Mach number M of 3.2. Pressure coefficient is plotted as a function of axial station. The second-order solution is compared with experimental data and a characteristics solution as standards of accuracy and with a linearized solution to show the improvement. The experimental data and the characteristics solution agree almost identically. The second-order solution is about 8 percent high at the tip but coincides with the characteristics solution beyond the 50-percent station. The linearized solution is too low at the tip by 45 percent and crosses the experimental curve at the 50-percent station so that its drag error is reduced by compensation. In the right-hand part of this figure, shock-expansion theory is applied to a slightly thicker ogive at a higher Mach number, 4.5. Again, the experiment and the characteristics solution disagree only a little. The shock-expansion solution follows the characteristics solution perfectly at first and falls below a little at the rear of the nose.

From this figure it is evident that, under some circumstances at least, these two theories are useful tools for design work. It is desirable to define, as specifically as possible, the range of conditions over which each can be applied. Experience shows that the accuracy of approximate theories depends on three things, the Mach number, the fineness ratio, and the shape. Recently it has been found that, for a given shape, the ranges of application of the various theories can be stated reasonably well in terms of a single variable, the hypersonic-similarity parameter, which is the ratio of Mach number to fineness ratio. This parameter, hereinafter designated by the symbol K, identifies those conditions for which flow fields will be similar. Increasing the similarity parameter corresponds to increasing the Mach number at a given fineness ratio, or decreasing the fineness ratio at a given Mach number. In terms of this parameter, the range of application of three theories - linearized, second-order, and shock-expansion - to two shapes, cones and ogives, is presented in figure 2. The drag error of each theory in percent is plotted as a function of K. These curves were obtained by integrating a large number of theoretical pressure distributions of the type shown in the preceding figure to obtain the drag and comparing with exact solutions to determine the error. The results show the second-order theory to be accurate within 2 percent for the drag of ogives out very nearly to the fundamental limit of the theory. The second-order theory is even better for cones than for ogives, having a wider range of application and smaller errors at a given value of K. For ogives, it underestimates the drag by 5 percent or less for values of K above 1.2. In contrast, the linearized theory shows errors of 10 to 47 percent for cones and 4 to 17 percent for ogives and is accurate only at values of K of the order of 0.4 or less.

It should be noted that in the past the second-order theory has been considered difficult to apply. In some cases, this difficulty was due to the fact that source points were taken too close together in performing the solution, since the labor increases as the square of the number of points. At present, rules are being formulated for the maximum allowable spacing of the source points and a computing procedure is being devised which will make it possible for a person with no detailed knowledge of the theory to obtain solutions at the rate of about one a day (reference 3).

All of the above theory is restricted to bodies with pointed noses. For blunt-nosed bodies having detached shock waves at the tip, there is no adequate theory. Blunt bodies are of interest for two reasons: First, they have been proposed as necessary for adequate radar installation. Second, some of the mathematically derived optimum shapes have a small blunt region at the tip. Bodies in both of these categories, extremely blunt for radar and moderately blunt for optimization, have been investigated experimentally. The latter will be discussed first. Two mathematically derived optimum shapes of fineness ratio 3 are shown in figure 3. Both were optimized for a given length and base diameter, one by von Kármán by use of slender-body theory and one by Eggers and collaborators by use of hypersonic theory (reference 4). The bluntness at the tip is difficult to see except under magnification. Foredrag coefficients C_{D_F} of these shapes, based on frontal area, are presented in the figure as a function of Mach number and comparison is made with a cone and ogive of the same length and base diameter. The optimum bodies have about 15 percent less foredrag than the cone and about 35 percent less than the ogive. The incremental differences are of the order of a few hundredths in drag coefficient.

Elementary considerations indicate that drag reduction can be achieved with blunt tips in another way. If, for example, a cone of fineness ratio 3 is opened at the tip and a spherical tip inserted while the fineness ratio is held constant, there will be an increase in drag at the tip, but a decrease over the sides as a result of the decreased inclination of the sides to the stream. The increase at the tip occurs within a small frontal area whereas the decrease on the sides occurs over a large frontal area. The net effect on drag depends on the balancing of these opposite tendencies. This effect can be calculated by using experimental data for the foredrag of hemispheres and assuming that the side pressures will be the same as on a pointed cone of the same slope. The results of such a calculation are shown in figure 4, where increment of wave drag of the blunt shapes over that of the cone is plotted as a function of the ratio of tip radius to maximum radius for Mach numbers 1.5, 3, and 6. A small initial reduction in drag coefficient is indicated at all Mach numbers. The effect on these curves of the assumption that the side pressures remain conical is uncertain in the absence of experimental data. Therefore, the drag coefficients of the family of bodies shown at the left in figure 5 were measured in the Ames supersonic free-flight wind tunnel (reference 5) and two of the experimental curves are shown. The bluntest shape in this family had a tip radius of 0.5 but the curves are extended toward an end point at a tip radius of 1 based on the best available values of the foredrag of a hemisphere. As can be seen by comparing, at a Mach number of 6, the calculated curve with experiment, the measured initial drag reduction is greater in both magnitude and extent than predicted so that favorable effect of the spherical tip on the side pressures is indicated. The comparison at a Mach number of 6 is typical of those obtained. The calculated curve is least quantitative in the region of the optimum bluntness. It is exact at either extreme of bluntness, zero or maximum, by definition. It is quantitatively useful for predicting the variation of drag with bluntness for tip radii greater than 0.5. The drag coefficients at the minimum points of these curves were lower than those of the cone by 0.01 to 0.02. The indicated optimum tip radius ranged from 0.2R at a Mach number of 1.5 to 0.1R at a Mach number of 6.

A second way of forming a family of blunt noses is to shorten progressively the parent shape, the pointed tip being replaced with a series of spherical tips of increasing diameter. Such a family was tested in free flight by the Langley Pilotless Aircraft Research Division (reference 6) and is shown in figure 5. In this case, no drag reduction due to opening the sides occurs since the sides are not disturbed. Nevertheless, the measurements show an initial decrease in drag coefficient. In this case, the skin friction changes in a manner favoring the blunter shapes, but this effect is too small to account for the drag improvement. Again, the indication is that reduction of the side pressures occurs in the presence of the spherical tip. The fact that this curve shows smaller drag penalties than the other two is a Mach number effect. At Mach numbers where the two sets of data overlap, the penalties are smaller for the first family than for the second as would be expected. Furthermore, there is some reason to suspect that, in the case of blunting by shortening, the drag minimum which exists at a Mach number of 1.2 would not occur at higher Mach numbers although the penalties would still be smaller than might be expected. It definitely appears, however, that for fixed values of the fineness ratio, the optimum shape at all supersonic Mach numbers will have a slightly blunt tip. Aside from the reduced drag, other advantages are associated with the blunt tip. The nose volume is greater for a given length and base diameter. A blunt nose has higher heat capacity at the tip than a pointed shape and is not so apt to burn off as a result of aerodynamic heating. A blunt nose is more rugged and less dangerous for handling in the field.

The abscissa scale of figure 5 extends out to a fully blunt hemispherical tip. The data in the right half of the figure apply, therefore, to noses suitable for radar. The incremental drag penalties at high bluntness are very severe, in the order of several tenths in drag coefficient, and the severity increases with Mach number. The maximum bluntness which can be used with zero penalty ranges from about 0.4 at a Mach number of 1.2 to about 0.2 at a Mach number of 6. Some of the noses represented in figure 5 are compared in figure 6 with some additional highly blunt shapes. Here, Mach number is the abscissa and the increment in total drag coefficient over that of the pointed parent shape is again the ordinate. Bodies carried over from the previous slide include the blunted conical shapes with tip radii of 0.3 to 0.5, and the blunted parabolic shapes with tip radii of 0.5, 0.7, and 0.8. Additional shapes include a parabola of revolution, an ellipsoid, and a shape defined by $\frac{y}{R} = \left(\frac{x}{l}\right)^{1/4}$. The additional data are from the Ames 10- by 14-inch and 1- by 3-foot supersonic wind tunnels. The Mach number effect is surprisingly consistent for data collected from so many sources for so many shapes. At Mach numbers below 2, the penalties diminish rapidly until at a Mach number of 1.2 a 50-percent blunt nose is acceptable. This reduction of penalty is due jointly to a rapid reduction in hemispherical wave drag below Mach number 2 and a simultaneous increase in the drag of the pointed shapes to which the penalties are referred.

In view of the severe drag penalties associated with large spherical tips and the apparent desirability of the spherical tip for guidance purposes, attention has recently been given to shielding the sphere aerodynamically. Three designs which have been proposed for use with infrared seekers are shown in figure 7 (reference 7). One is a conical-tipped spike projecting in front of the sphere along the body axis. The second is a slotted cone for which the slots comprise 50 percent of the frontal area. The third is a quartz cone, made with 12 flat-sided triangular elements in order to reduce distortion of the incoming radiation. In the figure, the drag coefficients of these noses are compared with those of the blunt shape desired for guidance and the pointed shape from which the others were derived at Mach numbers between 1.0 and 1.8. The three shielded noses have about the same drag and show substantial improvement over the unshielded sphere. The improvement increases with increasing Mach number. The choice between these three designs would be based on considerations of guidance, structure, and simplicity. The drag-reducing effectiveness of the spike at angle of attack has not been investigated. The effects of spike length and diameter at Mach numbers near 2 have been investigated by Moeckel (reference 8) at the Lewis Laboratory.

So far, the effect of fineness ratio on drag has not been discussed. For severely blunt shapes, with tip radii equal to or greater than 0.5, the effect of fineness ratio is small since the drag of the spherical tip dominates the nose drag. However, for basically slender shapes, the fineness ratio is an important variable as is shown in figure 8. In this figure, the increment in foredrag, pressure plus friction, over that of the same shape at fineness ratio 4 is plotted as a function of the fineness ratio. These results were obtained from theory for cones and ogives (reference 9). A single curve can be faired reasonably well through data for both shapes at three Mach numbers: 2, 5, and 8. Two boundary-layer conditions are postulated, laminar flow at a Reynolds number of 5×10^6 representing a condition of low skin friction, and turbulent flow at a Reynolds number of 30×10^6 representing a typical high-friction condition. The two curves are nearly identical except that the high-friction curve shows a definite tendency to turn up at the extremes of fineness ratio plotted, whereas the low-friction curve continues down. These curves show relatively large drag changes with small changes in fineness ratio up to a fineness ratio of about 6. Beyond a fineness ratio of 6, the drag changes are smaller and other considerations might outweigh the drag improvement.

The final subject to be considered in this paper is the effect of body surface condition on the drag. This subject is one of great interest in connection with the mass production of missiles where perfect surfaces cannot be expected. Some data of this type are now available (reference 10) from flight tests of the RM-10 research vehicle at Mach numbers up to 2. The Reynolds numbers of the investigation were of the order of 50 million so that the boundary layers were predominantly turbulent. Several models with highly polished surfaces were tested to establish the drag coefficient for the smooth condition. The effect of roughness protruding from the surface was investigated with a body thickly coated with 0.01-inch-diameter sand particles. This dimension can be compared with the maximum body radius which was 3 inches. A second model was made to simulate a partly ground aluminum casting. Its surface was about 70 percent smooth, the remainder being pitted below the level at which grinding was stopped. Although the pits were only about 0.002 inch deep, the model looked and felt rough. The effect of longitudinal waves, such as might occur in the manufacture of metal bodies by the spinning technique, was investigated with a third model having waves about 0.02 inch deep and about 0.5 inch long extending over the entire length. The results of these tests are shown in figure 9. It will be noted that neither the wavy surface nor the pitted surface of the simulated casting caused any measurable increase in drag. The sand-coated surface, however, increased the drag substantially. It was established that this drag change was not a change in base drag. It appears from these exploratory tests that, at very high Reynolds numbers at which the boundary layers are naturally turbulent, some degree of surface roughness due to pitting or waviness can be tolerated but that roughness projecting from the surface can cause substantial drag increases.

In summary, it appears that the nose of minimum drag for a given fineness ratio will have a slightly blunt tip at all supersonic Mach numbers. For noses with spherical tips, the optimum tip radius varies from 0.1 to 0.2 of the maximum radius depending on the Mach number. Tip radii twice the optimum can be tolerated without increasing the drag over that of the pointed parent shape. Beyond this bluntness, severe drag penalties occur which increase with increasing Mach number. Only semiempirical methods exist for calculating the drag of these shapes. The theory for pointed shapes seems adequate, since reasonably accurate estimates of pressures and pressure drag can now be obtained for most of the Mach numbers and fineness ratios of current interest.

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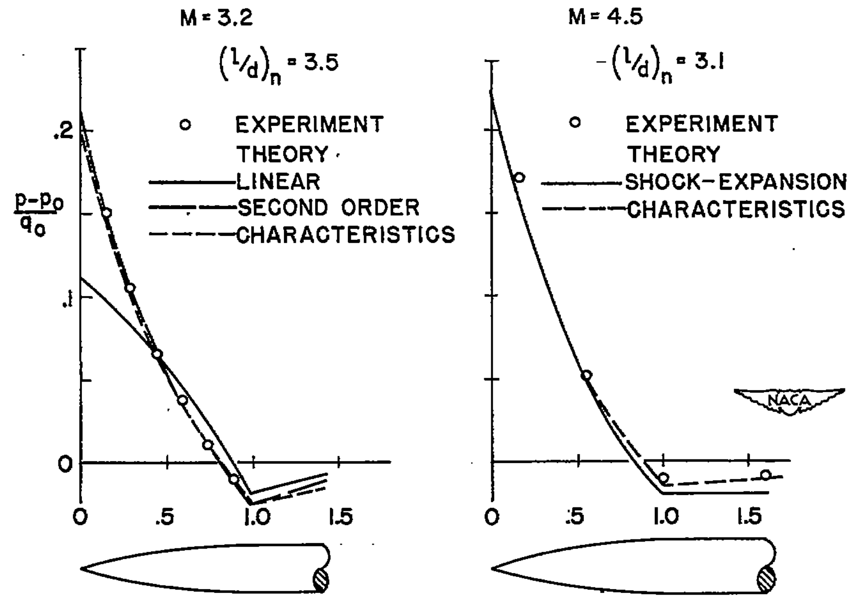

Figure 1.- Comparison of approximate theories with characteristics solutions and experimental data.

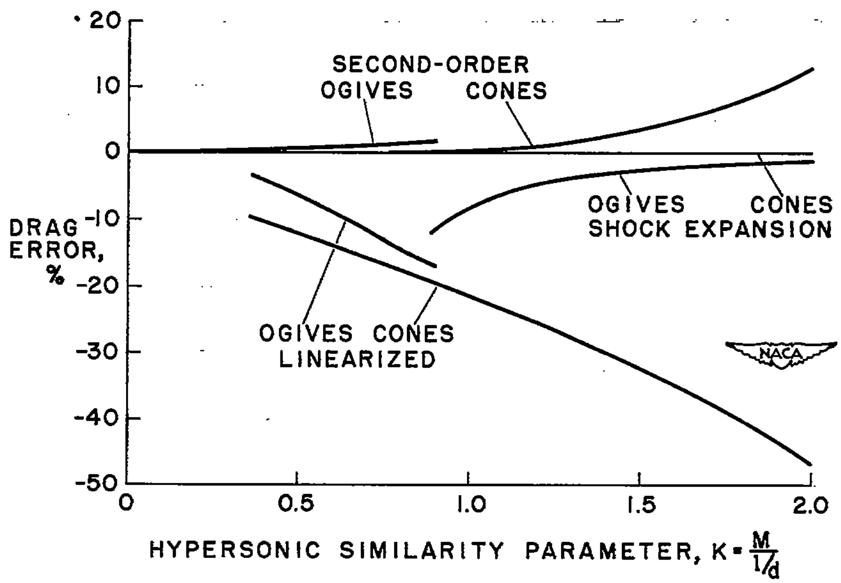

Figure 2.- The drag errors of three approximate theories as a function of the hypersonic similarity parameter.

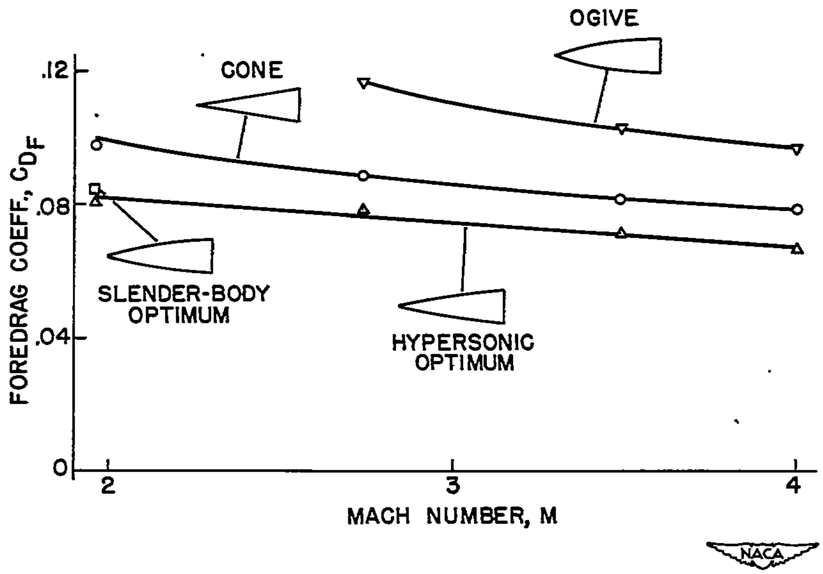

Figure 3.- Foredrag coefficients of two optimum shapes compared with a cone and tangent ogive of the same length and base diameter.

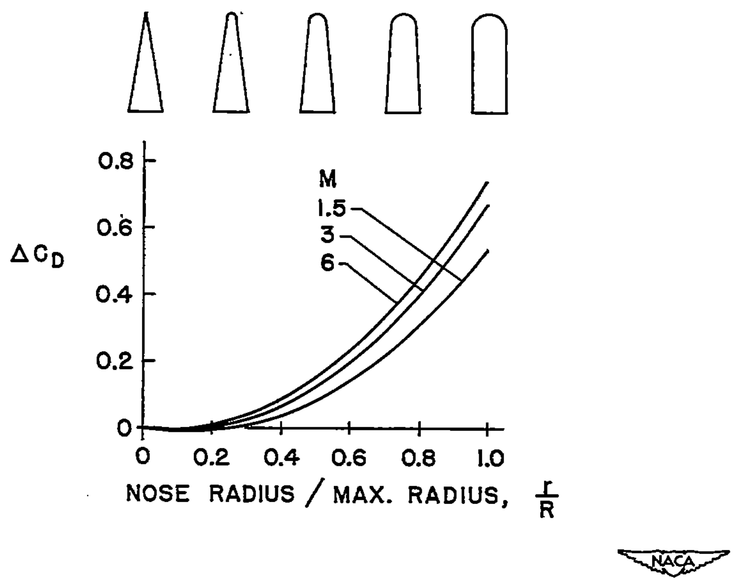

Figure 4.- The calculated variation with tip radius of the drag increment due to bluntness for truncated conical noses with spherical tips.

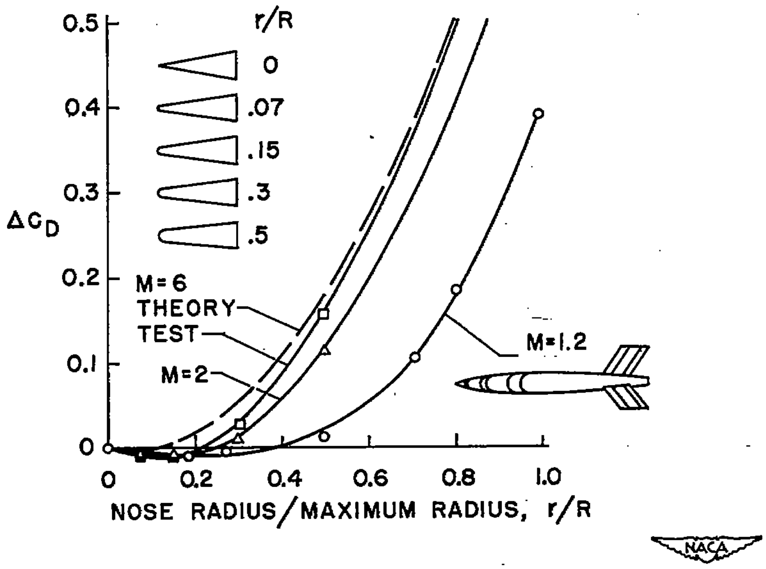

Figure 5.- The experimental variation with tip radius of the drag increment due to bluntness for two families of shapes.

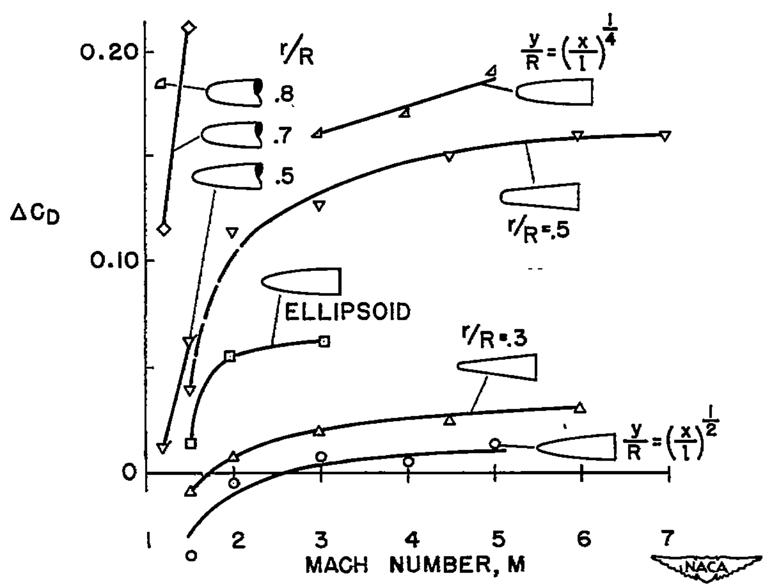

Figure 6.- Dependence on Mach number of the drag penalty due to bluntness.

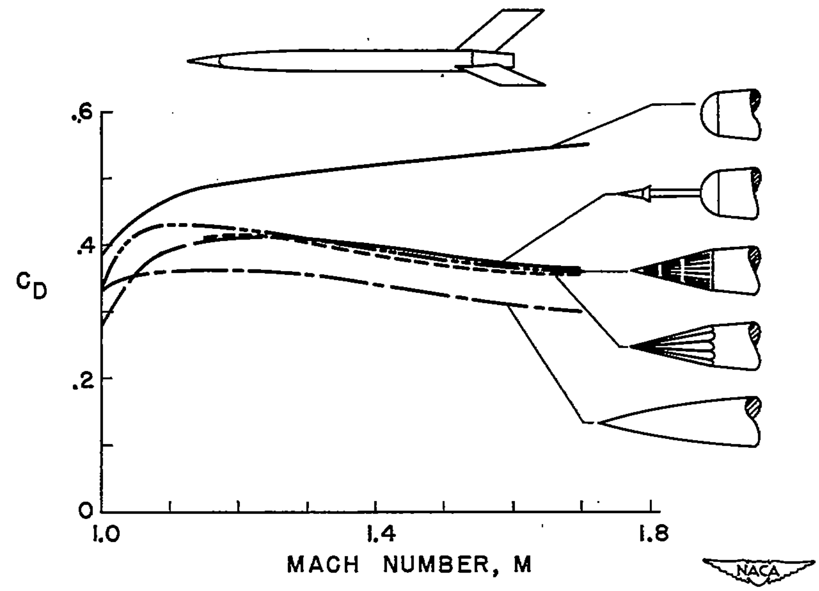

Figure 7.- Use of a projecting spike or slotted cone to reduce the drag of a spherical-tipped infra-red seeker.

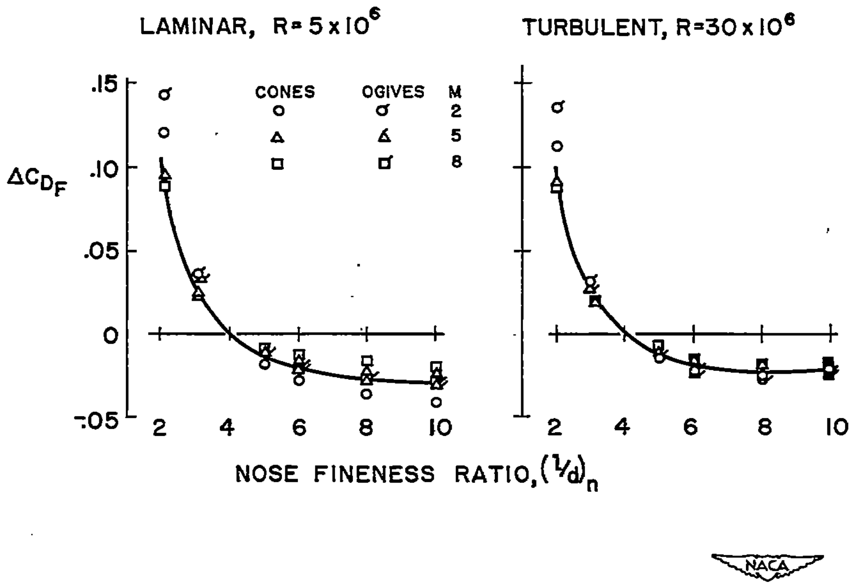

Figure 8.- The effect of fineness ratio on foredrag for cones and ogives.

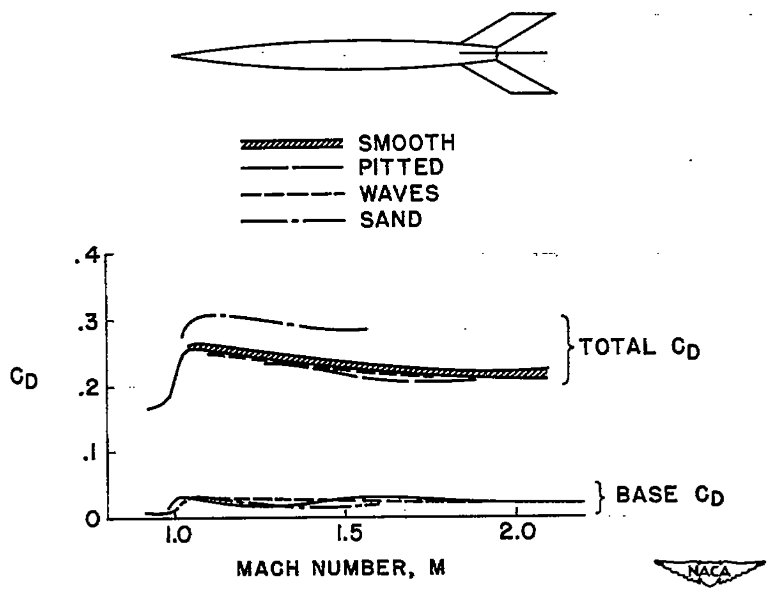

Figure 9.- The effect at very high Reynolds numbers of three kinds of surface imperfections on the drag.