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A Note on the Interpretation of Base Pressure Measurements in Supersonic Flows

by

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A NOTE ON THE INTERPRETATION OF BASE PRESSURE MEASUREMENTS IN SUPERSONIC FLOWS

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R. C. Hastings

SUMMARY

Empirical theory and experimental methods are reviewed in the light of the existing knowledge of the flow behind the blunt base of a body in a supersonic flow.

A discussion of the interpretation of small-scale experiments with natural transition from laminar to turbulent boundary layer flow shows that some difficulty may be encountered in deriving these from the base drag at the high Reynolds numbers of practical interest. While tests with artificial transition, which include boundary layer measurements, may help to overcome this difficulty, investigations at large scale may also be required. Increase of high Reynolds number is thought to raise base drag appreciably at Mach numbers less than 2.

Although none of the empirical methods of estimating base drag is entirely satisfactory, one due to Love is recommended provisionally. The inclusion of jet effects, which are not otherwise considered in the present Note, influences this choice.

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1 INTRODUCTION

During the past few years the estimation of the pressure at the base of a body of revolution moving at supersonic speed has received a great deal of attention because the base drag can be comparable with the skin frictional drag of a typical, clean, body. The base pressure is linked to the pressures acting in the mixing zone immediately downstream of the body and determined by the momentum transfer process taking place in this region. The development of theoretical methods of estimation has been impeded by the difficulty of calculating quantities in the mixing zone, especially if the upstream flow is turbulent. Empirical methods of correlating experimental values have however been proposed.

The work reported here was undertaken with the intention of comparing these methods when applied to tests on cone-cylinder models. This configuration was chosen because of its simple geometry, its popularity with experimenters, and the existence of extensive and accurate theoretical pressure distributions for it.

Practical interest is focussed on the case in which the transition from laminar to turbulent flow in the boundary layer takes place well upstream of the base of the body. The limitations of available test facilities are such that it is not often possible to attain this condition naturally. Attempts have been made to simulate it by the use of various triggering devices to promote transition near the nose of the model. It is not clear how existing results from such tests are related to the values found when natural transition takes place. Rejection of these results leaves so few that a final decision in favour of any one of the suggested methods must be postponed. Nevertheless it is felt some useful information on the base pressure problem has emerged: in particular, at high Reynolds number, an increase of Reynolds number may cause an appreciable reduction in the base pressure. The concomitant increase in base drag with Reynolds number is largest at low supersonic Mach numbers.

2 THE FLOW FIELD BEHIND THE BASE OF A BODY IN SUPERSONIC FLOW

Fig.1(a) shows pressure distributions measured behind half models without boattails in two-dimensional[1] and axi-symmetric[2] flow. In each case the pressure is approximately uniform for 0.8 base diameters or heights, rises steeply for about the same distance and then more gradually to a maximum at about 3 of these units. In two-dimensional flow this maximum is nearly the same as the pressure ahead of the base. The trailing compression, being distributed over a considerable distance, is performed almost isentropically and in turning the flow back to the free-stream direction must almost complete the pressure recovery by virtue of the Prandtl-Meyer relation. In axi-symmetric flow this unique relation between changes of flow direction and pressure, no longer holds; the pressure can therefore overshoot and subsequently return to the value upstream of the base. It is apparent that the displacement surface of the base flow, which is initially wedge-shaped in two dimensions, is not truly conical behind a long body of revolution since the pressure is roughly constant in both cases. This point is illustrated in Fig.1(b).

Fuller and Reid[1] found in their two-dimensional experiments that the end of the constant pressure region was roughly where the mixing zone ceased to entrain fluid from the dead-fluid area and started to return it. They also found that the upstream velocities induced by mixing, were too low to be measured. This is the justification for the assumption that the reflection plate boundary layer does not invalidate the conclusions drawn from the half-model results. It shows too that the flow in the upstream part of the mixing region must be very similar to the mixing of a jet with a fluid at rest; this concept has been used in the development of two-dimensional base pressure theories[3,4].

Further aft, the pressure increases; therefore, when the flow is initially set up, some of the lower energy boundary layer fluid is trapped to form the so-called dead fluid region. This must be of such a shape and size that, when the mean flow becomes steady, the fluid in the mixing region has sufficient energy to negotiate the trailing compression in its passage downstream. It follows that any difference between the base pressure on a long body of zero surface slope and the pressure on the base of a body of any other shape at the same local Mach number will stem from two causes: the difference in the size and profile of the boundary layer approaching the base, and the extra pressure gradients which act on the mixing zone.

Studies of support interference, considered in section 3.3, and measurements of the point at which a shock wave entering the wake of a fin-supported body begins to affect the base pressure[5] both show that quite large disturbances have negligible effects on a turbulent wake if they are more than 3 base diameters downstream of the body. It seems likely that the pressure peak is always within some 3 diameters of the base and therefore any interference pressure field should be allowed for at all points closer to it. This distance should be increased, perhaps to 5 diameters, if the wake is laminar.

3 FACTORS AFFECTING BASE PRESSURE MEASUREMENTS ON BODIES OF REVOLUTION IN AXIAL FLOW

3.1 The position of the base pressure orifice

Except at extremely low Reynolds numbers[8], the pressure variation across the base does not exceed 5% of the value at any point and is usually much less (for example Refs.2 and 5). It is normally lowest near the edge of the base on sting-mounted models.

3.2 Interference in wind tunnels and in free-flight

Wing tunnel models are usually supported either by fins extending to the tunnel walls or by stings projecting from the model bases. The former method alters the boundary layer approaching the base and may appreciably change the pressure field of the outer stream; the base pressure is normally reduced[2]. The same objections apply to stabilizing fins on free-flight models. If instead the models are spin-stabilized, transition is likely to be premature, but tests at M = 2.86 [9] showed other effects to be very small.

Love has collected American work on the effects of stings and issued the results together with some new work in Ref. 10. The minimum lengths of cylindrical sting which should be used are 5 and 3 base diameters for laminar and turbulent wakes respectively. If the sting diameter is progressively increased further downstream, the base pressure is unaffected. The upstream part of the sting should have as small a diameter as possible, and this should certainly be less than 0.4 base diameters. One test made at a Mach number of 2 has been published[11] in which the boundary layer approaching the base was turbulent and there were no fins to modify the wake flow. The base pressure rose by 5% as the diameter of the sting was reduced from 0.4 base diameters to zero. Some of the data of Ref. 10 suggest that greater variations might be found between M = 2 and M = 3 for the same ratios of sting to base diameter.

3.3 Transition Reynolds numbers and the fixing of transition

The summary given as Appendix I of Ref. 14, shows that transition depends on Mach number, pressure, pressure gradient, heat transfer, and the surface condition of the body.

Since the most useful base pressure measurements are those made when transition is well upstream of the base, it is difficult to obtain them with natural boundary layers in wind tunnel tests. Attempts to overcome this difficulty by roughening the model to accelerate transition have the following effects :-

(1) the boundary layer is thickened,

(2) its profile is distorted for some distance downstream,

(3) the pressure distribution around the model may be altered in extreme cases.

Low-speed tests conducted by Klebanoff and Diehl[16] show that similar velocity profiles are not achieved for more than 100 ∂^* of the end of a band of roughness (where ∂^* is the displacement thickness of the first similar profile measured) and that thereafter the boundary layer grows as if it had been turbulent from some point upstream of the roughness. The length of this settling region varies with the type of roughness; for instance, wires attached to the model were found to be inferior to distributed roughness from this point of view.

Reference to Fig.2 will confirm that it is unwise to accept the measurements made on models with roughness without further study of its effects on the base pressure.

It is suggested that, because of low-speed experience on artificially-promoted turbulent boundary layers, base pressure measurements in such cases at supersonic speeds can be given quantitative value only if they are accompanied by sufficient information about the upstream boundary layer to show that its profile is undistorted and to determine its effective origin. None of the many investigations which have been reported in recent years has fulfilled these conditions.

4 EFFECTS OF BOUNDARY LAYER PROPERTIES ON BASE PRESSURE

4.1 General survey

Since the mixing behind the base and the energy contained in the boundary layer are important, it is relevant to consider the evidence afforded by the normal behaviour of boundary layers and wakes. The relative fulness of the velocity profile of a turbulent layer when it is compared with its laminar counterpart shows that the degree of mixing is much greater in the turbulent than in the laminar layer at a given Reynolds number. Because the degree of mixing controls the kinetic energy distribution across the layer, the turbulent layer has a much greater capacity for working against pressure forces. So, if as in a base flow at supersonic speed, a dissipative layer is subjected to compression it is to be expected that a greater proportion of it will be reversed (when the flow is first set up) if it is laminar than if it is turbulent; thus in the former case the dead fluid area will be larger, the expansion round the base corner less, and the base pressure higher. Increase of Reynolds number, by thinning either kind of layer, reduces the quantity of low-energy fluid so tending to reduce the base pressure. On the other hand by reducing the rate of growth of the layer, i.e. the rate of entrainment of high-energy fluid from the outer stream, an increase of Reynolds number tends to increase the base pressure. The relative importance of these counter effects changes with Reynolds number and perhaps with Mach number.

Fig.3 shows curves derived from tests by Kavanau[8,12] and Bogdonoff[13] on one configuration; letters attached to the curves indicate the important points. Below C, both the boundary layer and wake are laminar. As the Reynolds number rises, the reduction in mixing is supposed to be dominant at first, and the base pressure rises; decrease of thickness is thought to have an increasing and opposite effect which eventually produces a maximum pressure at C and might be expected to cause the pressure to fall as at D to some lower limit at very high Reynolds numbers. A similar, but generally lower, curve tending to the same limit is to be expected for a fully-turbulent, dissipative flow. In practice, if transition is not artificially induced, only part of this curve is found (in the example of Fig.3, the segment near C' and D'). It is joined to the curve for laminar flow by some transition curve, the precise form of which probably depends on the method of varying Reynolds number. If a single model is used and the Reynolds number is increased by raising the ambient pressure, the forward movement of transition is likely to be slow since there is evidence[14] that transition Reynolds numbers increase with ambient pressure; if several models of different sizes are used, transition will be affected by the different surface qualities of the models and their stings. Bogdonoff's use of both methods is considered to be the reason for the large scatter shown near E and F in the figure. He deduced from schlieren observations that between E and F, transition was occurring in the wake ahead of the trailing compression, and suggested that transition at the wake sting junction was taking place to the left of E. The latter implies a continuation of the reduction in base pressure due to decrease of the laminar boundary layer thickness as at CD, augmented by increased mixing due to the turbulent flow under the trailing compression where it is most effective; it is accordingly a likely explanation of the steep drop in pressure which is frequently observed. At Mach numbers up to 3 there is usually a minimum pressure between E and F. Reference 6 shows that transition may reach the base on either side of the minimum and that the minimum itself tends to disappear at the higher Mach numbers.

Crocco and Lees[15] who first advanced such an explanation as this for the behaviour of base pressure, identified the minimum with the occurrence of transition at the base, and the point C' with the point at which the change in boundary layer thickness due to the forward movement of transition on the body is just negligible. It is felt that such conclusions are too definite to be drawn from the qualitative argument, since they require exact balance at all Mach numbers between the effects of thickness and mixing at these points. It may be true, as suggested in Ref.6, that the normal behaviour pattern on which the argument is based, is altered close to transition.

Since the scatter in Fig.2 near E and F is thought to reflect differences in transition between the various tests, the curve F C' is not considered to be representative of turbulent flow below a Reynolds number of about 4.5×10^6; the point C' then becomes the analogue of C in the laminar flow. This argument raises difficulties in the interpretation of measurements with turbulent boundary layers. If results are obtained with early transition and confined to the region to the left of C' the apparent and wrong trend of base pressure at high Reynolds number is an increase; alternatively, if transition is late and C' lies somewhere in the transition region it is difficult to decide where the "fully turbulent" curve is attained. This difficulty is found in the higher Mach number results of Ref.6 as mentioned above. Isolated points obtained at Reynolds numbers below about 10^7 are suspect because of this.

Because of the complexity of the problem, simplifying assumptions about the behaviour of the mixing region have been made. A degree of similarity between base flow and the flow up a forward facing step has led Love to postulate[2] that the base pressure can be deduced from the pressure rise required to separate the boundary layer ahead of a step. An empirical extension to bodies of revolution has been made. This method is similar to an earlier one by Cortright and Schroeder based on an assumption that the angle between the separated flow just behind the base and the axis of symmetry depends only on the Mach number approaching the base. The differences are:-

(1) The effective afterbody angle for a body of revolution is assumed to depend linearly on the ratio of base diameter to maximum diameter, but in the earlier method it is the true afterbody angle.

(2) Love, by using the pressure rise which causes separation ahead of a step, is able, unlike Cortright and Schroeder, to estimate when the boundary layer will separate from the afterbody upstream of the base.

Love's method is in fair agreement with experiment although some of the assertions in its development are surprising; for instance, that the flow at a two-dimensional base is more reliably indicated by the existing results on forward-facing steps than by those on rearward-facing steps.

4.2 The Reynolds number effect for a turbulent boundary layer

In the earliest attempt to explain the influence of Reynolds number, Chapman[7] suggested that the thickness of the boundary layer approaching the base was of prime importance. (This view is partially supported by the later work indicated in section 4.1). He proposed that the parameter $\ell/d_b(Re)^{1/5}$ should be used as a measure of the relative height of this (turbulent) layer, in terms of the base diameter d_b of a body of length ℓ. This parameter owes its origin to the low-speed empirical theory of the turbulent boundary layer on a flat plate at zero incidence. As is well known, the formula begins to overestimate the Reynolds number effect near Reynolds number of 10^7. It is, however, true that when transition is well ahead of the trailing edge, the boundary layer there behaves as if it had been turbulent from the leading edge. Even if it is assumed that axial symmetry of the mean flow about a body of revolution can be taken into account empirically[14] by means of the transformations developed for laminar flow, and that the effects of compressibility are confined to an alteration of the coefficient of such a formula, the objections remain that the parameter ignores both pressure gradients and variations in mixing. Since, as was argued in section 4.1, these latter oppose the effects of thickness, and since also the formula begins to err at high Reynolds number, an index numerically less than 1/5 is to be expected in a region where a power law is still adequate to express the scale effect on base pressure. If the base pressure tends to a non-zero limit at very high Reynolds number, any such power law must eventually fail.

4.3 Heat transfer

If a gas has constant specific heats and a coefficient of viscosity proportional to a power of the static temperature, inclusion of the effect of compressibility as a multiple of a low-speed power law (as implied in the previous section) is a special case of a more elaborate correction given by Monaghan[14]. This states that formulae for the skin friction in incompressible flow may be used for high-speed flow with heat transfer if the density and viscosity are evaluated at a temperature corresponding to an intermediate enthalpy in the boundary layer. This provides a possible way of including the consequences of heat transfer in the scale effect.

Experimental data on this subject are limited to Kurzweg's tests[21] which show that the base pressure increases with surface temperature of the body for some laminar and turbulent boundary layers, and Kavanau's observation[8] that the reverse is true at low Reynolds numbers. If Kurzweg's results are in regions like CD and C' D' of Fig.3, these opposing trends are explainable on the present hypotheses.

5 THE CORRELATION OF BASE PRESSURE MEASUREMENTS IN AXI-SYMMETRIC FLOW

Accurate account of the effects of body shape and boundary layer properties on the wake behind a blunt-based body can be taken only by providing simultaneous solutions for the flow in the mixing region and for the inviscid external flow. The mixing problem having been discussed in section 4, the approximate treatment of the external flow is now considered briefly.

Strictly there occurs a loss of total pressure due to shock waves from the body, causing the local Mach number to be less than the free-stream Mach number when the pressure returns to its free-stream value. The body shape will also cause the pressure just upstream of the base to differ in general from the free-stream value, and cause an extra pressure gradient to be felt by the base flow.

5.1 Elimination of the effects of body shape

Fortunately, the use of reference pressures and Mach numbers at various points near the base has served to interrelate measurements on various bodies fairly sucessfully. This suggests that the mixing process behind the base is insensitive to small, externally-imposed pressure gradients.

Reference points which have been proposed are:-

(1) the body surface just upstream of the base, if there is no separation from the afterbody[2,7],

(2) on a hypothetical cylindrical extension of the body beyond the base,

- (a) a point just downstream of the base[6]
- (b) a point one diameter downstream of the base[7]
- (c) the points of average pressure and Mach number over the length of the dead fluid region. [Chapman]

(Since section 2 indicates that this region is about 3 diameters long, and the shape effect decays downstream, this suggestion implies points a little less than $1\frac{1}{2}$ diameters downstream of the base).

If the afterbody is cylindrical (1) and (2a) are the same. For cones without afterbodies (2a) is used instead of (1) in Ref.2; a cone is thus treated as the limit of a cone-cylinder rather than as an example of a diverging afterbody.

5.2 A limited comparison of the methods of correlation using results for cone-cylinders

The results thought most reliable in the light of the considerations of sections 3 and 4 have been corrected for nose effect using the 'characteristics' solutions of Ref.17 where possible. These calculations are confined to the region in which the nose shock is unaffected by the expansion at the cone's shoulder and the flow about the body is consequently irrotational. This severely limits the cylinder length for which solutions are available if the nose-angle of the cone is large. Because Cronvich[18] found experimentally that the pressures on a cylinder following either a slender cone or a hemisphere were the same and very near free-stream pressure more than 4 calibres from the shoulder at Mach numbers of 1.5, 1.73 and 2, such a result has been assumed to hold for all cone angles and the Mach numbers used. Free-stream pressure and the appropriate Mach number allowing for the conical head shock loss are therefore the reference quantities when the cylinder is more than 4 calibres long.

Figs.4(a) and(b) show the relation between base pressure ratio and Mach number when reference conditions at the base and the averages over a 3 calibre extension of the cylinder are used. It will be seen that there is very little to choose between the two methods; this finding agrees with Fig.6 which shows as percentage scatter, two larger data collections. Many tests are common to both, which include the results of wind tunnel and free-flight experiments. In neither collection are there any coefficients for unfinned bodies below $M_r = 1.5$.

Fig.5 is complementary to Fig.4 in showing the same data plotted against Reynolds number. The reference length for the Reynolds number is the length of a generator of the body surface - chosen because it is the length of the boundary layer path, which appreciably exceeds the axial length of the body for some shapes. On this graph, full lines show measurements covering ranges of Reynolds number at constant Mach number. In such cases dotted extensions of the lines indicate data which have otherwise been rejected because they may be affected by transition. The approximate position of Bogdonoff's data[13] quoted in Figs.2 and 3 is shown by a series of crosses; the exact position cannot be given without extending the calculations of Ref.17.

Even for the simple cone-cylinder shape, the base pressure ratio is a function of four variables:- nose semi-angle, cylinder length, Mach number, and Reynolds number. The correction for nose effect almost removes the effect of the first two on the pressure field near the base, but, since they also affect the boundary layer thickness, this does not reduce the number of variables. It is therefore unlikely that such a picture as Fig.5, which takes account only of two variables, will afford a completely satisfactory explanation of the scatter of the data. Nevertheless the results near $M_2 = 1.6$ do lend weight to the view that a scale effect similar to the observation of Ref.13 is an important contributory factor. The curve XX suggests the form this variation might be expected to take. The point of maximum base pressure for the turbulent layer (C' of Fig.3) appears to lie near a Reynolds number of 8×10^6 for Mach numbers below 3. If the results for the cone ($M_2 = 4.18$) are reliable, this point apparently moves to lower Reynolds numbers at the higher Mach numbers, in which case a curve like YY should be found for $M_2 \approx 3.15$. Since this test on a cone[6] showed transition to pass the base of the model at a Reynolds number of about 2×10^6, (the top of the dotted portion of the curve) the full line is thought to be representative of turbulent flow.

If such scale effects are present, they sometimes have a practical importance in addition to their theoretical interest. This may be seen by considering the curve XX and the results of Ref.13. In each case p_b/p_r decreases by some 5% from the peak to the value at a Reynolds number of 2×10^7, but the drag coefficient, being proportional to $(1 - p_b/p_r)$ increases by 14% in the former example, compared with 4% in the latter. It appears then that small-scale tests could seriously underestimate the base drag of an aircraft for Mach numbers below below 2. This point would appear to deserve further experimental investigation.

Meanwhile it seems advisable to regard the existing theories rather as bases on which to compare different configurations than as sources of accurate drag prediction. There are a number of reasons for preferring Love's method[2] to the others for such work: it is simpler to apply than, and of comparable accuracy to, Chapman's; reference 22 shows that it remains useful when applied to a thin base annulus surrounding a supersonic jet.

6 CONCLUSIONS

Empirical theory and experimental methods applied to the base pressure problem have been reviewed in the light of the present knowledge of the flow at the blunt base of a body in supersonic flow. Some points worthy of consideration in the design and analysis of experiments are emphasized.

(1) The base pressure is determined by the flow within a length of some 3 or 5 base diameters aft of the base, depending on whether this flow is turbulent or laminar. In experimental work this region should be kept free from large extraneous disturbances.

(2) The relative magnitude of the thickness and mixing effects of the dissipative layer is believed to change with Reynolds number in such a way that the base pressure first increases and then decreases as the Reynolds number is raised. If the base pressure has a non-zero limit, a power law cannot correct it with Reynolds number when the latter is very large.

(3) The Reynolds number at which the maximum base pressure occurs at a given Mach number and with a fully turbulent boundary layer may decrease as the Mach number is raised.

(4) Perhaps for the latter reason, and because transition from laminar to turbulent flow depends on several variables, it is sometimes difficult to see where measurements made with natural transition become representative of fully turbulent flow.

(5) Tests with fixed transition will overcome this difficulty if it can be confirmed that sufficiently far downstream of the 'triggering' device its effect is that of Reynolds number increase by increase of length. This implies that in future such tests, unlike those reported in the past, should be accompanied by boundary layer measurements.

(6) Scale effect on base pressure, though not as rapid as the previously suggested inverse variation as the fifth root of the Reynolds number for a turbulent boundary layer, may not always be negligible. It may indeed cause an appreciable increase in base drag at low supersonic speeds as the Reynolds number is increased.

(7) The use of reference pressures and Mach numbers derived from inviscid flow conditions near the base fairly successfully eliminates the effects of nose shape. The pressure just upstream of the base on a cylinder is near free-stream pressure if the cylinder is more than 4 diameters long. Two earlier analyses of base pressure measurements, using many of the same data, indicate that the consistent use of any one reference pressure collapses measurements on models with cylindrical afterbodies within ±1.5% of a mean curve of base pressure coefficient.

(8) The present preferred method of estimating base pressure is that of Love[2], since it has fairly successfully been used for bodies with convergent afterbodies, and also for the thin base annulus surrounding a supersonic jet. The method ignores scale effects completely; it is suggested therefore that it be regarded rather as a means of comparing alternative configurations than as a source of accurate drag prediction.

LIST OF SYMBOLS

d	Diameter
ℓ	Length
M	Mach number
Re	Reynolds number based on free-stream conditions and axial length of body
Re_m	Reynolds number based on free-stream conditions and meridional length of body
θ	Semi-nose angle of conical head

Suffices

b	Base
r	Reference point
s	Cylindrical sting
1	Station at base
2	Quantities averaged over a 3 calibre cylindrical extension of a body
∞	Free-stream values

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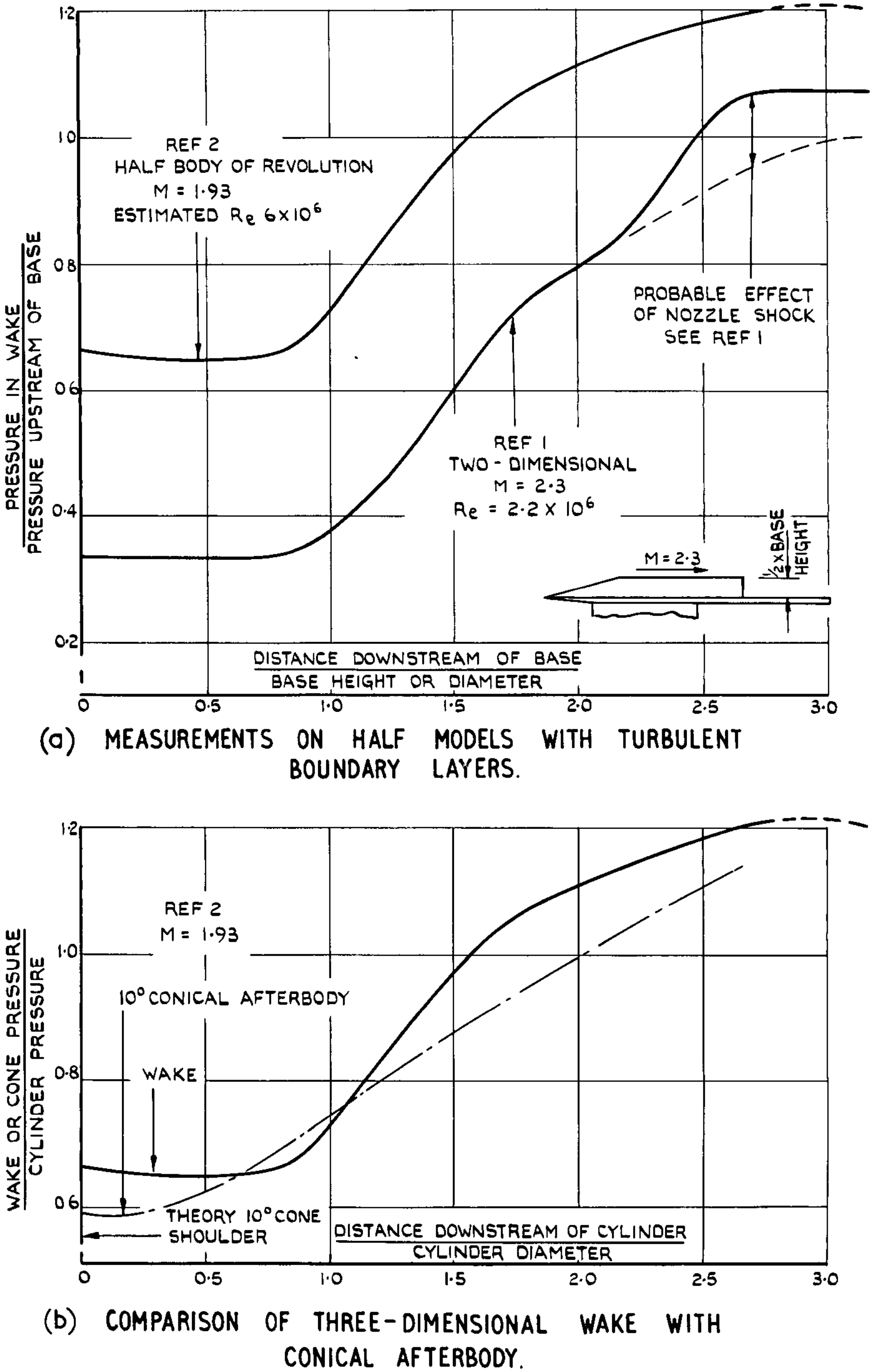


(a) MEASUREMENTS ON HALF MODELS WITH TURBULENT BOUNDARY LAYERS.

(b) COMPARISON OF THREE-DIMENSIONAL WAKE WITH CONICAL AFTERBODY.

FIG.1. THE PRESSURE IN THE WAKE OF A BLUNT-BASED BODY WITH A TURBULENT BOUNDARY LAYER.

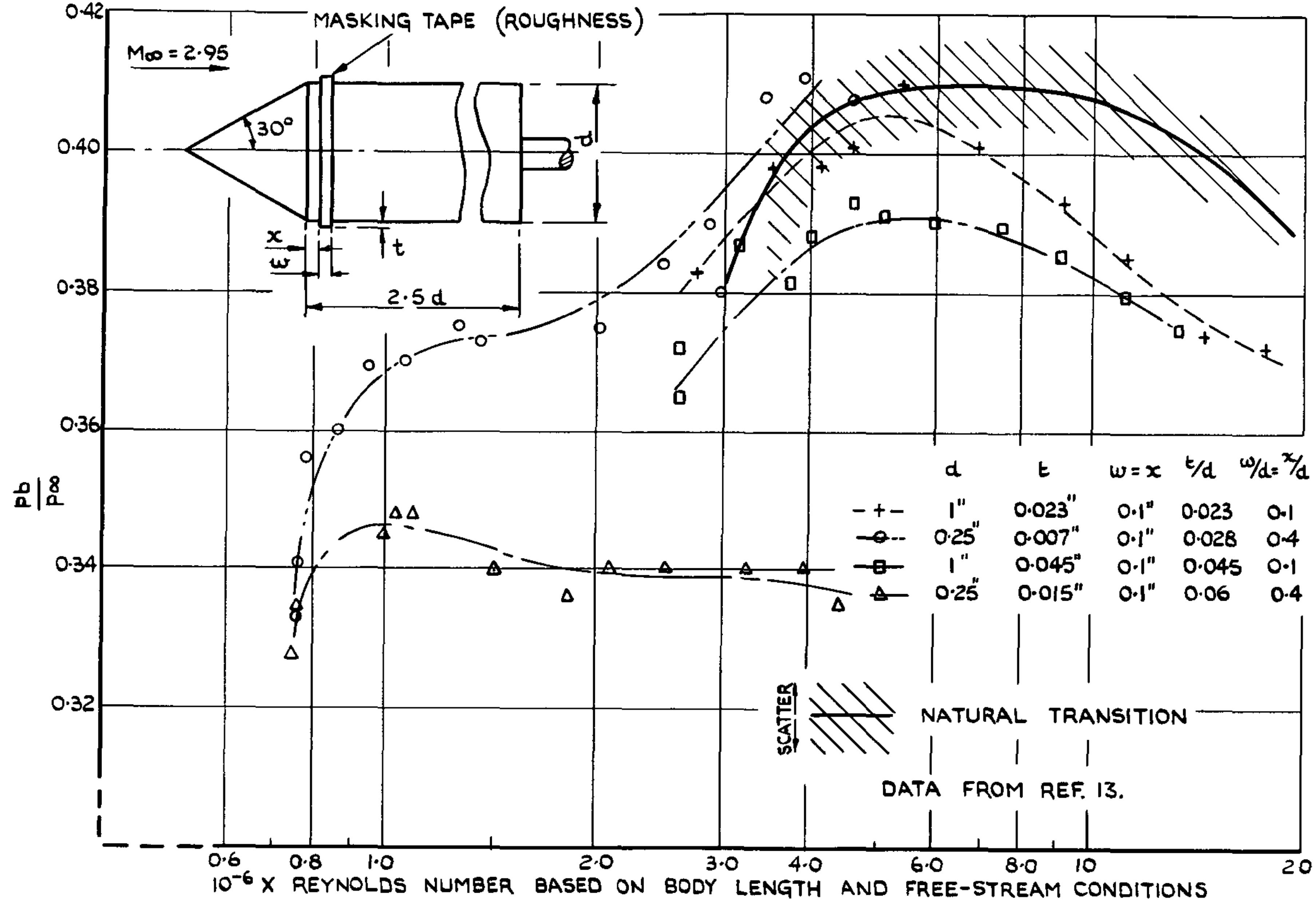


FIG.2. AN EXAMPLE OF THE EFFECTS OF ROUGHNESS ON BASE PRESSURE.

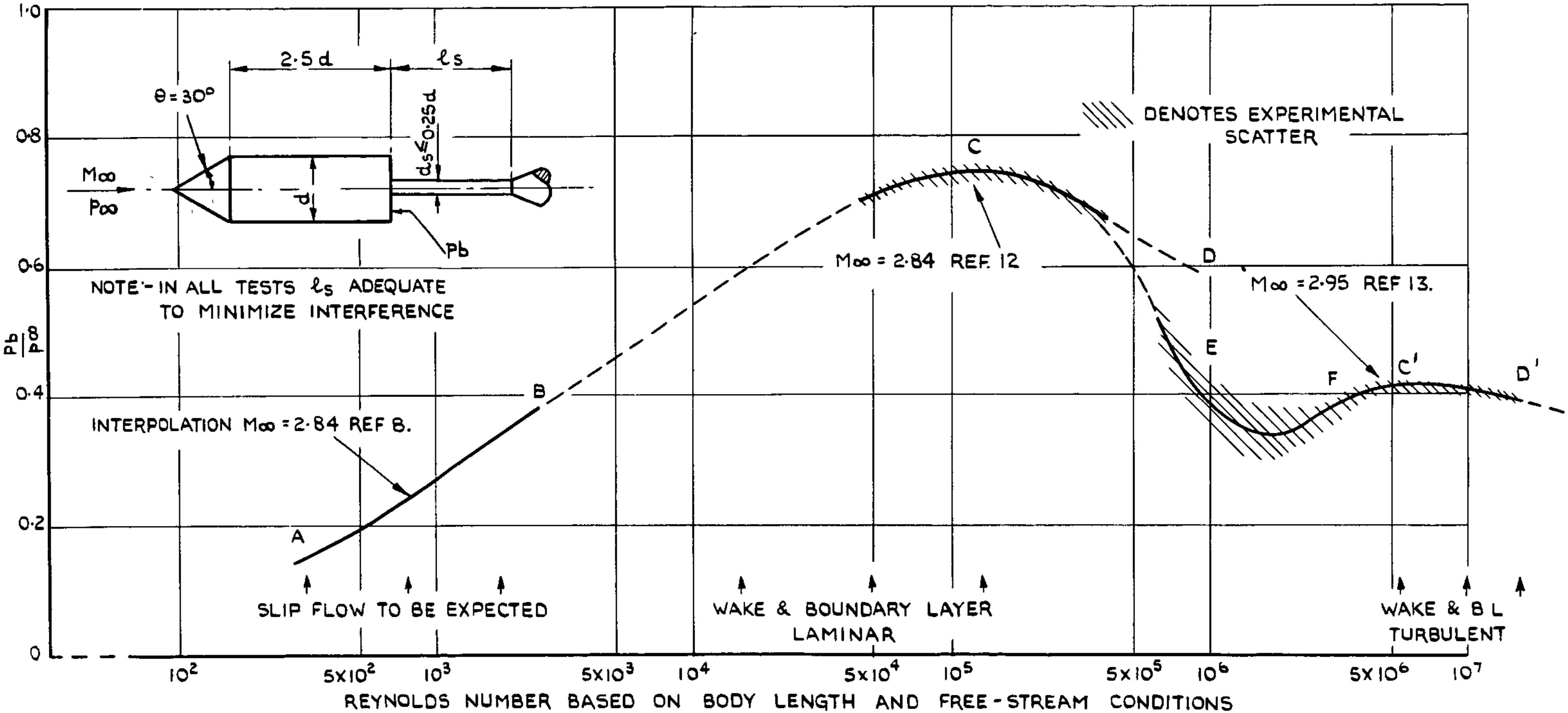
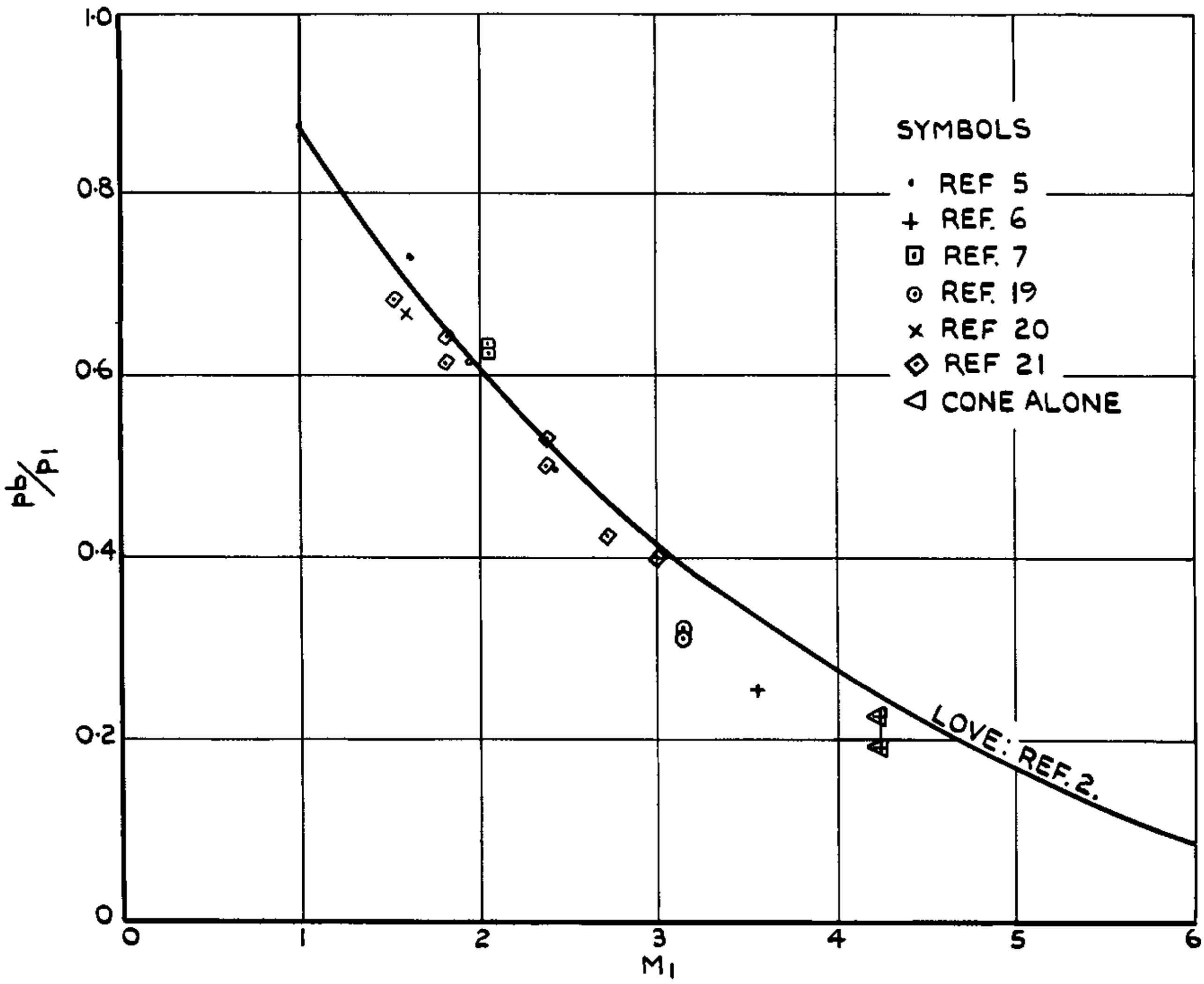
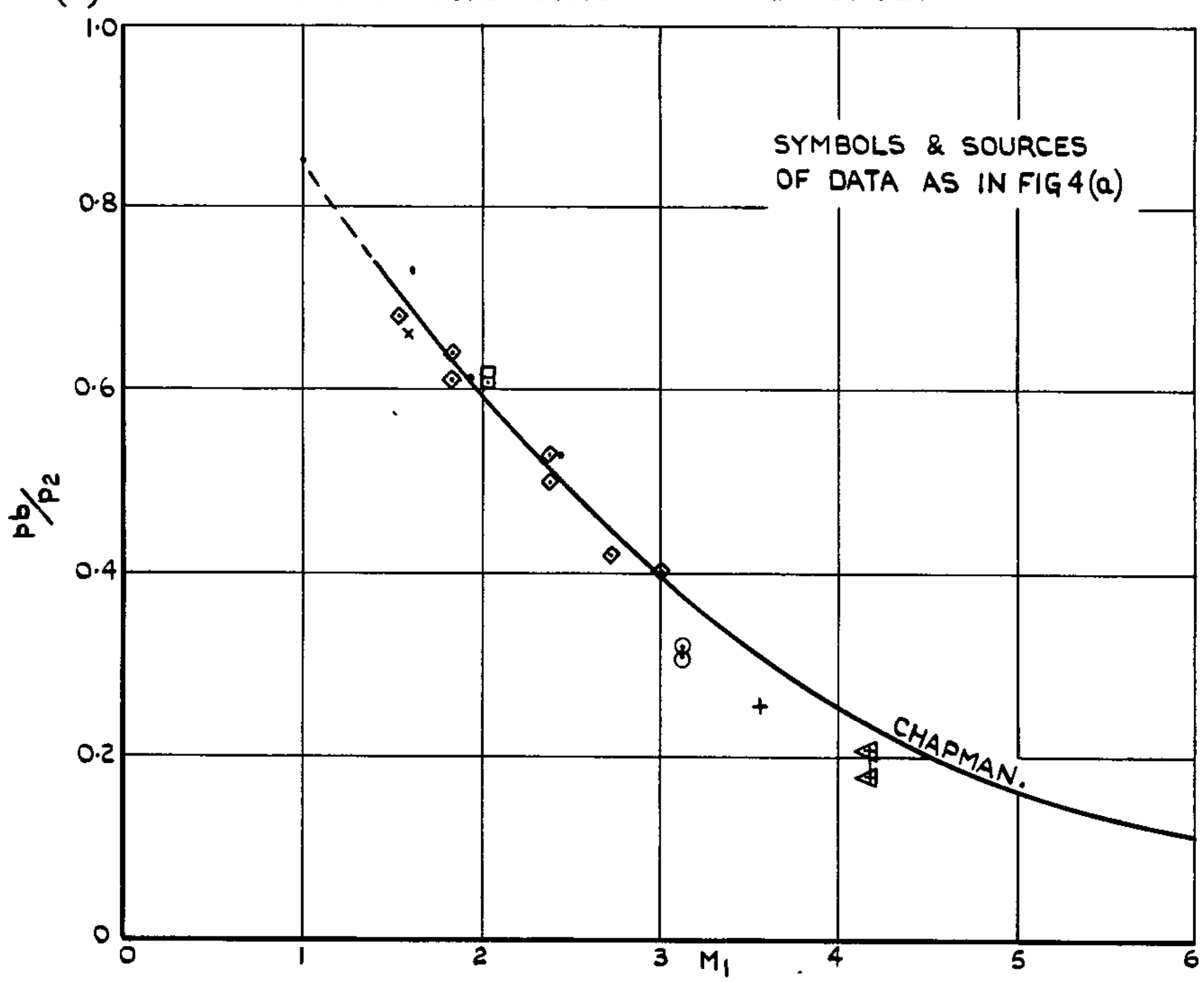


FIG. 3. THE EFFECT OF REYNOLDS NUMBER ON THE BASE PRESSURE OF A CONE-CYLINDER NEAR M = 2·9.



(a) USING CONDITIONS AT THE BASE.



(b) USING CONDITIONS AVERAGED OVER A 3 CALIBRE CYLINDRICAL EXTENSION OF THE BODY.

FIG. 4. BASE PRESSURES ON CONE CYLINDERS CORRECTED FOR NOSE EFFECT (BODY BOUNDARY LAYER TURBULENT)

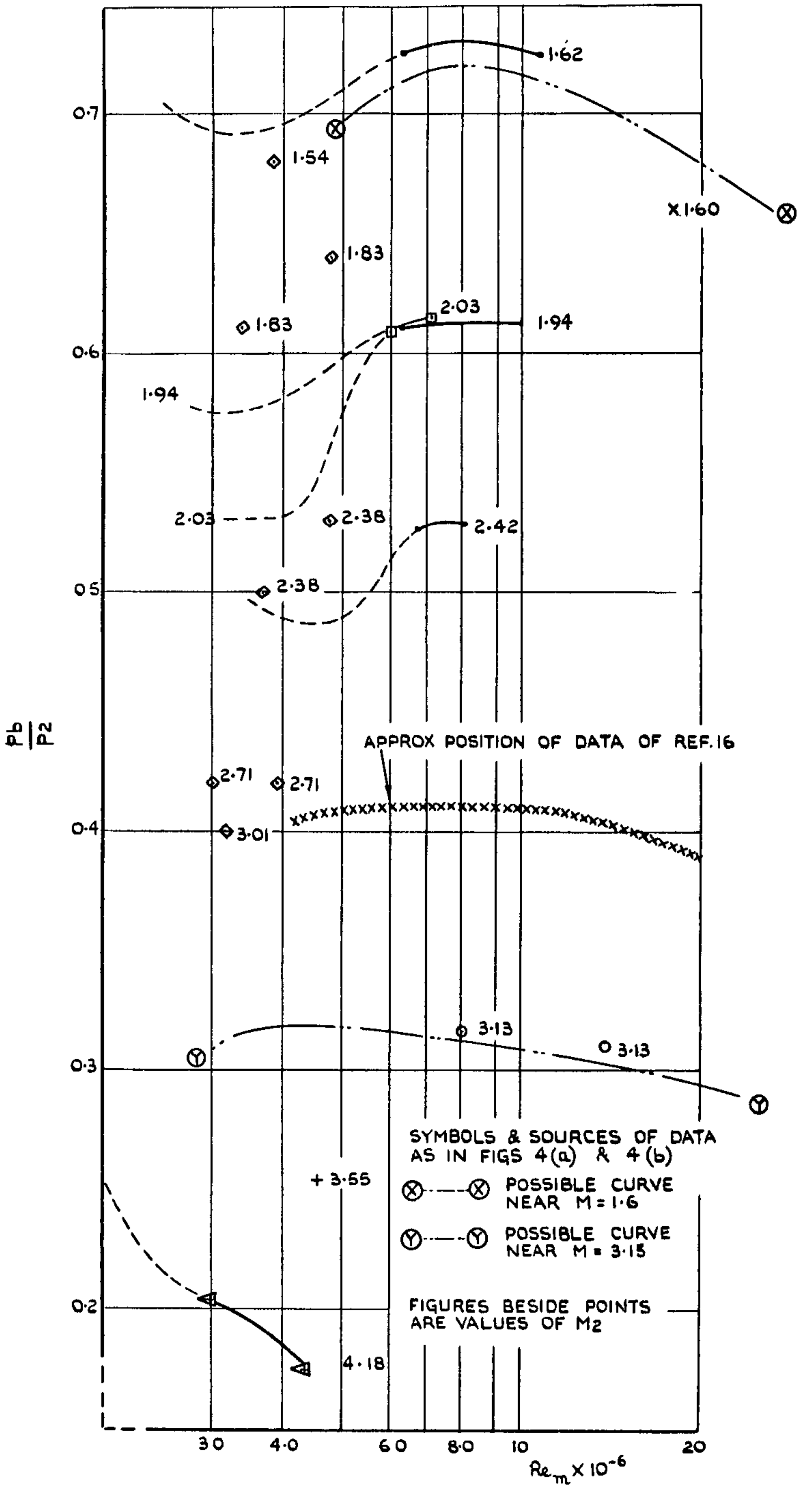


FIG. 5. CORRECTED BASE PRESSURE RATIO vs. REYNOLDS NUMBER WITH MACH NUMBER AS A PARAMETER FOR CONE-CYLINDERS WITH TURBULENT BOUNDARY LAYERS.

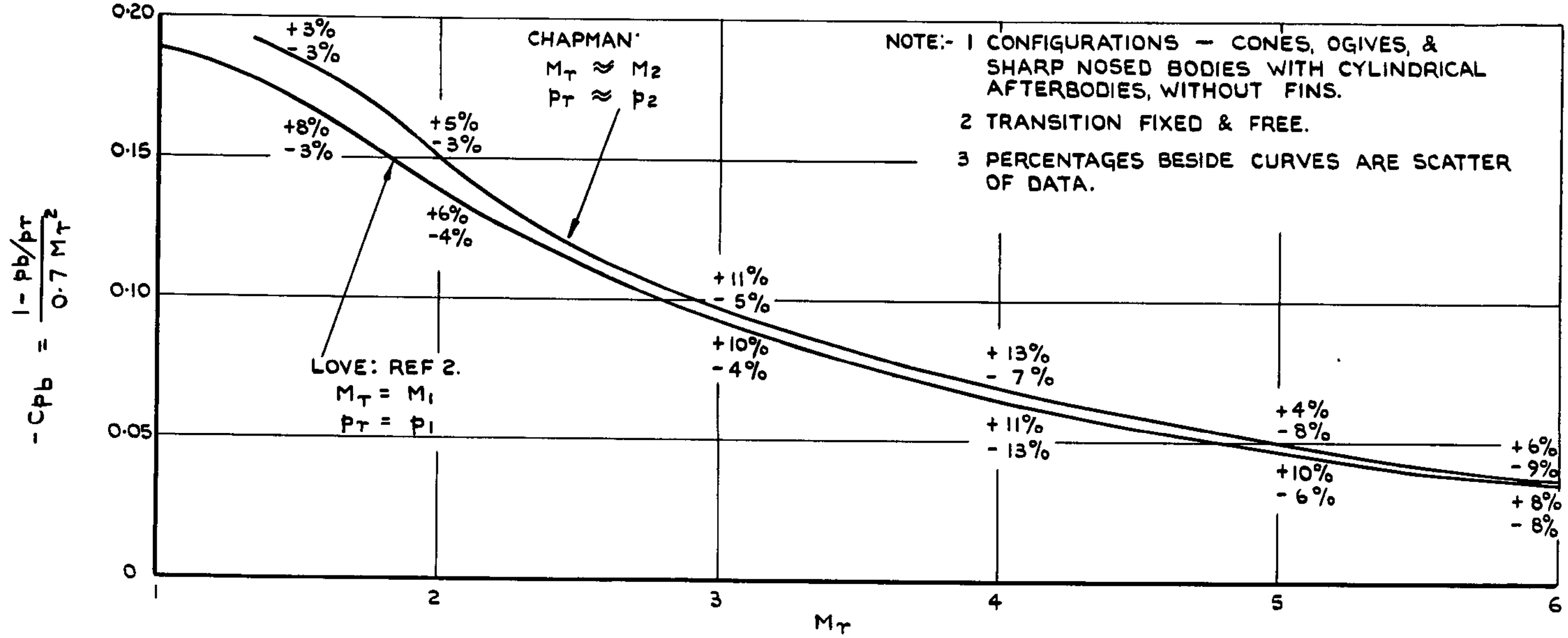


FIG. 6. BASE PRESSURE COEFFICIENTS vs MACH NUMBER FOR BODIES OF REVOLUTION WITH TURBULENT BOUNDARY LAYERS.

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