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Measurements of Zero-Lift Drag at Supersonic Speeds for a Symmetrical Slender Wing Model with Different Roughness Bands

By

E.C. Carter, D.C.Ae.

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Measurements of Zero-Lift Drag at Supersonic Speeds for a Symmetrical Slender-Wing Model with Different Roughness Bands

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SUMMARY

This paper gives the results of tests in the A.R.A. 30" × 27" Supersonic Tunnel on a slender ogee wing ($p = 0{\cdot}45$) to determine the drag at zero lift for the model fitted with various alternative roughness bands. Tests were made at Mach numbers from $M = 1{\cdot}6$ to $M = 2{\cdot}4$ over a wide range of Reynolds number from about $R = 2{\cdot}5 \times 10^6$ to $R = 7 \times 10^6$, based on the wing root chord of 2 ft.

The results show that to fix transition at the higher Reynolds numbers in this range, it may only be necessary to apply a roughness band over part of the span. If the band is kept to the minimum length that is essential and to the minimum practicable width (say, about 0·04") and if the roughness is applied as sparsely as possible, it is probable that the roughness drag increment may only be about 0·0001 - 0·00015 in C_D. On the other hand, full-span bands 0·125" wide can typically give an increment of 0·0006 - 0·0008. Within reasonable limits, however, the roughness drag increment does not appear to be particularly sensitive to the height of the roughness provided this is sufficient to fix transition.

The present results suggest that over the part of the wing where it is necessary to apply a roughness band, transition should occur fairly close to the band provided the roughness-height Reynolds number, R_k, exceeds the values that range from about 1000 at $M = 1{\cdot}6$ to 1800 at $M = 2{\cdot}4$. To ensure that the boundary layer was fully turbulent everywhere, however, particularly with a relatively sparse band and particularly at the higher Mach numbers, these values of R_k have to be increased by a factor which can be as high as 30% or more.

The evidence from these tests is not sufficient to define quantitatively the roughness application that should be used for other slender-wing models. On the other hand, the experience is sufficient to recommend a procedure for choosing an optimum roughness band that will be both effective in fixing transition and will give the smallest possible drag penalty. This procedure will involve some preliminary testing on any new model.

Replaces A.R.A. Wind Tunnel Note No. 48 - A.R.C.24 838.

LIST OF CONTENTS

LIST OF FIGURES

FIG. 7a:/

LIST OF FIGURES

1. INTRODUCTION

During recent years, a considerable number of slender-wing models have been designed and tested by the R.A.E. in a general research programme to find suitable shapes for supersonic transport aircraft. Broadly speaking, these models have either had a root chord of between 5 and 6 ft and have thus been of a size suitable for test in the 8 ft tunnel at R.A.E. Bedford and the A.R.A. 9 ft x 8 ft transonic tunnel or else, have had a root chord of about 2 ft for test in the 3 ft tunnel at R.A.E. Bedford and the A.R.A. 30" x 27" supersonic tunnel. In many of the tests, a primary objective has been to obtain experimental values for the wave drag at zero lift at supersonic speeds for comparison with theoretical estimates. With the larger models, it is possible to derive the wave drag directly from an integration of a detailed pressure-plotting survey over the surface of the wing but for models having a root chord of only about 2 ft, it would clearly be difficult to achieve sufficient accuracy by this method. It is necessary therefore to try and obtain the wave drag from a balance measurement of the total drag together with an estimate of the skin-friction drag. This poses quite a difficult experimental problem, particularly when considering the wave drag at zero lift because then typically, the skin-friction drag can be as much as 75% of the total drag, as measured in the tunnel test.

Methods are available for estimating the skin-friction drag both with laminar and with turbulent boundary layers but if no attempt is made to fix transition at a prescribed position, one has to use the sublimation technique with say, acenaphthene or azobenzene, to determine how much laminar flow is present. Then, by a strip-theory approach, the skin-friction drags of the laminar and turbulent regions are estimated separately with assumptions for the length of the transition region and its skin friction. This approach may prove particularly difficult if the slender-wing planform departs too seriously from a simple delta shape because the transition front may then vary somewhat erratically across the span of the wing and this would reduce the possible accuracy of the skin-friction estimate. In any case, the approach would be rather impracticable for routine testing over a range of Mach number and C_L because strictly, one would then have to determine the position of the transition front over a wide range of operating conditions. For this reason the preferred approach has generally been to try to fix transition at a definite position by using a band of distributed roughness. Even this method however is not as simple as it sounds: the basic problem is to choose a roughness band that is effective in provoking a turbulent boundary layer immediately behind the band but which on the other hand, does not give any significant drag penalty. It has been known for some time that unless special care is taken, this roughness drag penalty can be far from trivial and the present paper describes a fairly comprehensive investigation that has been made with one particular model to try and assess how large this drag increment can be and to show how it varies with different parameters. In addition to tests with different roughness bands over a range of Reynolds number, tests have also been made with natural transition and for one particular combination of M, R and C_L, the natural transition front was observed experimentally and the skin-friction drag calculated; this result therefore provides a yardstick against which the results with the different roughness bands can be assessed.

It is obvious that to keep the roughness drag penalty as small as possible, the height of the roughness elements should in principle be no greater than that needed to fix transition at the band. The curves given by Braslow and Knox[1] have frequently been used as a guide to the roughness height required but it has been shown that roughness bands chosen in this way are often inadequate because the curves merely define the minimum roughness height that has some effect on transition position. The work of van Driest and Blumer[6] indicates values of R_k for which the transition is brought "near" to the downstream edge of the roughness band. The values of R_k which they give are greater than the constant 600 used by Braslow and Knox and show an increase with Mach number. Potter and Whitfield[2] give very much larger values of R_k than either of the other two sources and for most applications, their roughness elements are greater than the local laminar-boundary-layer height. There is no evidence on the effect of model geometry and pressure gradients on any of these values of R_k and as a starting point for these tests, a range of roughness values embracing those predicted by Braslow and Knox for the highest Mach number were used. The wing chosen for the detailed study was the wing 15 design of the R.A.E. series, this being a slender ogee ($p = 0{\cdot}45$) which had also been tested to a larger scale in the R.A.E. 8 ft tunnel[3]. There are two main reasons for choosing this particular design: first, it was thought that the relatively large variation in leading-edge sweep across the span might make it a somewhat difficult example in the context of trying to fix transition everywhere without producing a significant roughness drag increment and secondly, the tests in the 8 ft tunnel had included a detailed pressure-plotting survey from which a fairly reliable measure of the wave drag had been obtained.

The tests in the A.R.A. supersonic tunnel were made over a range of Mach number from $M = 1{\cdot}6$ to $M = 2{\cdot}4$ and a range of Reynolds number from near $R = 2{\cdot}5 \times 10^6$ to near $R = 7 \times 10^6$, based on the wing root chord, corresponding to a range of tunnel stagnation pressure from about 10" Hg to 30" - 35" Hg. Other parameters investigated included the height of the roughness, the width of the roughness band, the spanwise extent of the band and finally, the density with which the roughness particles were applied within a given band. In all cases, the bands were composed of Ballotini, a commercial product consisting of finely graded glass balls.

2. TEST DETAILS

2.1. Model

The model chosen for this investigation was model No. 148, wing number 15 of the R.A.E. series. The basis of this design is described fully in Ref. 3. It is an uncambered wing having the slender ogee planform shown in Fig. 1 with the following specification:

Planform/

Planform parameter $p = 0{\cdot}45$

Span ratio: $s_T/c_o = 0{\cdot}208$, where s_T is the semispan and c_o is the wing root chord

Leading-edge equation

$$\frac{s(x)}{s_T} = \frac{x}{c_o}\left\{1{\cdot}2 - 2{\cdot}4\,\frac{x}{c_o} + 2{\cdot}2\left(\frac{x}{c_o}\right)^2 + 3\left(\frac{x}{c_o}\right)^3 - 3\left(\frac{x}{c_o}\right)^4\right\}$$

Volume parameter: $\tau = \dfrac{V}{S^{3/2}} = 0{\cdot}0415.$

The thickness distribution of this model is not specified mathematically because the surface forms an envelope of the required volume meeting the practical requirements of a project study of an integrated aircraft layout.

The model had a root chord of 2 ft and was made of fibreglass moulded on a steel support tube which provided the balance fixing datum and the balance shroud to the trailing edge. This shroud is shown in Fig. 1; its presence means that the longitudinal cross-sectional area distribution of the model over the rear 30% ahead of the trailing edge would not be the same as on the full-scale aircraft. It is important to note that allowing for the change in model scale, this shroud was to the same shape and dimensions as that used in the 8 ft tunnel tests on this design and estimates of the effect of the shroud on the model wave drag are included in Ref. 3.

The model was mounted on a 4-component balance.

2.2. Roughness Bands

In addition to a test transition free, the model was tested with the following alternative roughness bands:

(a) Ballotini bands, 0·125" wide, 0·1" behind the leading edge, both dimensions normal to the leading edge, Fig.1. This band width of 0·125" is typical of that used in much of the testing of models of this scale prior to the present investigation. As noted in the introduction, the range of required roughness heights were estimated from Ref. 1 and on this basis, tests were made with bands of

roughness height: k : 0·0083" - 0·0099"
0·007" - 0·0083"
0·006" - 0·007"
0·0049" - 0·006"

This wide range of roughness heights was needed partly to cope with the wide range of Reynolds number and Mach number in the tests and partly to show what extra penalties might be incurred

if/

if one used roughness that was coarser than that actually needed just to fix transition.

(b) A band of reduced width and spanwise extent which will be described in this paper for convenience as the "minimum roughness band". The aim in this particular case was to fix transition at M = 2·0 and the higher test Reynolds numbers with as small a penalty as possible. This "minimum band" was defined as follows:

i) width: 0·04" rather than 0·125". A width of 0·04" was chosen first as being about the smallest that was practicable and second, because it corresponds to 0·1" on the scale of the models being tested in the 8-ft tunnel at R.A.E. Bedford where 0·1" has recently been adopted as a standard.

ii) A roughness height of 0·0070" - 0·0083" which from the tests with the wider bands listed under (a) above, appeared to be the smallest height that would effectively fix transition at M = 2.0 and the larger test Reynolds numbers.

iii) A reduced spanwise extent such that the band was only applied over those parts of the span where, according to an acenaphthene picture transition free (Fig. 7a), transition did not occur naturally near the wing leading edge. Fig. 7a shows that on this basis, no roughness was needed over a large part of the inner wing. Also, the band was run out at the tip rather than being allowed to follow the streamwise tip as was done with the wider bands under (a) above.

This band was again sited 0·1" behind the wing leading edge. Fig. 7b confirms that it was effective in giving a transition front close to the wing leading edge over the complete span except possibly very close to the model nose. In this region, the acenaphthene seemed reluctant to sublimate even after a long running time although it must be admitted that the intensity of acenaphthene left in this area was not as great as in the laminar regions shown in Fig. 7a in the test with natural transition.

(c) In a further attempt to reduce the drag penalty to a minimum a test was then made with a band having the same width, height and spanwise extent as the "minimum band" of (b) above but with the number of roughness elements in the band reduced to a lower level considered satisfactory for this band width. In this sparse application, it was estimated that there were about 24 Ballotini balls per inch length of band as compared with roughly four times that density in the bands tested previously under (a,b).

(d)/

(d) To meet the uncertainty about a possible area of laminar flow close to the model nose, a single test was made at $M = 2{\cdot}2$ and $R = 6{\cdot}5 \times 10^6$ with the roughness application (c) together with an additional 0·04" wide band of roughness around the nose 0·25" back from the tip.

In all the above roughness applications, the elements were gently blown onto a band of wet coloured Araldite to which a small quantity of wetting agent had been added to stop the elements collecting together. For the last tests (c,d), the roughness was shaken from a very fine camel-hair brush onto the surface in a roughly controlled manner. As noted, except for these last tests the spacing of the elements could be described as thin rather than sparse.

2.3. Tests

In general, the tests were made at five Mach numbers, 1·6, 1·8, 2·0, 2·2 and 2·4 for the maximum range of Reynolds number possible at each Mach number.

The following table gives the range of Reynolds numbers and also the estimated accuracy of the results at the maximum and minimum Reynolds numbers at each Mach number:

M	1·6	1·8	2·0	2·2	2·4	
R/ft	3·67	3·71	3·66	3·67	3·55	Maximum
R/ft	1·63	1·53	1·41	1·29	1·18	Minimum
$C_D \cdot 10^4$	0·33	0·33	0·39	0·35	0·38	Maximum R
$C_D \cdot 10^4$	0·75	0·8	0·9	1·0	1·1	Minimum R

3. DISCUSSION OF RESULTS

3.1. General

The results of the drag measurements, which have been corrected to zero base-pressure coefficient, are given for the five test Mach numbers in Figs. 2 - 6 respectively. The drag coefficients are plotted against tunnel stagnation pressure or the Reynolds number based on the wing root chord. Results for the different roughness bands listed under (a,b) of Section 2.2 are given in all five figures; the test with the sparse band (c) was only made at $M = 2.2$ and hence results for this test only appear in Fig. 5 while the test (d) with the nose roughness added was only made at $M = 2.2$ and $R = 6.5 \times 10^6$ and thus contributes just a single point in Fig. 5.

On each figure, two estimated curves of C_D against R are shown for comparison. The first which appears near the bottom of each graph is the estimated variation of the skin-friction drag with R, assuming that the

boundary/

boundary layer is fully turbulent from the front of the roughness band to the trailing edge, with a laminar strip ahead of the band. These estimates were obtained by calculating the values for a flat plate and then factoring them by 1·07 which is the ratio of the wetted area/2 × plan area. The flat-plate values were derived by integrating over the planform using the intermediate enthalpy method of Ref. 5 applied to the Prandtl-Schlichting formula:

$$C_F = 0{\cdot}455 \frac{T_1}{T^*} \left[\log_{10} R_x - 1{\cdot}85 \log_{10} \frac{T^*}{T_1}\right]^{-2{\cdot}58}$$

where C_F is the mean skin-friction coefficient over length x

R_x is the local Reynolds number outside the boundary layer (assumed to be freestream R in this case)

T_1 is the freestream static temperature at the edge of the boundary layer

and T^* is a boundary-layer temperature corresponding to an intermediate enthalpy.

For zero heat transfer at the model surface

$$\frac{T^*}{T_1} = 1 + 0{\cdot}129\, M_1^2 \quad \text{for a turbulent boundary layer.}$$

With this particular specified planform it was shown that

$$\frac{C_F \text{ integrated}}{C_F \text{ based on } \bar{c}} = 0{\cdot}966 \quad \text{within the range of test Reynolds numbers}$$

The upper, dotted, curve on each figure represents the sum of the estimated turbulent skin-friction drag and the experimental wave drag for this wing with balance shroud, as obtained[3] from the integration of the pressure-plotting measurements on the larger scale model tested in the 8-ft tunnel, R.A.E. Bedford. The experimental results on any given figure, i.e., for a given Mach number, should therefore be compared with this upper dotted curve.

3.2. The Shape of the C_D versus R curves

Before analysing the results in detail in a quantitative sense, it is helpful to consider how the general shape of the measured C_D - R curves should be interpreted. This can conveniently be done by referring to Fig. 4 which gives the results for M = 2·0 and then later, by considering the effects of changes in Mach number.

The/

The first point to note from Fig. 4 is that with all the roughness bands, the measured values of C_D, irrespective of Reynolds number, lie above those estimated for the turbulent skin friction plus wave drag. The implication is that with all the bands, at all the test Reynolds numbers, the boundary layer over the wing surface must be largely turbulent. Leaving aside for the moment the possibility that the roughness drag increment may vary with Reynolds number, one can say however that for the roughness band to be fully effective in provoking transition at the band, the variation of C_D with R should be roughly parallel to the predicted curve for the turbulent skin friction plus wave drag. As would be expected, the Reynolds number above which this state of affairs is established increases as the roughness height is decreased: for example, from Fig. 4 for M = 2·0, this condition is achieved almost at the lowest test Reynolds number, i.e., above about $R = 2{\cdot}8 \times 10^6$ with the largest roughness tried (0·0083" - 0·0099") but not until about $R = 6 \times 10^6$ with the smallest roughness (0·0049" - 0·0060").

It should be noted that a distinction can be drawn between the values of R for which C_D with a given roughness band reaches a maximum and the somewhat higher values of R above which the variation of C_D is similar to the turbulent skin-friction curve. For a model of the present shape with a wide variation in local Reynolds number across the span, it is only to be expected that there will be quite a wide transitional range of Reynolds number between the value at which the roughness band first begins to exercise an effect on the transition position and the value at which it has finally provoked immediate transition over the whole span. Clearly this process is not complete at the Reynolds number corresponding to the maximum C_D on any given curve and hence these values can only be used to provide a very broad general indication of how the roughness grade required to fix transition may vary with Reynolds number and Mach number. To obtain consistent drag data with any hope of being able to estimate a roughness drag penalty, one must aim to be on the part of the curve where the variation with R is similar to that for the turbulent skin-friction drag.

At Mach numbers below 2·0 (Figs. 2,3), the trends are broadly similar to those at M = 2·0 although as expected, the Reynolds number range over which a given roughness height is apparently effective in fixing transition increases as the Mach number is decreased. This trend is also observed above M = 2·0 (Figs. 5,6), but at these higher Mach numbers and particularly M = 2·2, the interpretation of the measured results is not as clear cut as at M = 2·0. For example, at M = 2·2, as shown in Fig. 5, the curves for the two smallest roughness heights (0·0049" - 0·0060" and 0·0060" - 0·0070") do not appear to be running parallel to the predicted curve even at the highest test Reynolds number, $R = 7{\cdot}5 \times 10^6$. This is despite the fact that the steep increase in C_D with R is complete for these two curves by $R = 5{\cdot}5 \times 10^6$. In other words, the distinction between the Reynolds number for maximum C_D and the Reynolds number beyond which the turbulent skin-friction trends are achieved becomes more marked with increasing Mach number. This is possibly what one would expect from the fact that with increasing Mach number, it becomes steadily more difficult to provoke a turbulent boundary layer. In the present testing, M = 2·2 and a stagnation pressure 30" Hg corresponding to $R = 6{\cdot}5 \times 10^6$ was taken as a standard condition and the implication from the results in Fig. 5 with the different width roughness bands is that a roughness height in the grade 0·0070" - 0·0083" is needed in order to be sure that one has fixed transition over the whole span. It is clear that if no visual indication of transition position had been obtained and if only a small part of Fig. 5 had been obtained, one might easily have drawn a completely erroneous conclusion that a roughness height of only 0·0049" - 0·0060" would have been adequate.

The next noteworthy point in Fig. 5 is that the variation of C_D with R with a roughness height of 0·0070" - 0·0083" is much the same for the "minimum band" as for the original wide band - although as discussed later, there is a difference in the absolute values. This suggests that the roughness height needed to fix transition is not critically dependent on the width of the roughness band. It will be recalled that the spanwise extent of this "minimum band" was defined as the part of the span for which transition did not occur naturally near the leading edge at $R = 6{\cdot}5 \times 10^6$. The fact that the variation of C_D with R is so nearly the same for the minimum band as for the wide band of the same roughness height suggests that even at $R = 4{\cdot}3 \times 10^6$, the proportion of the span over which a roughness band is needed is still much the same as at $R = 6{\cdot}5 \times 10^6$. This is indeed borne out by the measured values of C_D, transition free, which imply that the skin friction even at the lowest test Reynolds number is still much closer to the fully turbulent than to the fully laminar value. It is also interesting to note that the variation of C_D with R with the "minimum band" remains closely similar to that with the wide band of the same roughness height for the other test Mach numbers (with a slight reservation about the results at $M = 2{\cdot}4$). From the point of view of practical testing, these results are very encouraging because they suggest that if one can establish the extent of a minimum band that is needed to cope with one particular Mach number, this should continue to be fairly suitable at other conditions provided one does not go outside the range in which that particular roughness height remains effective in fixing transition.

Turning now to the transition-free results, it is clear that these all lie in the upper part of the transitional range from the fully laminar to fully turbulent state. For example, for $M = 2{\cdot}0$ in Fig. 4, the fully laminar curve is well off the lower left-hand corner of the graph. However, although the boundary layer is evidently largely turbulent even at the lowest test Reynolds number, the forward movement of transition over the outer part of the span with increasing Reynolds number must occur relatively slowly since even in the highest part of the Reynolds number range, C_D is still sensibly independent of R instead of decreasing in sympathy with the turbulent skin-friction curve. It follows that even at the highest Reynolds number of the tests on the present wing, it is not possible to dispense with a roughness band altogether. These deductions from the transition-free drag results have been confirmed by a limited number of acenaphthene sublimation photographs, e.g. the example reproduced in Fig. 7(a) confirms the existence of an area of laminar flow over the outboard wing at the higher Reynolds numbers while other photographs confirmed that

there/

there was fully turbulent flow over a large part of the inboard wing at the low Reynolds numbers. Somewhat surprisingly, the results for $M = 1 \cdot 6$ in Fig. 2 are the only ones in which any sign of the rapid increase part of the transitional curve from fully laminar to fully turbulent appears within the test Reynolds-number range. If this trend was going to appear anywhere in the present results, one would have expected to find it at $M = 2 \cdot 4$ rather than at $M = 1 \cdot 6$.

3.3. Roughness height Reynolds number required to fix transition

As noted above, the Reynolds number at which roughness of a certain height is just adequate to fix transition over the complete span corresponds to where the measured C_D - R variation first becomes sensibly parallel to the predicted variation for the turbulent skin-friction drag. This point cannot however be determined from the curves with any great precision and in any case, as we have seen, it is dependent on when a localised area of laminar flow is eventually suppressed near the wing tip. It could therefore depend very critically on the particular planform of the wing under consideration. For these reasons, it seemed that less scatter in the analysis would be obtained if one considered the values of the roughness Reynolds number R_k at which C_D for a given Mach number and roughness height reached its maximum. These values of R_k are based on the local flow conditions outside the boundary layer and a reference length k and are plotted in Fig. 8. As might be expected, there is still a certain amount of scatter for any one Mach number but the trend of R_k increasing with M is quite definite - from a value in the region of 1 000 at $M = 1 \cdot 6$ to 1 800 at $M = 2 \cdot 4$. These results may be compared with the values given in Ref. 6 for R_k required to fix transition just downstream of the roughness band on a flat plate. It is found that the present results are about 25% greater than the R_k of Ref. 6 and show a very similar increasing trend with Mach number. It must be stressed that the values in Fig. 8 have only been shown to be applicable to the present wing planform with its particular variation of leading-edge sweep and further, once again it must be emphasised that if a roughness height is chosen on the basis of the values in Fig. 8, this will not be sufficient to ensure that the measured drag is on a curve parallel to the turbulent skin-friction characteristic. The values of R_k - and hence, roughness height - required to achieve this can be anything from 5% to even possibly 50% greater than those shown in Fig. 8 with again, a tendency for the discrepancy apparently to increase with Mach number.

3.4. Roughness drag increments

The measured drag results can now be analysed to assess the drag increments due to the different roughness bands applied and to see which factors are the most significant. To do this, it is better not to take the tests in the chronological order in which they were performed, i.e. the order set out in Section 2.2, but to start by considering the results with the smallest band that has been shown to be effective in fully fixing transition. This is test (d) with the sparse minimum band together with the additional nose roughness; this test gave the single result at $M = 2{\cdot}2$, $R = 6{\cdot}5 \times 10^6$ shown in Fig. 5.

At first sight, one should compare this result and the data with the other roughness bands with the predicted dotted curves made up of the turbulent-skin-friction-drag estimate and the pressure drag as deduced from the tests on the larger model in the R.A.E. 8 ft tunnel. This begs the question however of whether the genuine C_{D_F} or C_{D_W} for the two models is actually the same and it is suggested that for this one standard condition of $M = 2{\cdot}2$, $R = 6{\cdot}5 \times 10^6$ at least, the more reliable yardstick for the datum drag with no roughness should be the value derived from the transition-free test. This is obtained by taking the measured drag from this test and then correcting it to what it would have been if the boundary layer had been turbulent everywhere. For these correction calculations, it was assumed that fully laminar boundary-layer flow existed on the outboard region of the wing as indicated in Fig.7(a). This makes the assumption that sublimation of acenaphthene takes place at the front of a transition region.* However, any other assumption would give a larger correction and balance results show this to be very unlikely. Corrections for a possible region of laminar flow near the nose has not been applied because of insufficient evidence of the extent of such areas. This process gives $C_D = 0{\cdot}0076$ as the datum for $M = 2{\cdot}2$, $R = 6{\cdot}5 \times 10^6$ as compared with 0·0073 on the predicted curve based on the wave drag deduced from the 8 ft tunnel tests. This discrepancy will be discussed later in Section 3·5 but for the moment, it will be assumed that the higher value of 0·0076 deduced from the transition-free test is the appropriate starting point from which to consider the roughness drag increments.

Test (d) with the sparse minimum band and the additional nose roughness gave $C_D = 0{\cdot}0077_5$ for this condition of $M = 2.2$, $R = 6.5 \times 10^6$. The more comprehensive test (c) with the same sparse minimum band but without the nose roughness gave a value of $C_D = 0{\cdot}0076$. Particularly in the light of the results to be discussed below, it seems improbable that the very small roughness band (0·04" wide) round the nose, 0·25" back from the tip can have contributed a roughness drag penalty of as much as 0·00015 and hence, it seems probable that these results have confirmed that without the nose roughness, as suggested by the acenaphthene pictures, a small area of laminar flow is present. The evidence on this point is not as comprehensive as one would like but it seems that one should regard the agreement between the result with just the sparse minimum outboard band and the suggested datum no-roughness value as slightly coincidental and it would be better to increase the results from this test by something like 0·0001 - 0·00015 to allow for a possible small area of laminar flow.

The main conclusion therefore so far is that with the smallest band that is fully effective in fixing transition, the roughness drag penalty is probably about 0·0001 to 0·00015 in C_D. As noted earlier, it is considered that this band had the smallest width practicable (0·04"), was limited to that part of the span where transition was not occurring

naturally/

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*Fortunately the transition front in this case was either at the leading edge for the inboard section or behind the trailing edge for the outboard section and so the problem of estimating the skin friction in the transition region did not arise.

naturally near the leading edge and finally, was applied reasonably sparsely with a density of something like 24 Ballotini balls per inch length of band. It follows that for this particular model, the roughness drag penalty cannot be reduced below a figure of something like 0·00015 for this standard condition of $M = 2{\cdot}2$, $R = 6{\cdot}5 \times 10^6$. In principle, it could be argued that this result taken by itself could be giving a rather favourable picture because application of a sparse band of the smallest possible width and height to suit one standard condition could be a dangerous practice when one is required to test a model over a range of operating conditions. There is a possibility that for lower Reynolds numbers or higher Mach numbers, the band will not be fully effective in fixing transition while for higher Reynolds numbers, it is possible that the drag penalty might be greater than that quoted and certainly greater than the minimum possible by reoptimising the band for the higher Reynolds number condition. In practice, therefore, one may want to use a band that is not quite so tailored to one particular condition and which is a better compromise for a range of conditions. Hence it is important now to consider what the present results imply as regards the extra penalty that may be produced if one departs from the optimum band. This can be done under three headings, viz. density of application, extent of band and finally, roughness height.

3.4.1. Effect of density of roughness application

Some evidence on this is provided by the results for $M = 2{\cdot}2$ shown in Fig. 5 for the two "minimum bands" with alternatively, the sparse application of something like 24 Ballotini balls per inch length of band as compared with the standard thin application of roughly four times that number. It will be seen that at the higher Reynolds numbers where both bands are equally effective in fixing transition, the denser application appears to contribute a further 0·00015 increase in C_D, i.e., the minimum band with the standard thin application probably contributes about 0·00025 - 0·0003 in C_D allowing for the possible laminar flow area near the nose.

Clearly, therefore, to achieve a small roughness drag increment, it is important to apply the roughness as sparsely as possible. The results in Fig. 5 contain a warning however that the density of application may also affect the choice of roughness height required to fix transition. It may be noted that with the standard thin application, the maximum point on the C_D - R curve occurs at about $R = 4{\cdot}3 \times 10^6$ but with the sparse application, this condition is not reached until about $R = 5{\cdot}5 \times 10^6$. It follows that for the standard condition of $R = 6{\cdot}5 \times 10^6$, with the sparse application, the choice of a roughness height in the range 0·0070" - 0·0083" was probably about the smallest that was acceptable; with the standard thin application however one could probably have gone to a slightly smaller roughness. Hence the drag benefit from a sparse application of a given height has to be set off against the possibility of an increased drag increment due to having to choose a somewhat larger roughness height. Prejudging the results still to be discussed however it is still likely that in general, even when one has allowed for this factor, the sparse band will still appear the better.

One other point can be made tentatively by comparing the results in Fig. 5 for the two minimum bands. Earlier, it was seen that when a band was fully effective in fixing transition, the measured C_D - R

characteristic/

characteristic roughly followed the predicted variation in the turbulent skin-friction drag. In general, however, there is a tendency for the decrease in C_D with R to be less marked in the measured results; this trend appears to become more pronounced with increasing Mach number. One interpretation of this detailed discrepancy is that the roughness drag increments which we have so far been quoting for the $R = 6{\cdot}5 \times 10^6$ condition do in fact increase with Reynolds number. One cannot be certain about this because of the discrepancy already noted between the transition-free derived result and the estimate based on the 8 ft tunnel pressure drags: without knowing the source for this particular discrepancy, it is always possible that it is this discrepancy which is increasing with R rather than the roughness drag increment. Even so, it is of interest to note that the trend for the C_D - R variation to depart a little from the turbulent skin-friction variation is less pronounced in the test with the very sparse roughness application. This is a very fine distinction and probably not justified by the accuracy of the experimental results but it could be a slight pointer that the roughness drag increment does increase slowly with Reynolds number and that this trend also can be reduced by making the roughness application as sparse as possible.

3.4.2. Effect of roughness-band extent

Some evidence on the effect of roughness-band width and extent can be obtained by comparing the results for the standard minimum band, i.e. test (b), with those for the original wide band having the same roughness height. Figs. 2 - 6 show that the increase in drag in going to the full-span wide band is very considerable, varying from about 0·0003 at $M = 1{\cdot}6$ to 0·0004 - 0·00045 at the higher Mach numbers. With the wide, full-span band, no laminar flow should have been present near the nose and therefore to obtain the roughness drag increment at the standard condition of $M = 2{\cdot}2$, $R = 6{\cdot}5 \times 10^6$, one can do a direct subtraction from Fig. 5 and obtain a value of 0·0006, as compared with the figure of 0·00025 quoted earlier for the minimum band with the same density of application.

It is clear therefore that the wide full-span band is giving a very sizeable drag penalty but the difficulty comes in trying to interpret which factor is largely responsible since in deriving the minimum band, changes were made both to the width and to the spanwise extent of the band. It could be argued that a large part of the drag improvement with the minimum band comes from the removal of the useless inboard part of the roughness band and of the streamwise roughness at the tips. In the absence of a direct comparative test with different band widths, no definite conclusion regarding the effect of band width can be drawn although again it seems plausible that this is a significant factor. Another point to be remembered is that these comparative results are with the standard roughness application; with a sparser application, the increased penalty from a full-span wide band might well have been less.

One other point to remember about the effect of roughness-band width is that apparently, it has no major effect on the roughness height required to fix transition. The slight differences between the values of R for maximum C_D are of little significance; what may be more important is

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the trend visible particularly at $M = 2{\cdot}4$ in Fig. 6 for the results with the minimum roughness band to lie more nearly parallel to the C_D - R variation for the turbulent skin-friction drag than do the results with the corresponding wide, full-span band. This may imply that as the band width and extent are increased, there may be an increased tendency for the roughness drag increment to become more sensitive to changes in Reynolds number.

3.4.3. Effect of Roughness Height

The evidence on this has to be taken from the comprehensive tests made over the full Mach number and Reynolds number range with wide, full-span bands of the four different heights specified in Section 2·2. In making this comparison, one has to be careful that one is comparing results for two or more bands that are both fully effective in fixing transition and so in this context, one should possibly look first at the results for $M = 2{\cdot}0$ in Fig. 4 rather than those for the higher Mach numbers such as $M = 2{\cdot}2$. The results in Fig. 4 suggest that within the experimental accuracy, the height of the roughness band does not have a significant effect for three of the four grades tested but with the largest height (0·0083" - 0·0099"), an additional drag increment of about 0·00015 in C_D is obtained. These conclusions do not appear to depend significantly on Reynolds number; the changes with Reynolds number that are evident appear to be more a function of whether the bands are being fully effective in fixing transition.

For the lower Mach numbers, very similar results are seen in Figs. 2, 3 although the extra drag increment with the largest grade does not appear to exist. At the higher Mach numbers, the situation at first sight does not appear to be so tidy. However, this is largely because the two smallest grades tested do not appear to be adequate in fixing transition except at the extreme top end of the test Reynolds number range. At $M = 2{\cdot}2$, Fig. 5, the results for all the roughness grades appear to meet on a common curve at the maximum test Reynolds number and it might be expected that they would continue together along a common curve roughly parallel or perhaps more probably, diverging slowly from the turbulent skin-friction curve at higher Reynolds numbers, i.e., reproducing the trend evident at the lower Reynolds numbers at the lower Mach numbers. At $M = 2{\cdot}4$, Fig. 6, the results are very similar showing an even slower progression of the curves towards the fully fixed curve obtained with the maximum roughness grade.

The general conclusion from these results therefore is that the roughness drag penalty for a band of given width and extent does not appear to be extremely sensitive to the roughness height chosen, provided always that this height is sufficient to fix transition everywhere, i.e., provided the results under consideration are on the part of the C_D - R characteristic that lies roughly parallel to the turbulent-skin-friction-drag curve. This is an important and encouraging result because in practice, for a test programme over a range of Mach number at approximately constant Reynolds number, one would have to choose the roughness height that would fix transition at the highest Mach number and then, it might be feared that one

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was having to accept an unnecessarily large roughness drag increment at the lower test Mach numbers. On the present evidence, this seems unlikely (a conclusion also stated in Ref. 1). Obviously, there must be an upper limit to the roughness height that can be accepted without an extra penalty. The results with the largest grade, 0·0083" - 0·0099", at M = 2·0 in Fig. 4 suggest that this condition may have been reached in this instance although since this trend is not evident at the other test Mach numbers, one can almost say that it lies outside the range covered in the present investigation.

3.5. Model Wave Drag

Values for the wave drag at zero lift for this particular model have been derived from the curves in Figs. 2-6 by subtracting the estimated turbulent skin-friction drag from the results obtained with the standard minimum outboard band. As noted earlier, these results should be substantially the same as those that would have been obtained using a sparse minimum outboard band together with an additional band round the nose in order to induce a turbulent boundary layer everywhere. This direct subtraction of the curves should give, leaving aside any question of the roughness drag increment, the wave drag of the model including its balance shroud. The real objective of the test would be to obtain the wave drag for the wing itself and so these results have been further corrected for the presence of the shroud, using the corrections given in Ref. 3. The resulting apparent wave drags are plotted against Mach number in Fig. 9 and compared with those obtained by integration of the pressure plotting data on the larger scale model[3]. Also included is the result for M = 2·2 derived from the transition-free test on the present model.

The apparent wave drags deduced from the tests with the minimum roughness band still include a roughness drag penalty which as noted earlier to judge from the comparison at the transition-free point, amounts to about 0·00015 in C_D at M = 2·2 with probably little variation with Mach number. This still leaves unexplained a discrepancy of 0·0004 at M = 2·2 between the results for the two models which increases as the Mach number is decreased to become as much as 0·0006 at M = 1·6. It seems quite implausible to suggest that the value from the transition-free test and the conclusion that the roughness drag increment for this minimum band is about 0·00015 are both in error by this amount. To argue this way would imply that the minimum roughness drag penalty could be as much as 0·0005 which seems quite unrealistic in the light of the magnitude of the additional penalties that have been observed when the size of the roughness band is increased. The comparative evidence from the tests with the different roughness bands all suggest that the initial starting figure of 0·0001 - 0·00015 as a basic minimum penalty is much more likely.

One is forced then to the conclusion that the genuine wave drag (or friction drag) of the two models differs by an amount varying from 0·0006 at M = 1·6 to 0·0004 at M = 2·4. Other test evidence from unpublished work by Mabey of R.A.E. Ref. 4, has shown similarly high drag results at two Mach numbers for the same model (see Fig. 9). Inspection of the model has shown a certain amount of leading-edge warp but very little error in wing volume and certainly not enough to account for the above discrepancy in terms of a wave drag due to volume. No definite conclusion can therefore be drawn as to the reason for the discrepancy between the results for the two models. The important point in the present context however is that the presence of this discrepancy does not seem to case any serious doubt on the conclusions drawn earlier regarding the probable roughness drag increments.

4. DETERMINATION OF ZERO-LIFT WAVE DRAG OF SIMILAR MODELS

The following method is suggested when starting to test slender-wing models of a new design:

(1) Obtain an acenaphthene-indicator test photograph near the maximum Reynolds number at the design Mach number, transition free. From this picture, determine the regions where it is necessary to fix transition artificially.

(2) Using the values of R_k given in Fig. 8, calculate the roughness height required at the design Mach number for a freestream Reynolds number about 80% of the test Reynolds number. Check that this roughness height is of the same order (±25%) as the boundary-layer height at the front of the roughness band.

(3) Apply this roughness grade sparsely in as narrow a band as possible near the leading edge in the regions indicated in (1).

(4) Obtain C_D versus R results with this roughness band and check that the shape of the resultant curve near the Reynolds number to be used in the main tests corresponds closely to the variation predicted for the turbulent skin-friction drag.

(5) Assuming condition (4) has been met satisfactorily, the results will still include a roughness drag penalty which is likely to be in the region of 0·0001 - 0·0003 in C_D depending on the area of band that has had to be applied. The results obtained in the present tests should be useful as a guide in this context.

(6) For other Mach numbers, C_D - R curves should also be determined primarily to check that at higher Mach numbers, the selected roughness band is fully effective in fixing transition but also to see whether at lower Mach numbers, the curve is still reasonably parallel to the predicted variation of the turbulent skin-friction drag. Provided a narrow, sparse band has been used, the results should be satisfactory on this last count and there is little likelihood that the roughness drag increment will be any larger than that predicted for the design Mach number.

5. CONCLUSIONS

The precise quantitative results regarding the size of roughness band required to fix transition and the roughness drag penalty present with this and other bands are of course to some extent peculiar to the particular wing that has been tested but nevertheless, it is possible to draw certain general conclusions from the investigation.

Provided the roughness band is effective in fixing transition over the whole span, the results have shown that one can obtain a C_D - R relationship at a given Mach number that is broadly similar to that predicted for the turbulent skin-friction drag. The Reynolds number above which this result applies can be significantly greater than the Reynolds number at which C_D is a maximum. For the present wing, this factor can vary from about 5% at M = 1·6 to 30% or more at M = 2·4. Nevertheless, the Reynolds number at which C_D is a maximum can usually be determined more precisely and converting these values to a roughness-height Reynolds number R_k gives the values plotted in Fig. 8. These critical values of R_k range from about 1 000 at M = 1·6 to about 1 800 at M = 2·4 and are about 25% greater than those obtained by van Driest and Blumer of Ref. 6. A cautionary note should be added however that these values were obtained from the tests with roughness bands in which the roughness application was thin but not sparse and there is some evidence that the really sparse distributions which are preferable from the point of view of minimising the roughness drag increment could demand larger values of R_k and hence larger roughness heights to fix transition effectively. There are therefore two reasons why in practice, the roughness height required for tests on slender wings at say, M = 2·2 could be some 30% - 50% greater than that given by the curve in Fig. 8.

The results have shown that in tests at near 30" Hg stagnation pressure with slender-wing models of about 2 ft root chord, it will probably not be necessary to fix transition artificially over the whole span. If care is taken to apply the band over merely that part of the span for which it is required and to use as small a band width as possible (say, 0·04" on a model of this size) and to apply the roughness as sparsely as possible (say, 25 grains per 1 in. length of band) then there is a good chance that the roughness drag increment can be kept to near 0·0001 in C_D. At the worst, it is unlikely to exceed 0·0003. On the other hand, if wider, full-span bands are used such as was normal practice some time ago, the roughness drag increment can easily be as large as 0·0006 - 0·0008. A fortunate result from the practical viewpoint is that the drag increment does not appear to depend very critically on the actual roughness height - at least, within certain undefined limits. This means that in practice, the roughness height can be selected to fix transition at the design Mach number and then, the same roughness band can be used for tests at lower Mach numbers without incurring an unnecessarily large roughness drag penalty. If the carefully optimised sparse bands of minimum extent are used, it seems possible that the roughness drag increment may be relatively insensitive to changes in Reynolds number and Mach number.

A procedure is set out in Section 4 for establishing the most suitable roughness band for a wing of new design and for assessing the likely size of the associated drag increment.

Although the present investigation included tests with seven different roughness bands over a wide range of Reynolds number and Mach number, and took some time to complete, it cannot be described as sufficiently comprehensive even to answer all the questions for this one particular wing. For example, direct evidence on the effects of band width, other variables

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being held constant, is still desirable and so are checks against transition-free tests for a wider range of conditions. Nevertheless, it is hoped that the results and comments will have contributed a little to an appreciation of the size of problem involved.

6. ACKNOWLEDGEMENTS

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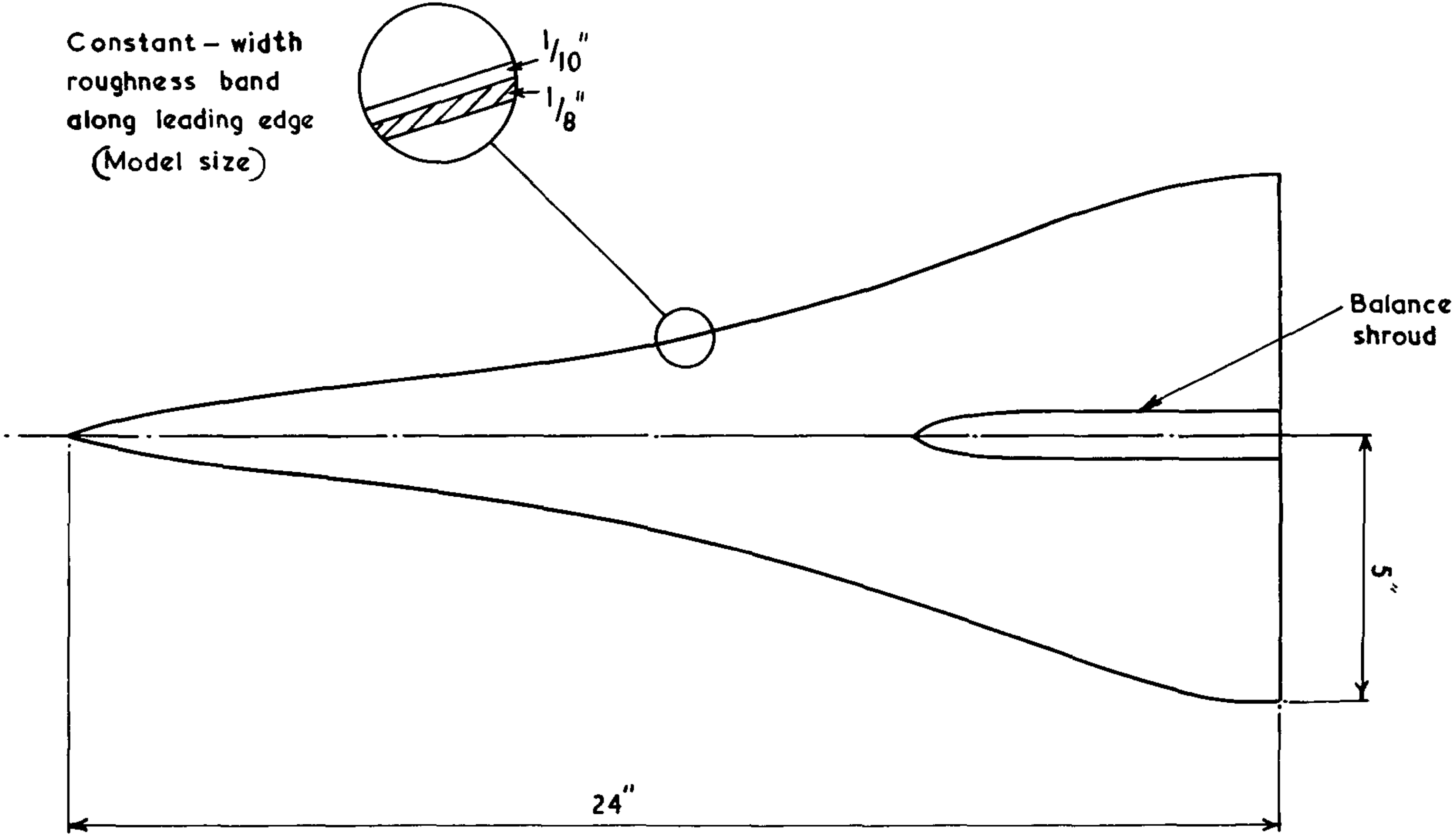

FIG.1. Symmetrical slender ogee Model 148. Wing 15.

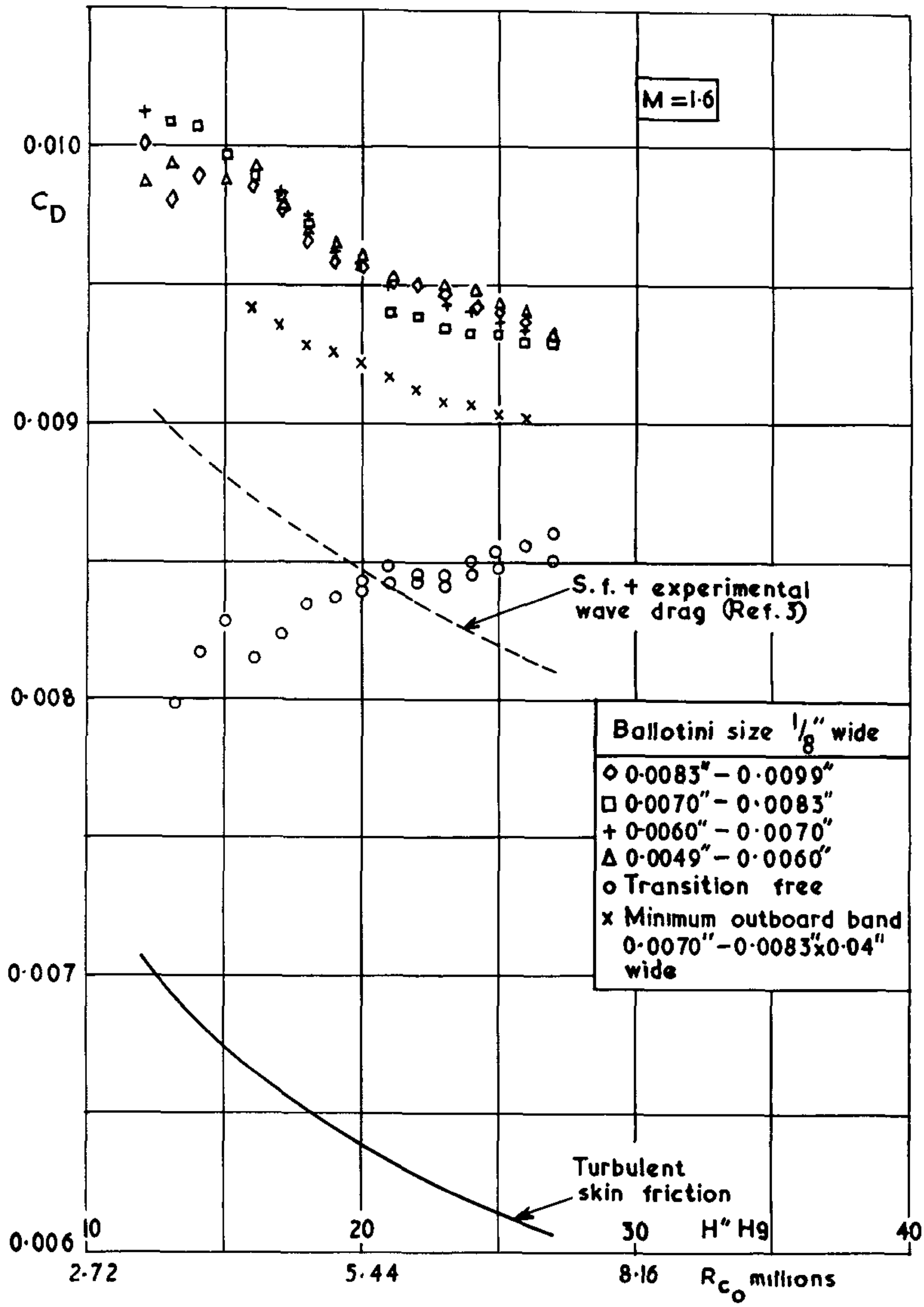

FIG. 2. Effect of transition band roughness on axial force. M = 1·6. Model 148, slender ogee planform.

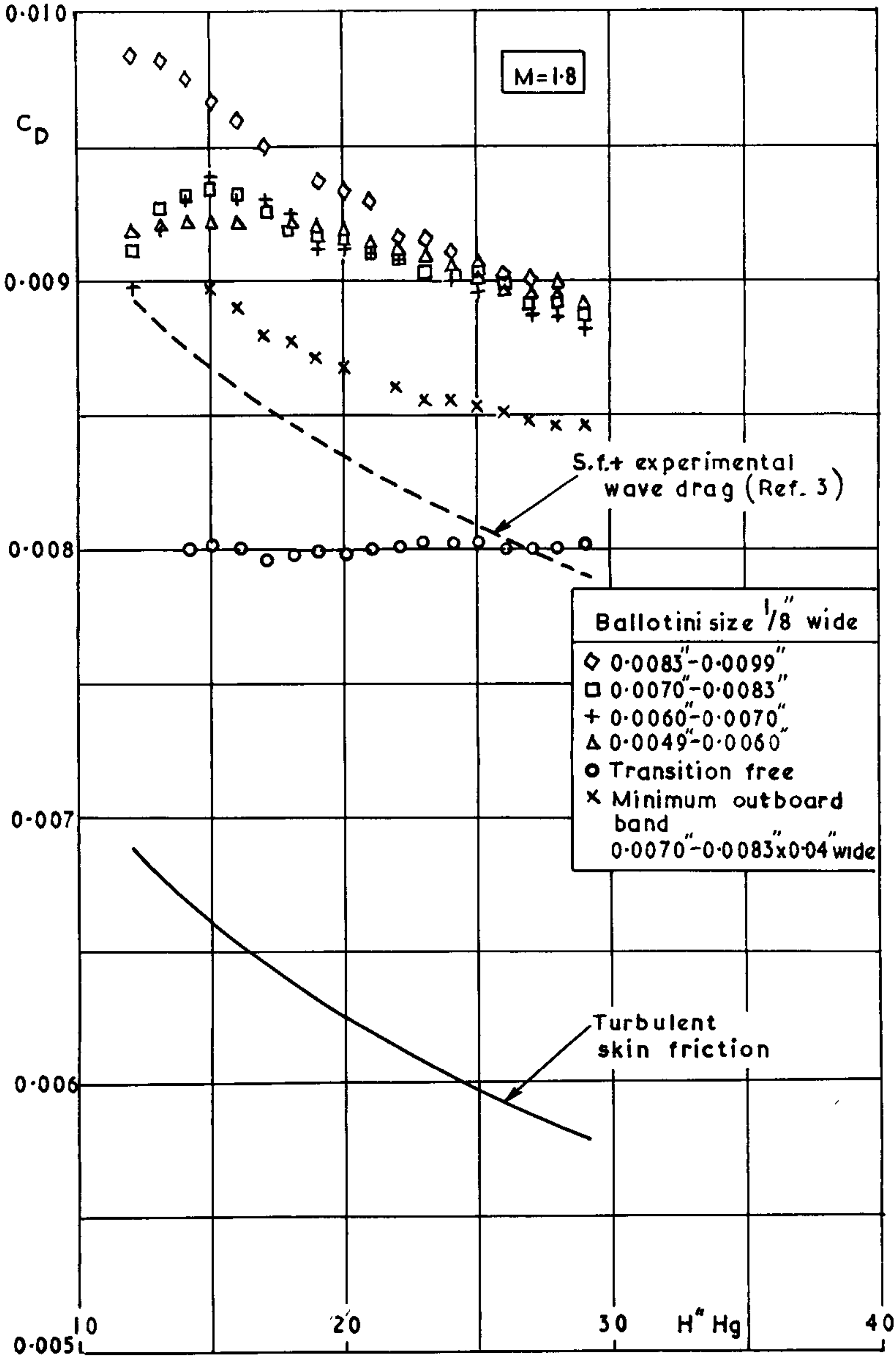

FIG. 3 Effect of transition band roughness on axial force. M=1·8. Model 148, slender ogee planform

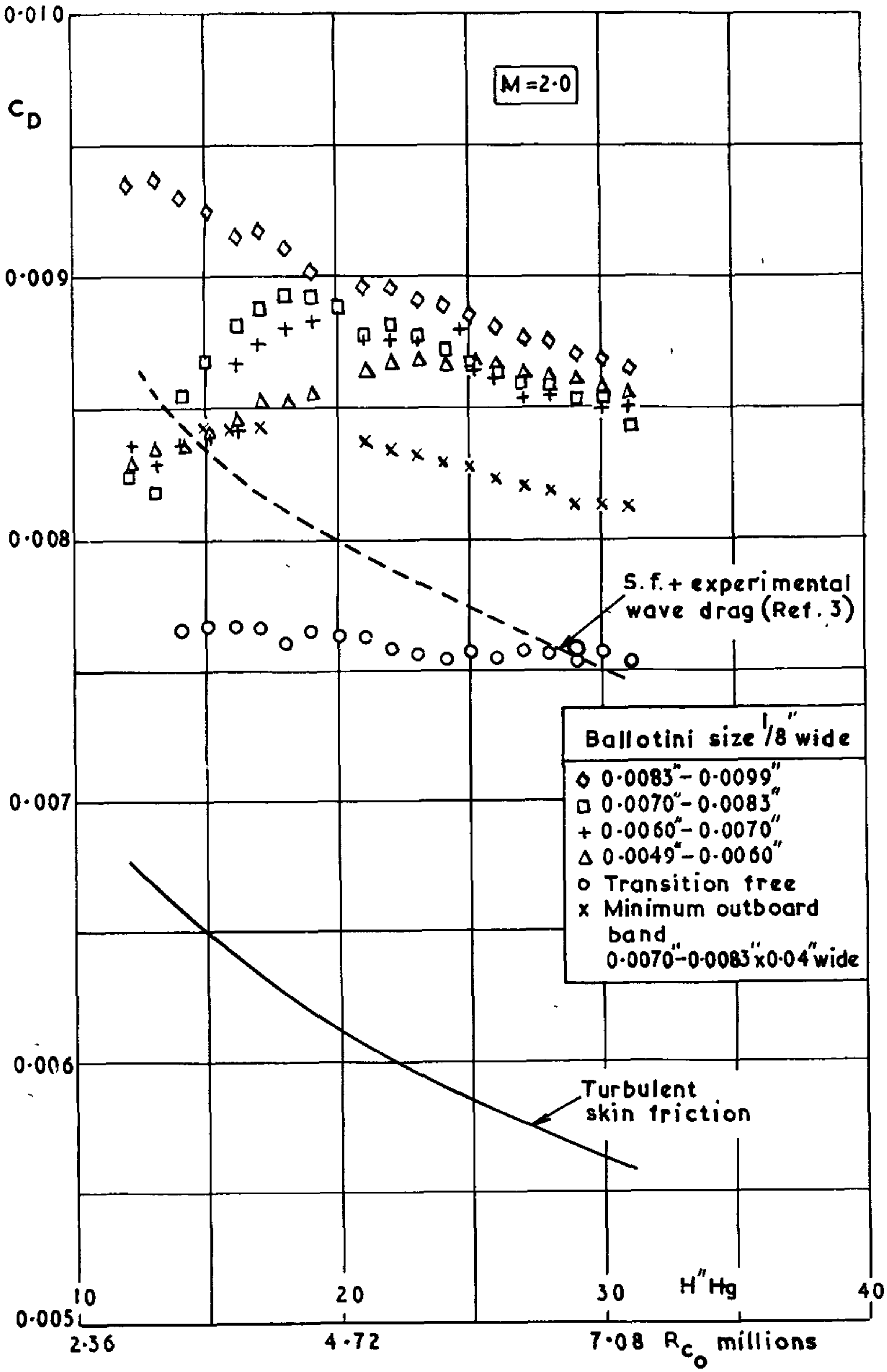

FIG. 4 Effect of transition band roughness on axial force. M = 2·0. Model 148, slender ogee planform

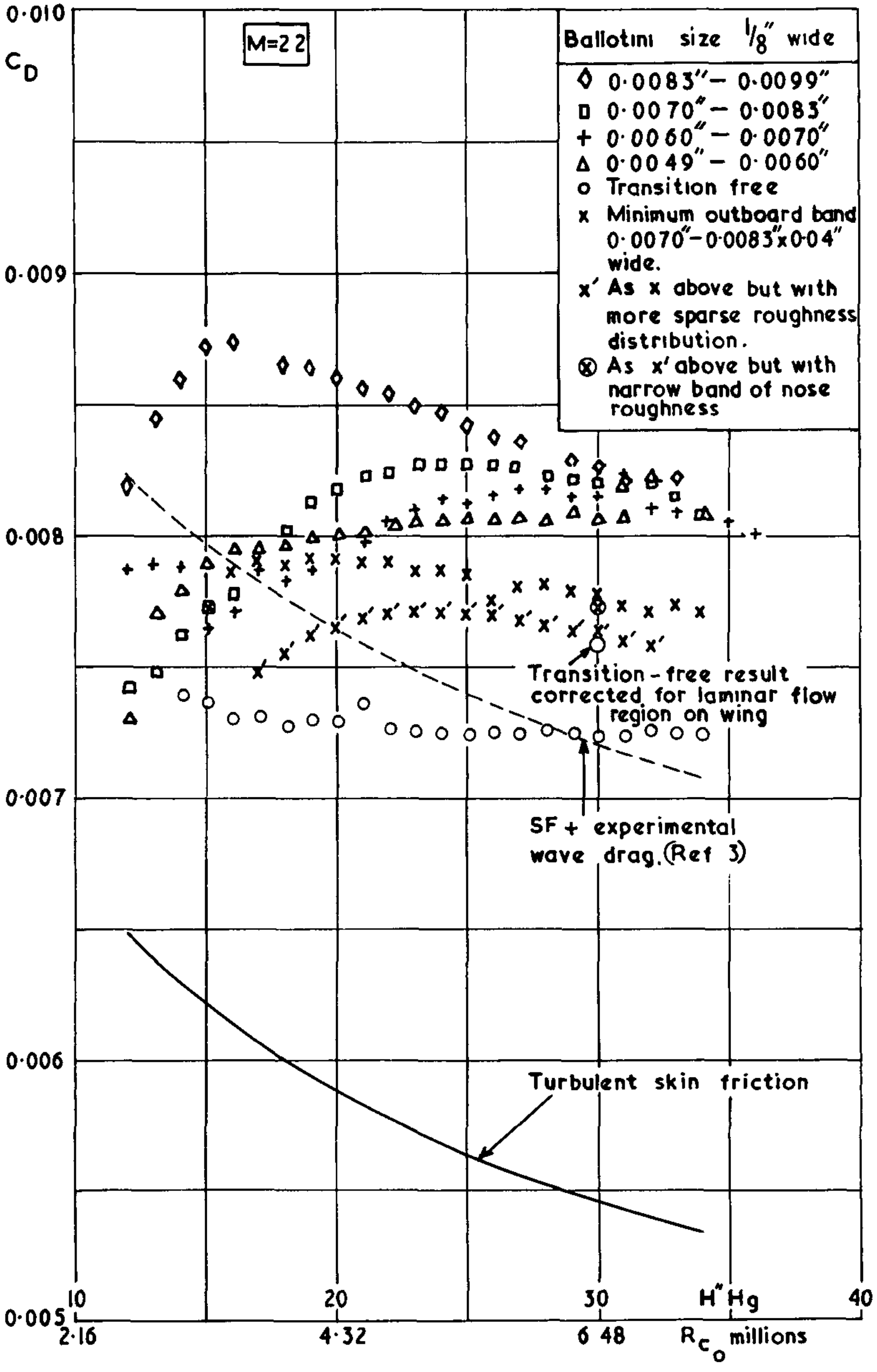

FIG.5. Effect of transition band roughness on axial force M= 2·2. Model 148, slender ogee planform.

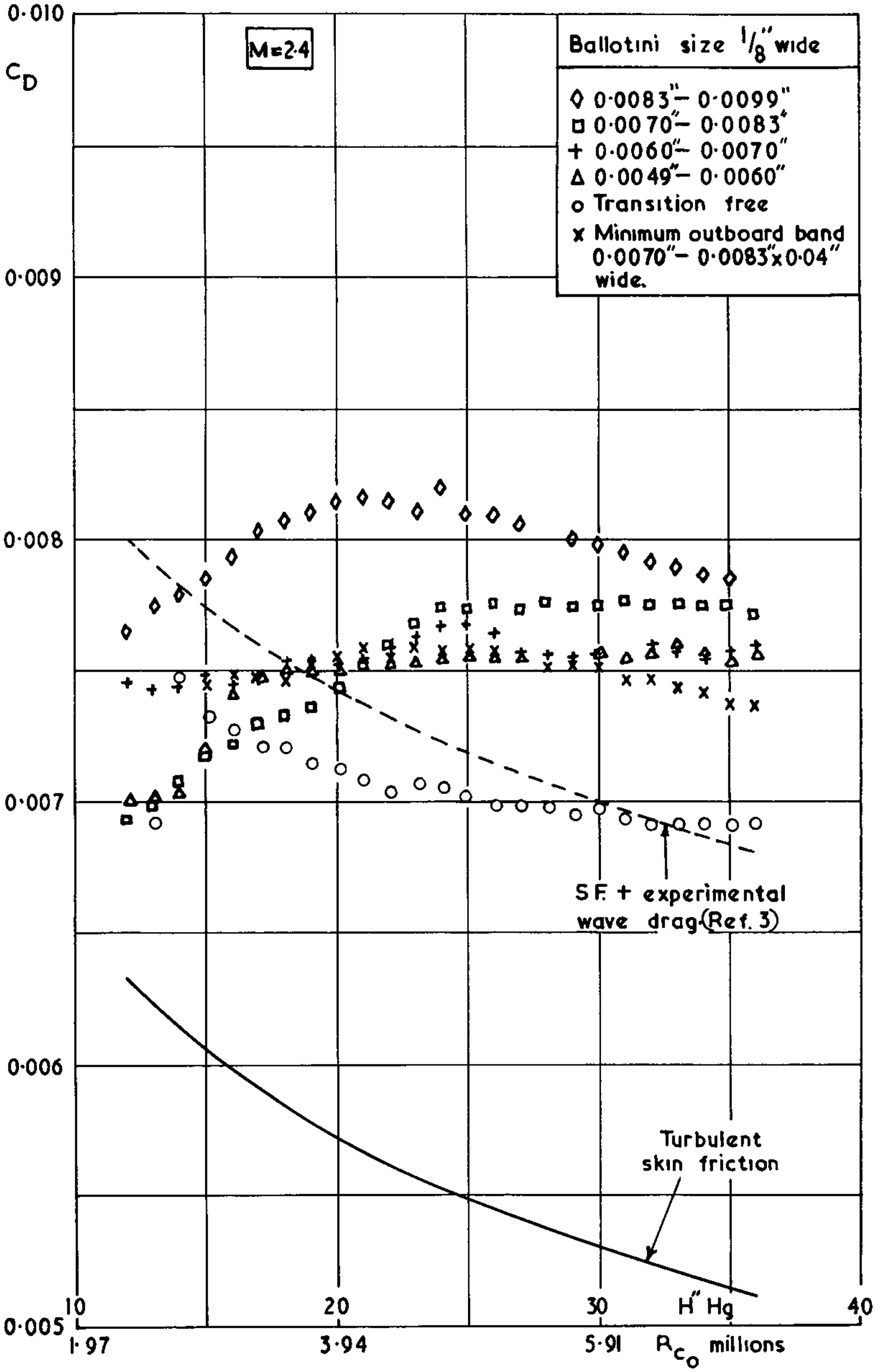

FIG. 6. Effect of transition band roughness on axial force. M = 2 4. Model 148, slender ogee planform

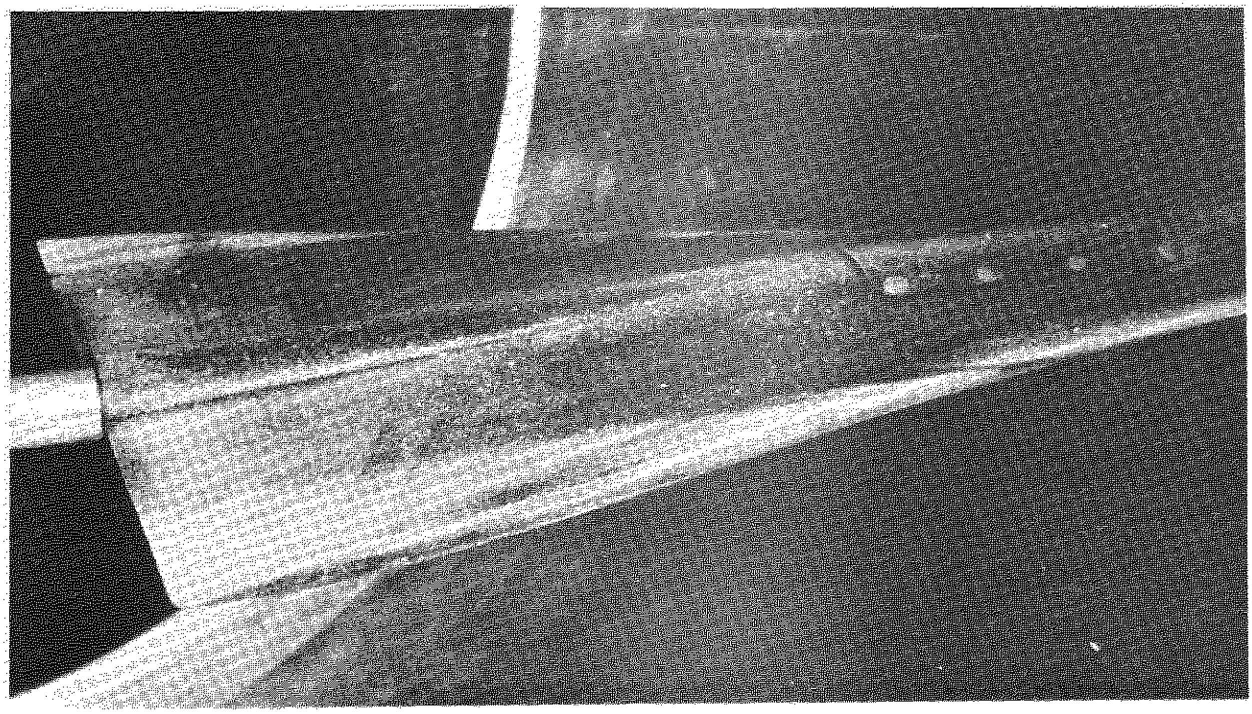

FIG. 7a Transition free — acenapthene test.

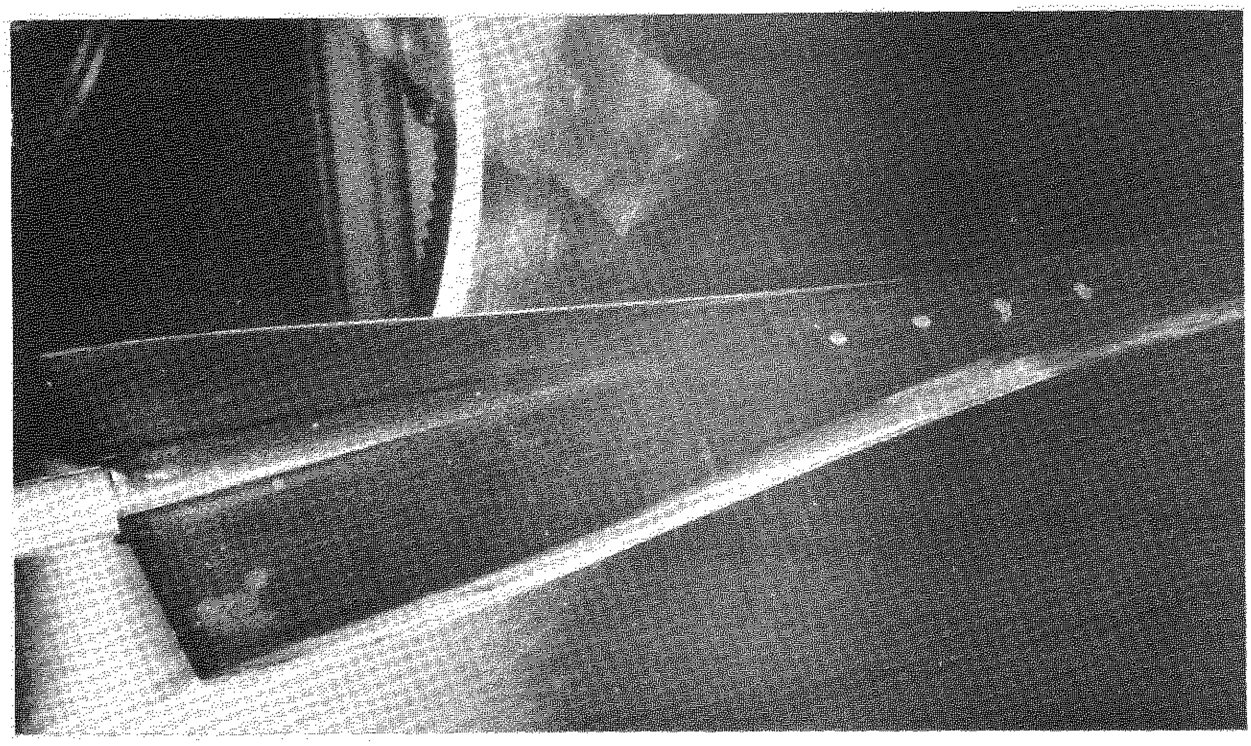

FIG. 7b Minimum band, transition fixed. Acenapthene test.

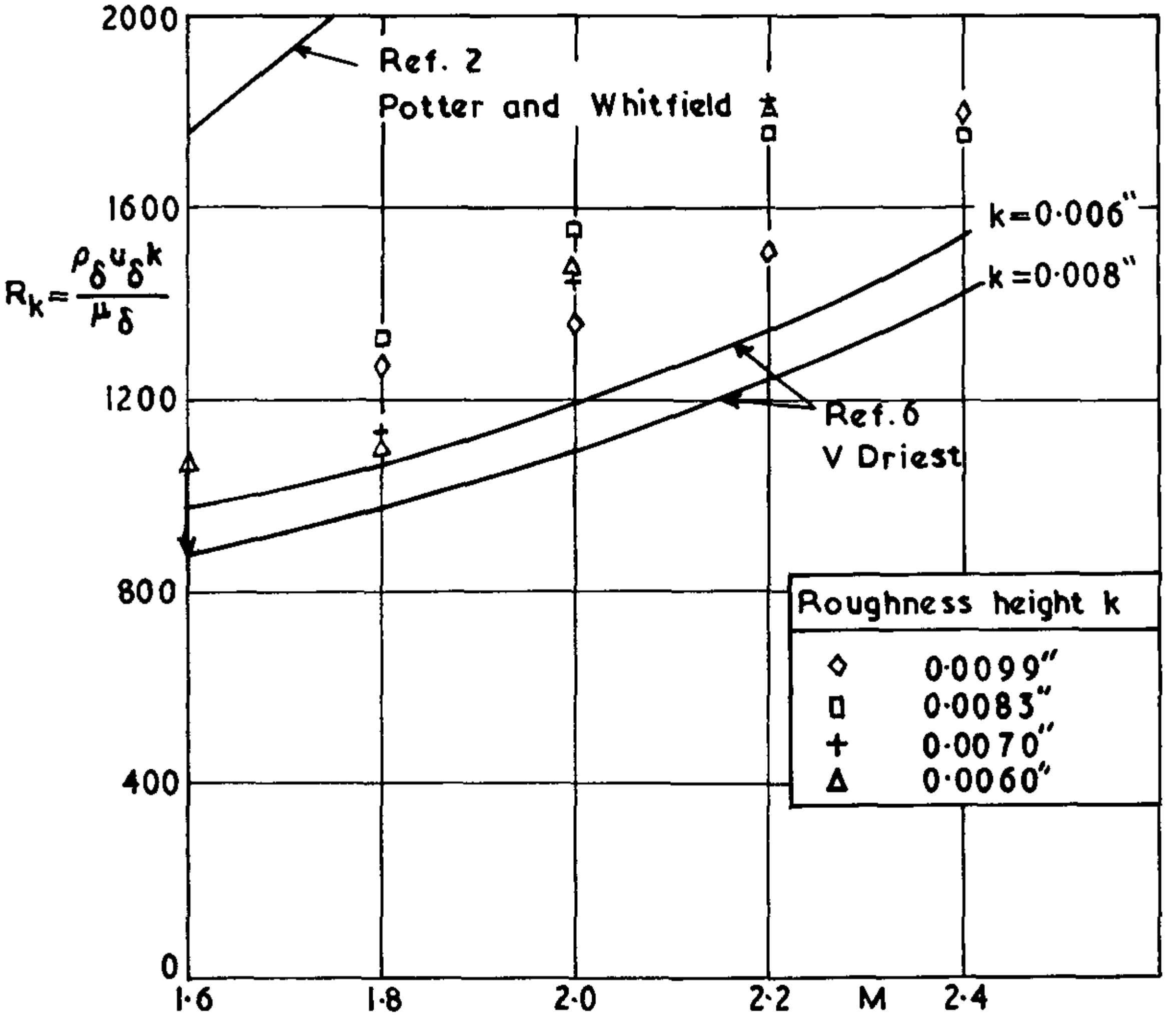

FIG.8 Roughness height Reynolds number required to fix transition up to the band for model 148.

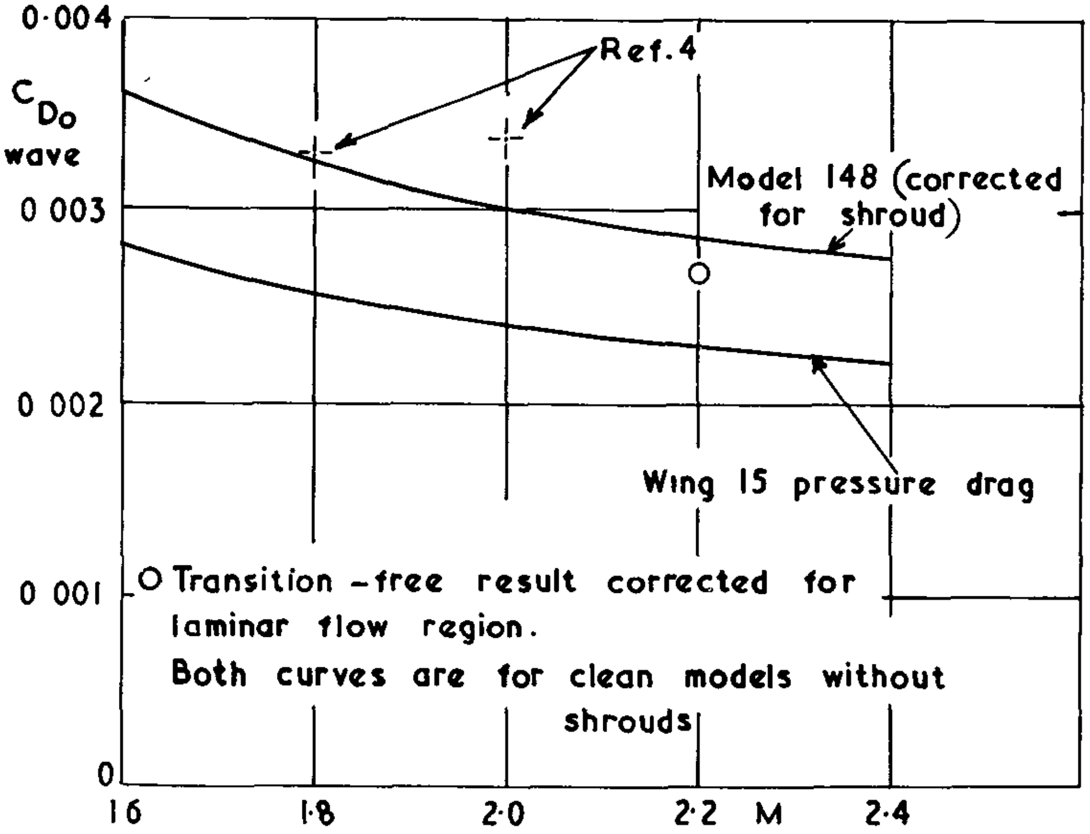

FIG.9 Comparison of measured wave drag with pressure drag.

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