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Roughness Criteria and Drag Penalties for Bands of Distributed Roughness on Two Slender Wings at Supersonic Speeds

by

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ROUGHNESS CRITERIA AND DRAG PENALTIES FOR BANDS OF DISTRIBUTED ROUGHNESS ON TWO SLENDER WINGS AT SUPERSONIC SPEEDS

by

D. G. Mabey, M.Sc.(Eng.)

SUMMARY

The variation of zero-lift drag coefficient with Reynolds number is used to determine the effectiveness of bands of distributed roughness on two slender wings at supersonic speeds.

Results show that the roughness height required to ensure fully turbulent flow up to the position of roughness increases rapidly with Mach number ($M = 1{\cdot}4$ to $2{\cdot}0$) and that the roughness drag penalties may be significant.

Wing planform and camber both influence roughness effectiveness.

Replaces R.A.E. Tech.Note No. Aero 2885 - A.R.C. 24844.

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1 INTRODUCTION

Analysis of drag measurements at supersonic speeds is difficult for slender wings because the wave drag is often much smaller than the skin friction. Skin friction estimation is hampered by unsteady heat transfer effects on free flight models[1], even under fully turbulent conditions, and by the difficulty of attaining fully turbulent conditions on wind tunnel models[2].

In wind tunnels a fully turbulent boundary layer is usually required over the complete model and so a band of distributed roughness is applied close to the leading edge to fix transition[3,4].

The present drag measurements made between September 1961 and January 1962 on two typical slender wings (Figs.1 and 2) show that the height of roughness required to ensure transition at supersonic speeds increases rapidly with Mach number. Roughness bands commonly used also have a significant drag penalty i.e. a drag increment greater than that due to the forward movement of the transition front.

2 EXPERIMENTAL DETAILS

2.1 Models

Figs.1 and 2 show the planforms and some typical sections of the wings tested. They are Wings 9 and 15 of a larger series and are fully described in Refs.2 and 5 (Table 1 gives some important details).

Wing 9 was a machined, steel model. The leading edges were in good condition and the plates covering the balance attachment fitted well. This model was symmetric.

Wing 15 was moulded in fibre glass and araldite round a steel core. The leading edges had several small notches and the plates covering the balance attachment did not fit very well. The surface finish of this model was poor compared to that of Wing 9. The model was nominally uncambered. However a non-zero C_{m_0} was detected during stability tests[5] and subsequent inspection showed that the model was slightly cambered. A larger uncambered model of this shape was tested[6] in the R.A.E. 8 × 8 ft wind tunnel, and a similar model tested in free flight[1].

2.2 Test conditions

Wings 9 and 15 were tested in the 3 ft supersonic wind tunnel at zero incidence from M = 1·4 to 2·0. Table 2 gives the range of total pressures: the low Reynolds numbers should be noted.

The first roughness used on Wing 9 was a band of carborundum grains in aluminium paint, 0·50" wide normal to the leading edge, as in earlier slender wing tests in flight[1] and wind tunnels[6,7]. The carborundum was not sieved but several inspections of sample bands showed that the highest particles were usually:

100 grade:	0·007"
60 grade:	0·012"

Subsequently, ballotini* bands 0·50" and 0·15" wide were used. The ballotini were sieved between the following limits:

Nominal 0·012" dia	(0·0083" - 0.0116")
Nominal 0·014" dia	(0·0116" - 0·0138")

The ballotini were attached to the models by a thin araldite film. The thickness of a coloured araldite film was easily judged; a typical thickness was 0·002" to secure ballotini 0·012" diameter. Ballotini form a very uniform roughness distribution when seen under a microscope whereas even carefully sieved carborundum grit gives a random roughness height. The ballotini density was about 400-600/sq in.

Only ballotini bands 0·15" wide were used on Wing 15.

2.3 Measurements and accuracy

Lift, pitching moment and axial force were measured on an internal strain-gauge balance within each model. Lift and pitching moment were used to correct for flow asymmetries and the small balance interactions on axial force. The model base pressure was measured and used to correct the axial force to free stream static base pressure.

Only the variation of zero lift drag (C_{D_o}) with Reynolds number ($R\bar{c}$) is presented.

The estimated accuracies are:

Wing 9	C_{D_o}	±0·0004
Wing 15	C_{D_o}	±0·0002

A more accurate balance was used for Wing 15.

3 RESULTS

In this section the curves of C_{D_o} vs. $R\bar{c}$ are analysed to derive criteria for transition onset and complete transition and to find the magnitude of the roughness drag penalties.

The Reynolds number for transition onset ($R\bar{c}_1$) is that at which the drag first shows a marked change in slope (e.g. $R\bar{c} = 0·9 \times 10^6$ in Fig.3a). The Reynolds number for complete transition ($R\bar{c}_2$) is the lowest value for which the curves of measured and estimated C_{D_o} for a completely turbulent boundary layer become essentially parallel (e.g. $R\bar{c} = 1·5 \times 10^6$ in Fig.3a). It is assumed that there is no further forward movement of the transition front for Reynolds numbers greater than $R\bar{c}_2$ and that the roughness drag is the difference between the measured and estimated drag coefficients for these Reynolds numbers.

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* Small glass spheres as used by Rogers et al.[8]

The estimated zero lift drag coefficients are the sum of a friction drag and a pressure drag. The estimated friction drag is the flat plate value for $R\bar{c}$ with zero heat transfer[9]*, multiplied by the ratio of wetted area to twice the planform area. The pressure drag was estimated by the slender wing theory for Wing 9 and measured on a larger model for Wing 15.

3.1 Critical roughness criteria

Fig.3 shows the variation of C_{D_o} with Reynolds number at constant Mach number for Wing 9 with 100 grade carborundum. Transition onset is sharply defined at $M = 1{\cdot}4$ but indefinite at $M = 1{\cdot}6$. At $M = 1{\cdot}8$ and $2{\cdot}0$, C_{D_o} increases slowly after transition onset and complete transition (R_2) is not achieved. Hence 100 grade carborundum is inadequate on Wing 9 at $M = 1{\cdot}8$ and $2{\cdot}0$ as Mabey and Ilott[2] had suggested, and higher roughness is required as Mach number increases.

Fig.4 shows how the roughness height for complete transition movement (the important practical question) increases with Mach number on both Wings 9 and 15. These roughness Reynolds numbers are based on free stream conditions ($R\bar{c}_1$ and $R\bar{c}_2$) and the roughness height k (i.e. $R_k = R\bar{c} \times k/\bar{c}$). The roughness Reynolds numbers for complete transition movement increase from 800 to 1,000 on Wing 9 and from 900 to 1,500 on Wing 15 as Mach number increases from 1·4 to 2·0. Measurements on Wing 15 in the A.R.A. tunnel[10] with three different ballotini diameters have confirmed that $R_{k_2} \simeq 1{,}500$ at $M = 2{\cdot}0$. This roughness height increase with Mach number follows from the increased stability of the laminar boundary layer at supersonic speeds[11] and becomes more serious at high supersonic speeds[12].

Fig.4 also shows Van Driests' estimated roughness Reynolds numbers (Ref.13 and Table 3) at which transition moves close to the roughness. Agreement between these estimates and the measured values for complete transition is excellent for Wing 9 but poor for Wing 15. These estimates predict a rapid increase in critical roughness height with Mach number - an increase larger than that given by Braslows[3,4] suggestion - that $R_k = 600$, based on conditions at the top of the roughness (Table 3).

The difficulty of fixing transition on Wing 15 compared to Wing 9 is consistent with the variation of roughness effectiveness with planform parameter on other slender wings tested in the 3 ft wind tunnel. Roughness effectiveness depends on the sweepback angle, which varies more widely along the leading edge as planform parameter p decreases. Roughness effectiveness is here related with the planform parameters.

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* Skin friction calculated by the Prandtl-Schlichting method with a Mach number correction based on intermediate enthalpy.

Variation of roughness effectiveness with planform parameter

Wing	p	"Laminar bucket"	Roughness
1	0·67	None M = 1·4 to 2·0 (Ref.7)	Carborundum Height 0·007"
5	0·58	M = 2·0 only (Ref.14)	
9	0·53	M = 1·8 and 2·0 (Ref.2)	
15	0·45	M = 1·4 to 2·0	Ballotini 0·012" dia
		None M = 1·4 to 2·0	Ballotini 0·014" dia

(Standard conditions, Table 2)

The variation of x_k/k with sweepback angle is not sufficient to explain this variation in roughness effectiveness.

The wide variation of roughness effectiveness with planform parameter indicates that a single roughness cannot be recommended for all wings. The present results may be used as a guide to the roughness required on 3 ft tunnel models at low Reynolds numbers but the roughness effectiveness should always be checked during accurate drag measurements.

Roughness is more effective on a cambered slender wing than on an uncambered wing of the same planform. Fig.5 compares the variation of C_D with Reynolds number for Wing 15 and two additional cambered wings[5] at the attachment incidence (flow attachment along the leading edge). These cambered wings have the same planform, thickness distribution and roughness as Wing 15. In contrast to Wing 15, neither of the cambered wings shows any region of completely laminar flow at low Reynolds numbers. At higher Reynolds numbers the drag on Wing 15 does not even attain the plateau observed when the roughness is barely adequate (e.g. Fig.3b), whereas the drag of the slightly cambered wing has a plateau. The drag of the heavily cambered gull wing has a maximum at about $R\bar{c} = 1{\cdot}2 \times 10^6$ and fully turbulent conditions above this Reynolds number.

Camber also improves roughness effectiveness on Wings 9, 10 and 11 [2]. These wings may be arranged in order of increasing camber and roughness effectiveness.

Variation of roughness effectiveness with camber

Wing	Camber	"Laminar bucket"	Roughness
9	Uncambered	At M = 1·8 and 2·0	Carborundum height 0·007"
11	Slightly cambered	At M = 2·0 only	
10	Heavily cambered	No buckets	

(Standard conditions, Table 2).

Camber has also improved roughness effectiveness on some highly swept wings[15].

3.2 Roughness drag penalties

Even at low supersonic Mach numbers, when small roughness ensures complete transition, the measured drag of Wing 9 is about 0·0004 higher than the estimate (Fig.3). This suggests a roughness drag penalty which is just significant.

The highest Mach number (M = 2·0) was selected for the subsequent roughness tests because the highest roughness is then needed. The results (Fig.6) show that with 60 and 30 grade carborundum the drag penalty is 0·0008 and 0·0018 respectively, proving that roughness drag increases with roughness height. Part of this penalty must come from wave drag because shock waves from the 30 grade carborundum were clearly visible in the tunnel schlieren.

The magnitude of the roughness drag penalties, even with 60 grade carborundum, indicates that a more refined transition fixing technique is required. One possible refinement is to replace the irregularly shaped carborundum grit by spheres. Fig.7 compares the drag measured with 60 grade carborundum and ballotini of the same roughness height (0·012"). Although transition onset and fully turbulent conditions occur at lower Reynolds numbers with carborundum than with ballotini* there is no drag reduction for the common region of turbulent flow.

Another possible refinement is to reduce the width of the roughness band. Fig.8 compares the drag measured with ballotini bands 0·50" and 0·15" wide. Transition onset occurs at about the same Reynolds number with both bands but the area of turbulent flow initially increases more slowly with the narrower band although fully turbulent conditions are reached at the same Reynolds number $R\bar{c} = 1{\cdot}3 \times 10^6$. The drag of the 0·15" band is then 0·0008 lower than that of the 0·50" band and is about 0·0003 higher than the estimate. If the roughness drag is proportional to the band area the drag of the 0·15" band at M = 2·0 is still about 0·0004. The balance could not discriminate further drag reductions and so no further tests were made on this model. Some measurements on a delta wing at transonic speeds[8] also show a significant drag reduction as the ballotini band width decreases.

The measured and estimated drags for Wing 9 with the 0·15" wide ballotini band compared in Fig.9 suggest that at M = 1·4 the small drag penalty does not vary significantly over a wide Reynolds number range. This contrasts with measurements on Wing 15 with a 0·04" wide ballotini band in the A.R.A. tunnel[10], which show a larger drag penalty increasing with Reynolds number.

For the 3 ft tunnel tests Wing 15 had a ballotini band 0·15" wide. The results (Fig.10a) show that at M = 1·4 with ballotini 0·012" and 0·014" dia.

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* Probably because the carborundum bands have particles larger than the largest ballotini. (2.2 above).

the drag is 0·0007 and 0·0014 higher than the estimate. The drag at $M = 2{\cdot}0$ with ballotini 0·014" dia. is 0·0010 higher than the estimate (Fig.10b). Later and more extensive tests of Wing 15 in the A.R.A. tunnel indicate that the wave drag at $M = 2{\cdot}0$ is about 0·0004 higher than that of the larger model (Ref.10 Fig.9). Hence the probable roughness drag penalty in the present tests at $M = 2{\cdot}0$ with 0·014" dia. ballotini is still about 0·0006, even with this narrow band.

Fig.11 shows the variation of roughness drag coefficient (based on roughness band area) with (roughness height)^2 for both Wings 9 and 15 at $M = 2{\cdot}0$ and $R/ft \simeq 1{\cdot}4 \cdot 10^6$. Results from tests of Wing 15 in the A.R.A. Tunnel[10] and the larger model of Wing 15 in the 8 ft tunnel[16] are included. The data are limited but suggest that the roughness drag is proportional to roughness area and (roughness height)^2. A law of this type would explain why a difference in toughness drag penalty is only just detected in the A.R.A. tests between the two largest sizes of ballotini.

4 CONCLUSIONS

(1) Tests on two slender wings over the limited supersonic Mach number range from 1·4 to 2·0 show clearly that higher roughness is needed to produce fully turbulent conditions as Mach number increases (Figs.3 and 4).

(2) The effectiveness of the same roughness varies on different models (Figs.4 and 5) so that roughness effectiveness should always be checked.

(3) The roughness drag penalty at supersonic speeds may be significant but can be reduced by reducing the roughness bandwidth (Fig.8).

LIST OF SYMBOLS

$\bar{c}$	average chord
c_o	root chord
C_D	drag coefficient
k	roughness height
M	Mach number
p	planform parameter - wing area/enclosing rectangle = $\bar{c}/c_o$
R	Reynolds number
S	area
x,y	planform parameters
ΔC_D	(measured - estimated) drag coefficient
τ	(wing volume)/(wing area)$^{3/2}$
Λ	sweepback angle

Suffices

b	roughness band
o	zero lift
w	wing

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TABLE 1

Model details

	Wing	
	9	15
Leading edge equation	$y = S_T\, x(1 + x^3 - x^4)$	$y = S_T\, x(1{\cdot}2 - 2{\cdot}4x + 2{\cdot}2x^2 + 3x^3 - 3x^4)$
Planform parameter	$p = 0{\cdot}53$	$p = 0{\cdot}45$
Thickness parameter	$\tau = 0{\cdot}0424$	$\tau = 0{\cdot}0415$
Semispan/ root chord	$S_T/c_o = 0{\cdot}25$	$S_T/c_o = 0{\cdot}208$
Average chord	$\bar{c} = 11{\cdot}65''$	$\bar{c} = 10{\cdot}80''$
Reference	2	5

TABLE 2

Test conditions

Mach number (M)	Total pressure ("Hg)	Standard Conditions ("Hg)	Reynolds No./ft ($R/ft \times 10^{-6}$)
1·3	4 - 13	10·55	1·60
1·4	3 - 13	10·40	1·60
1·6	4 - 13·5	10·84	1·60
1·8	4 - 13·0	11·58	1·60
2·0	3 - 12·0	10·70	1·35

Tunnel total temperature 20 - 25° C

TABLE 3

Roughness criteria

Van Driests formula for effective tripping may be written

$$R_k = 150 \, (x_k/k)^{1/3} \, (1 + \overline{\gamma - 1}/2 \cdot M^2)^{4/3}$$

and depends weakly on (x_k/k). Selection of x_k is difficult for wings with curved leading edges but as both Wings 9 and 15 have minimum sweepback $\Lambda \simeq 73°$ ($\sec \Lambda = 3{\cdot}4$) a common $x_k = 0{\cdot}34$ in. was assumed.

Typical values

Wing	Mach number (M)	Roughness (Height in.)	R_k (free stream)	R_k (Top of roughness)
9	1·3	0·007	802	623
	1·6	0·007	942	760
	2·0	0·012	1,000	1,000
15	1·3	0·012	672	637
	2·0	0·014	950	950

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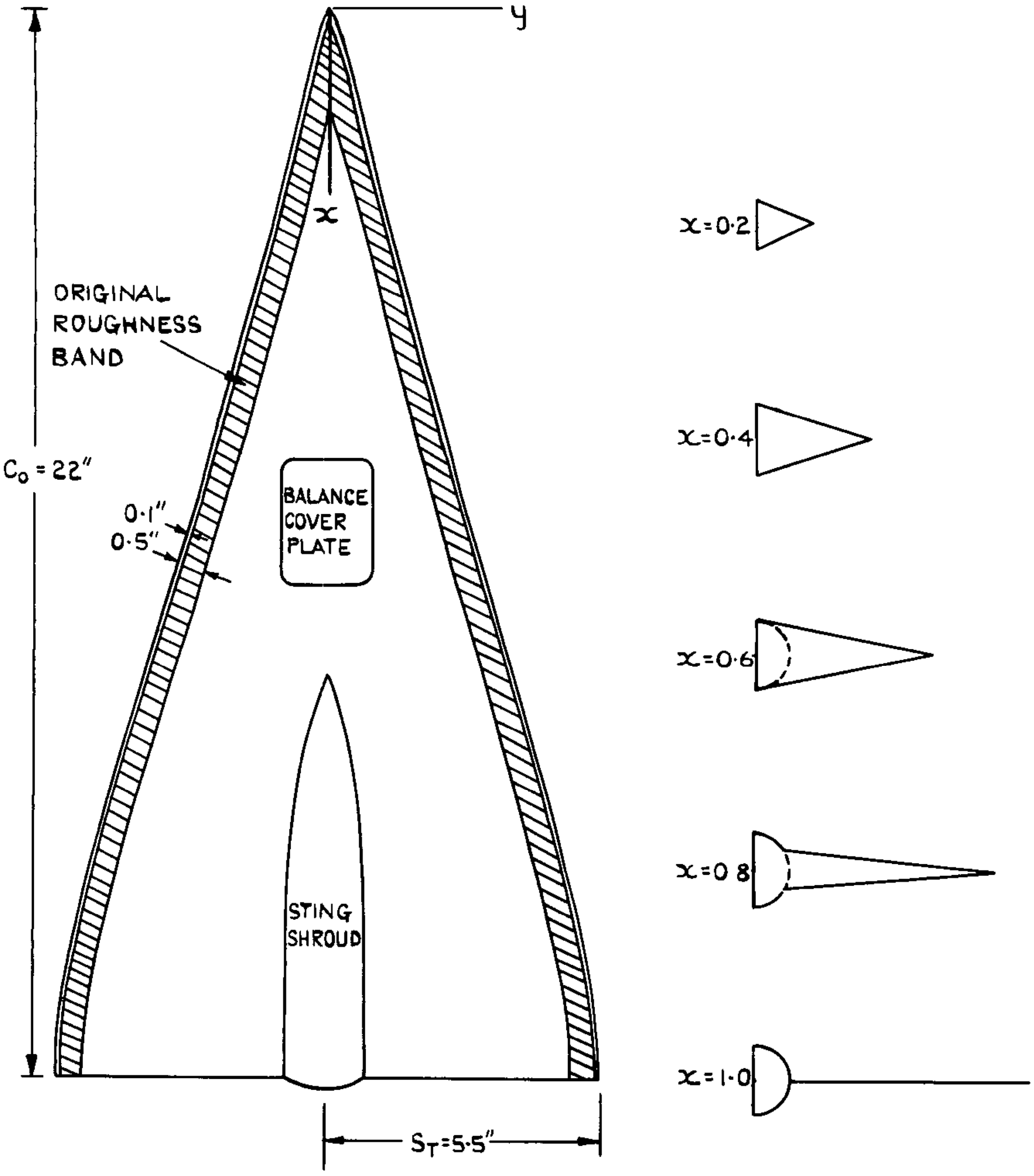


FIG. 1. GENERAL ARRANGEMENT OF WING 9.

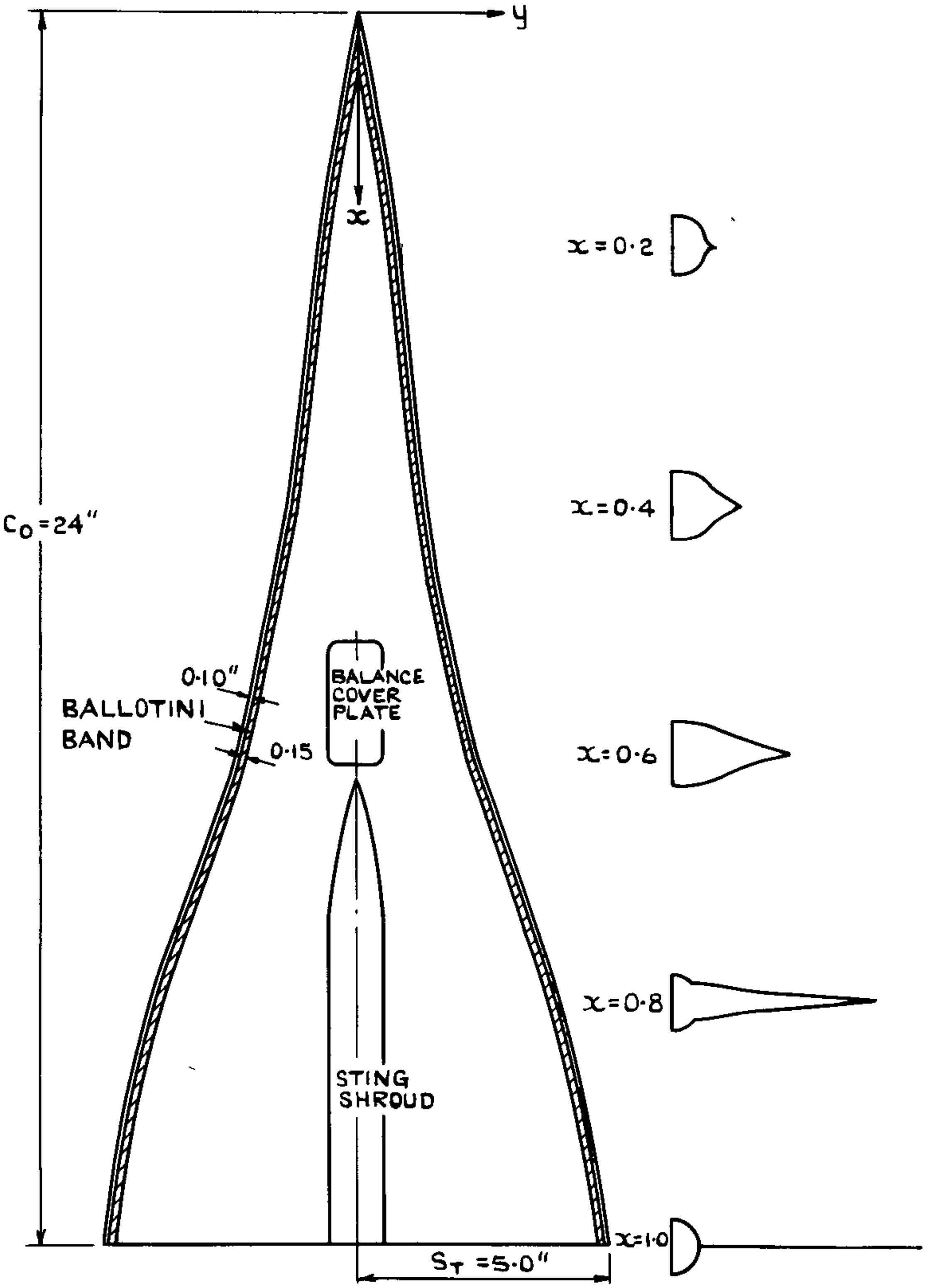
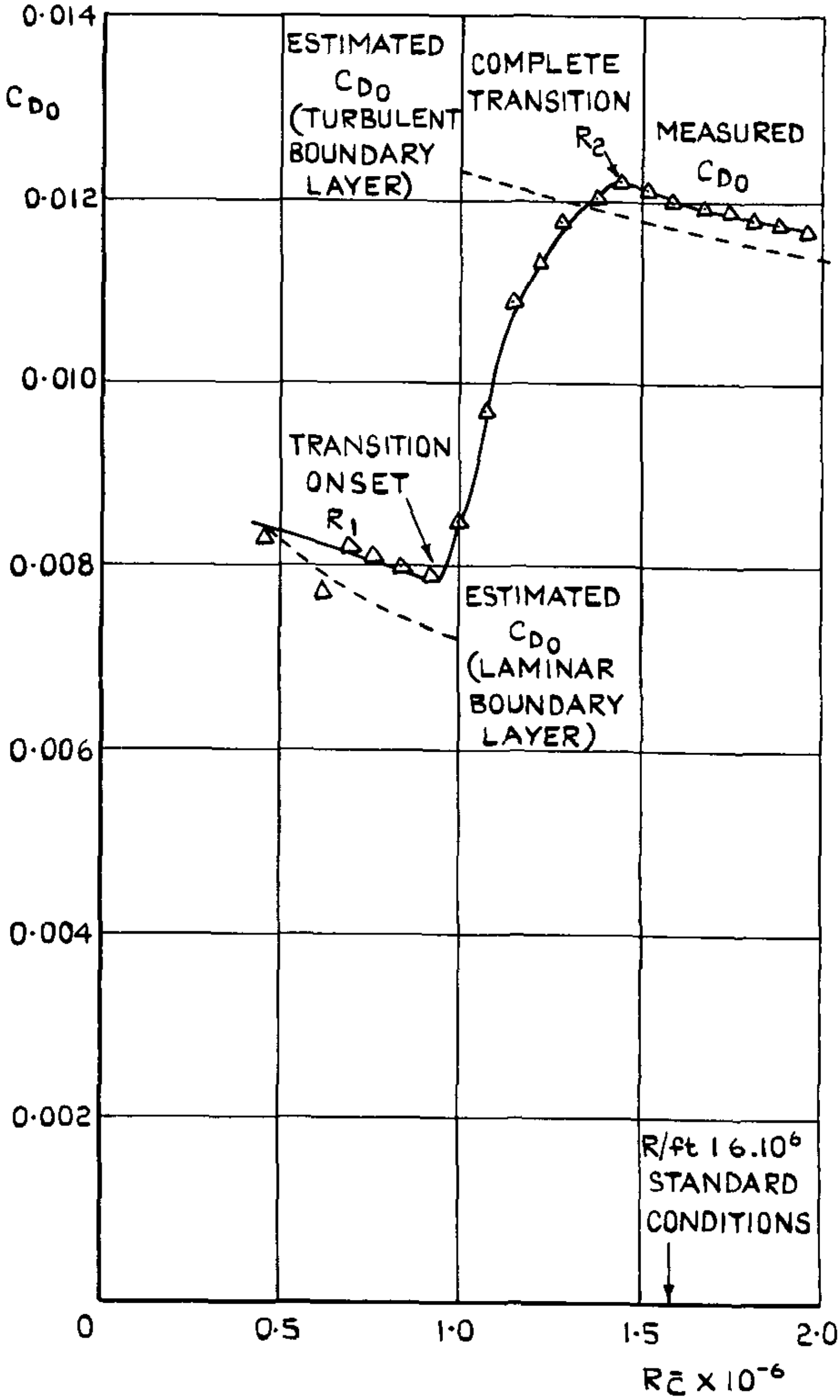
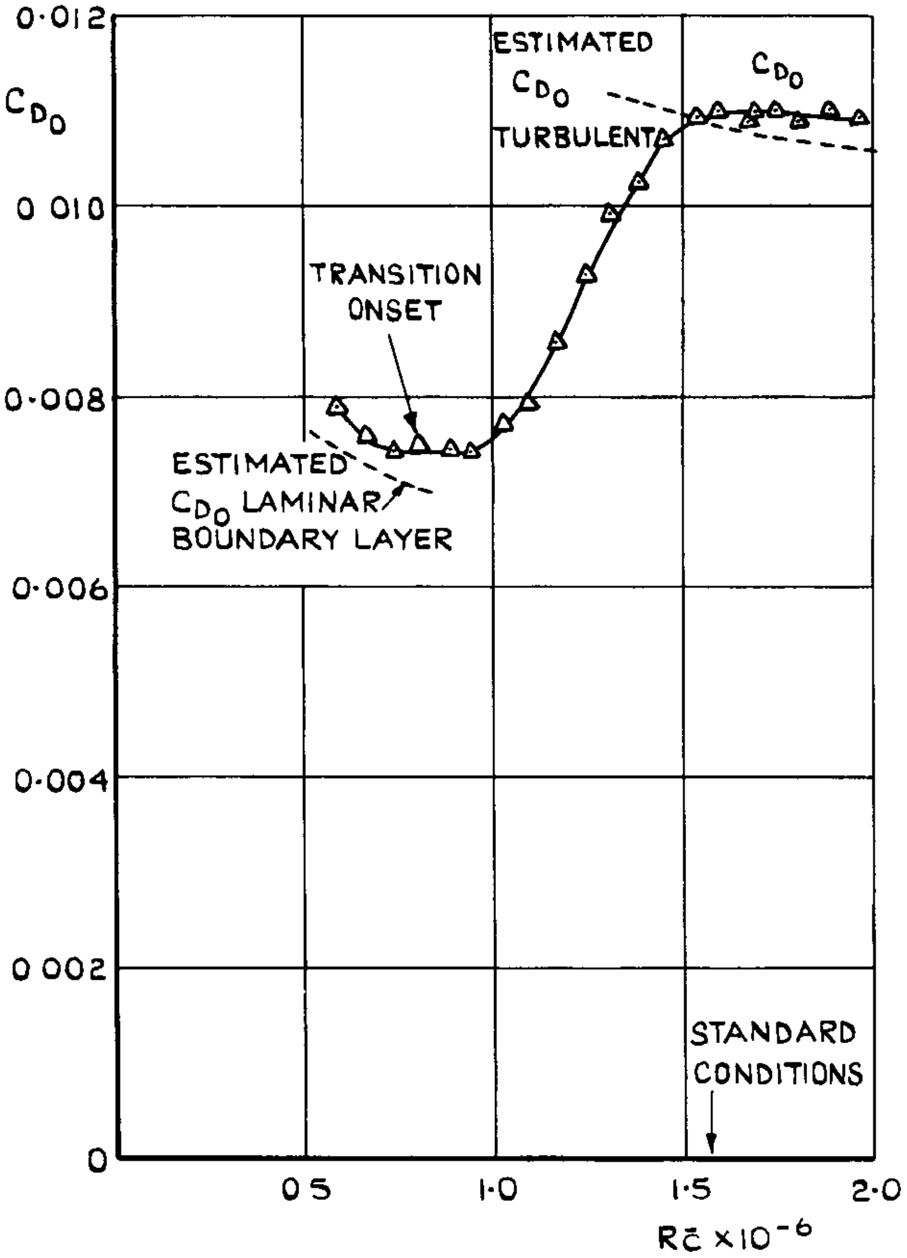


FIG. 2. GENERAL ARRANGEMENT OF WING 15.



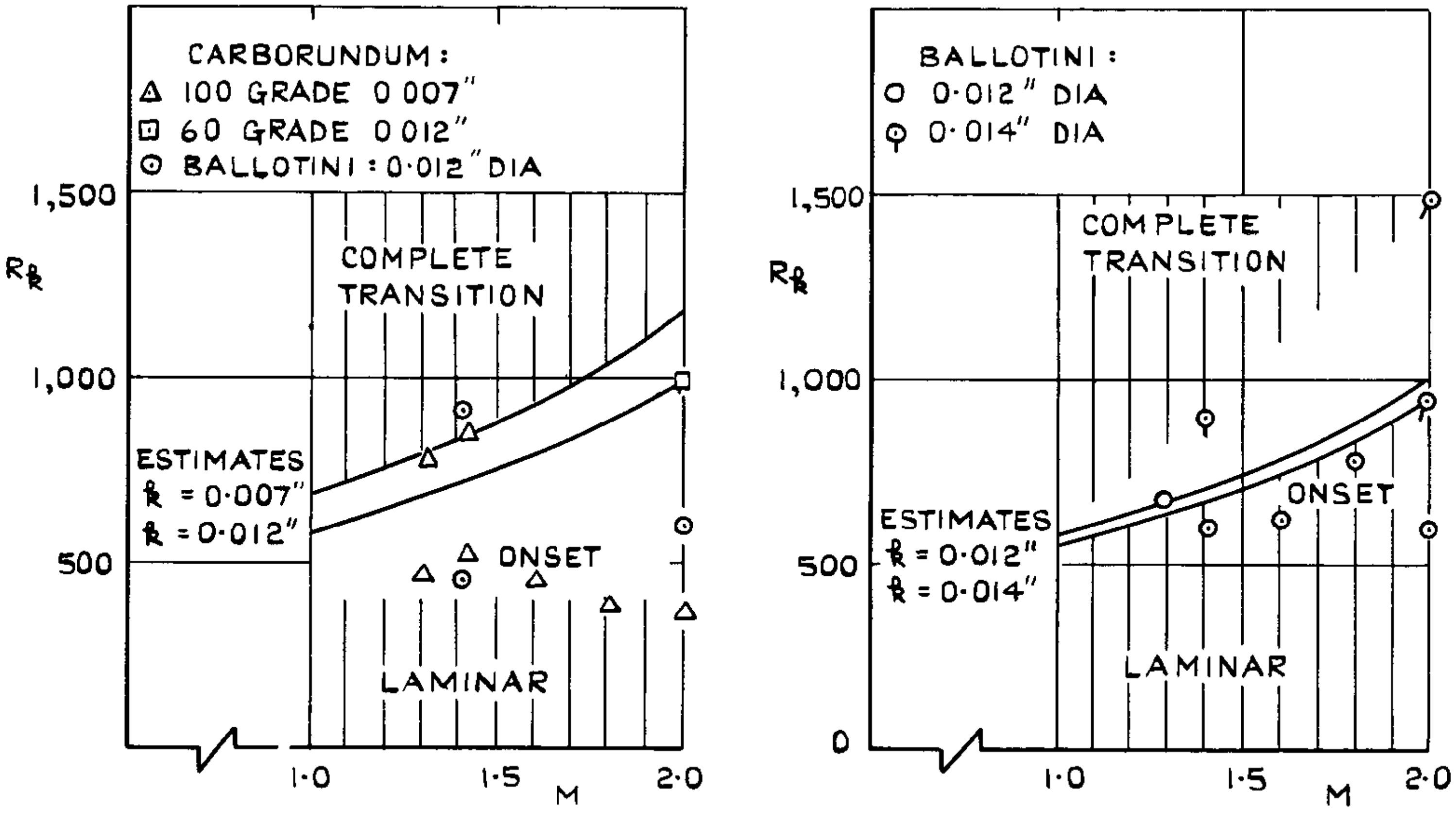
(a) M = 1·4

FIG.3. VARIATION OF ZERO LIFT DRAG WITH REYNOLDS NUMBER AT CONSTANT MACH NUMBER. WING 9. 100 GRADE CARBORUNDUM.



(b) M = 1·6

FIG. 3 (CONCLD.)



(a) WING 9.

(b) WING 15.

FIG. 4. VARIATION OF CRITICAL ROUGHNESS REYNOLDS NUMBERS WITH MACH NUMBER.

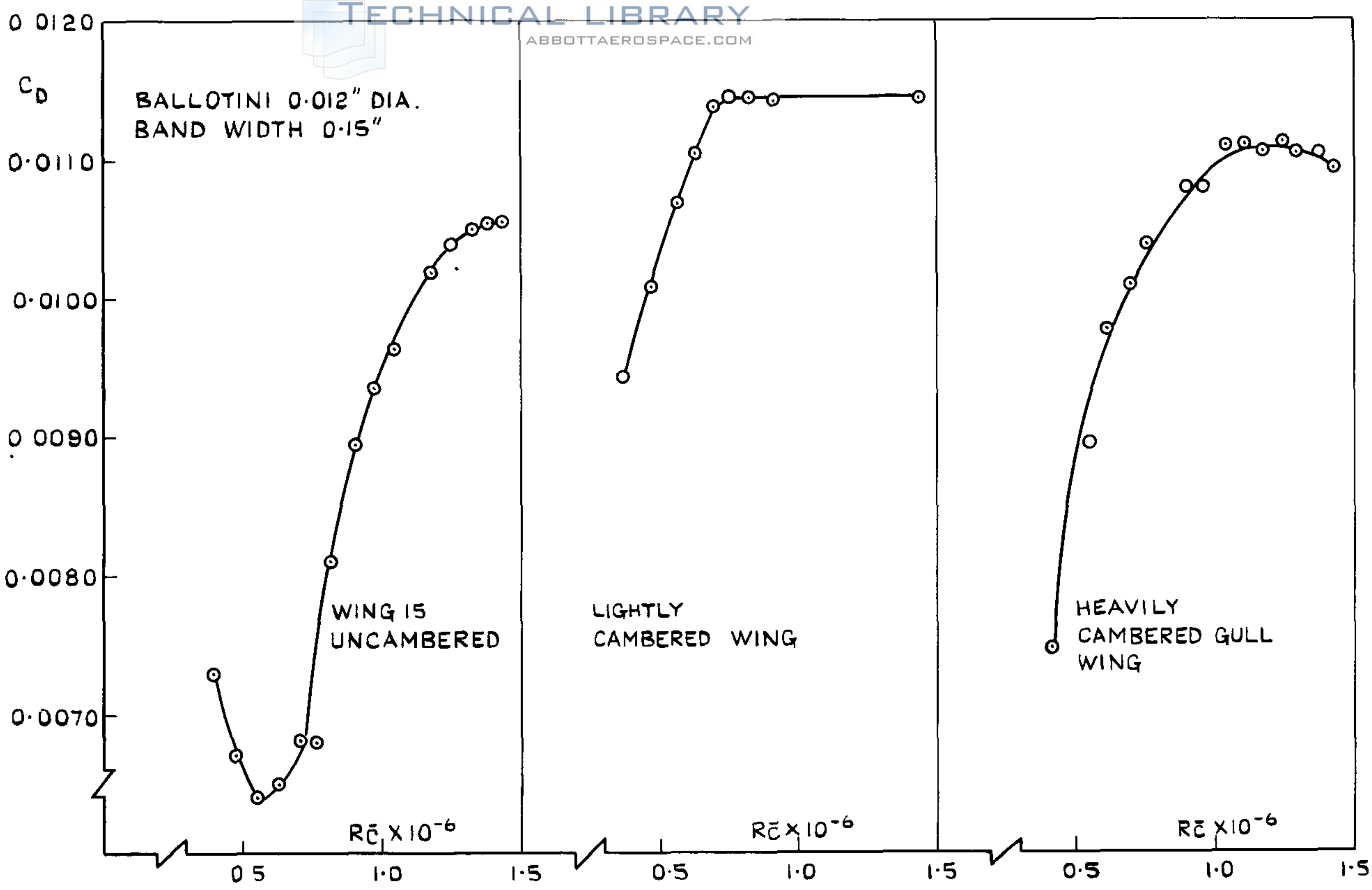


FIG. 5. INFLUENCE OF CAMBER ON ROUGHNESS EFFECTIVENESS, M=1·4.

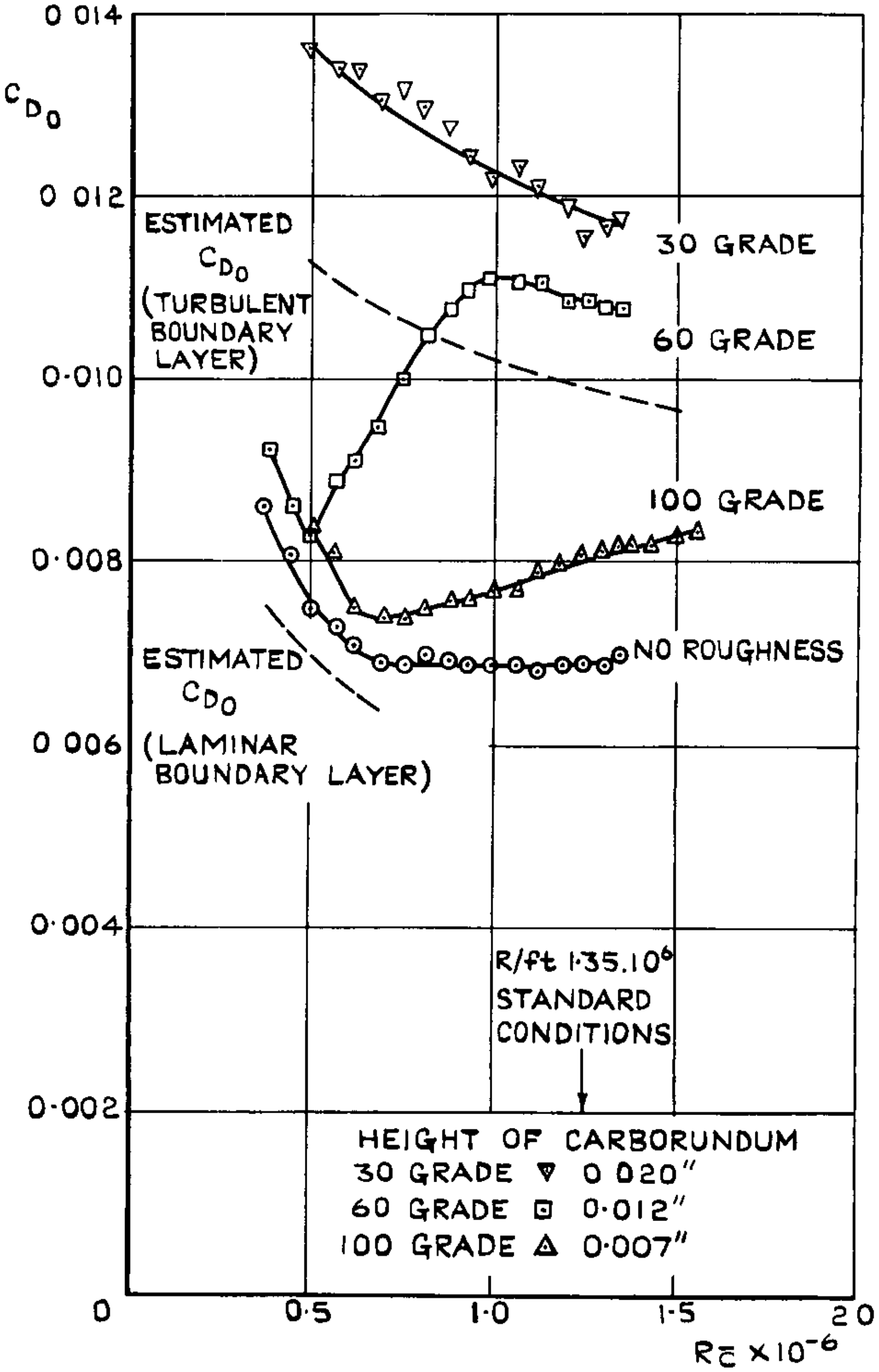


FIG. 6. VARIATION OF DRAG COEFFICIENTS WITH ROUGHNESS HEIGHT AND REYNOLDS NUMBER WING 9, M = 2·0. BAND WIDTH = 0·50"

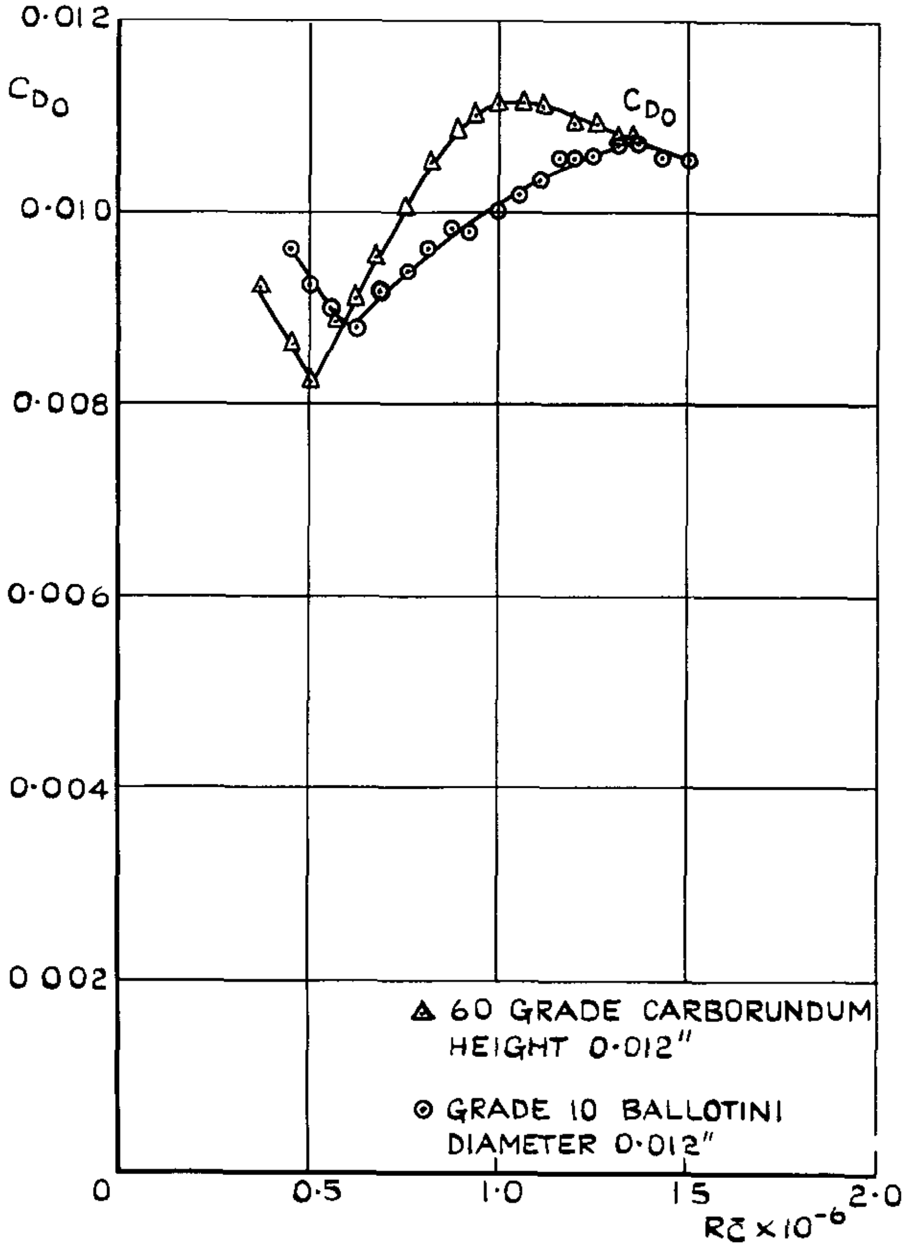


FIG. 7. COMPARISON OF DRAG COEFFICIENTS MEASURED WITH CARBORUNDUM AND BALLOTINI. WING 9. M=2·0. BAND WIDTH 0·50".

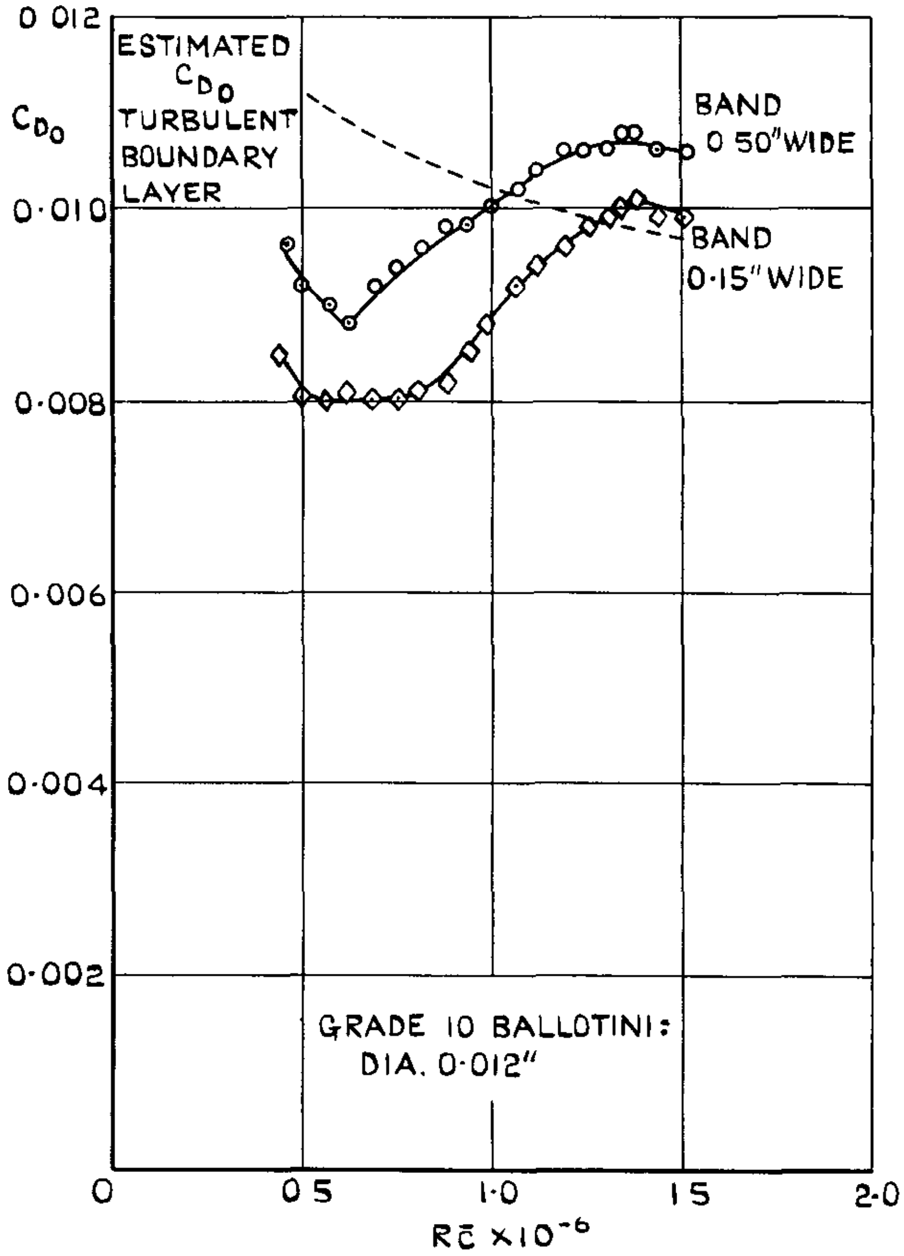


FIG.8. EFFECT OF BAND WIDTH ON DRAG COEFFICIENTS. WING 9. M=2·0. BALLOTINI.

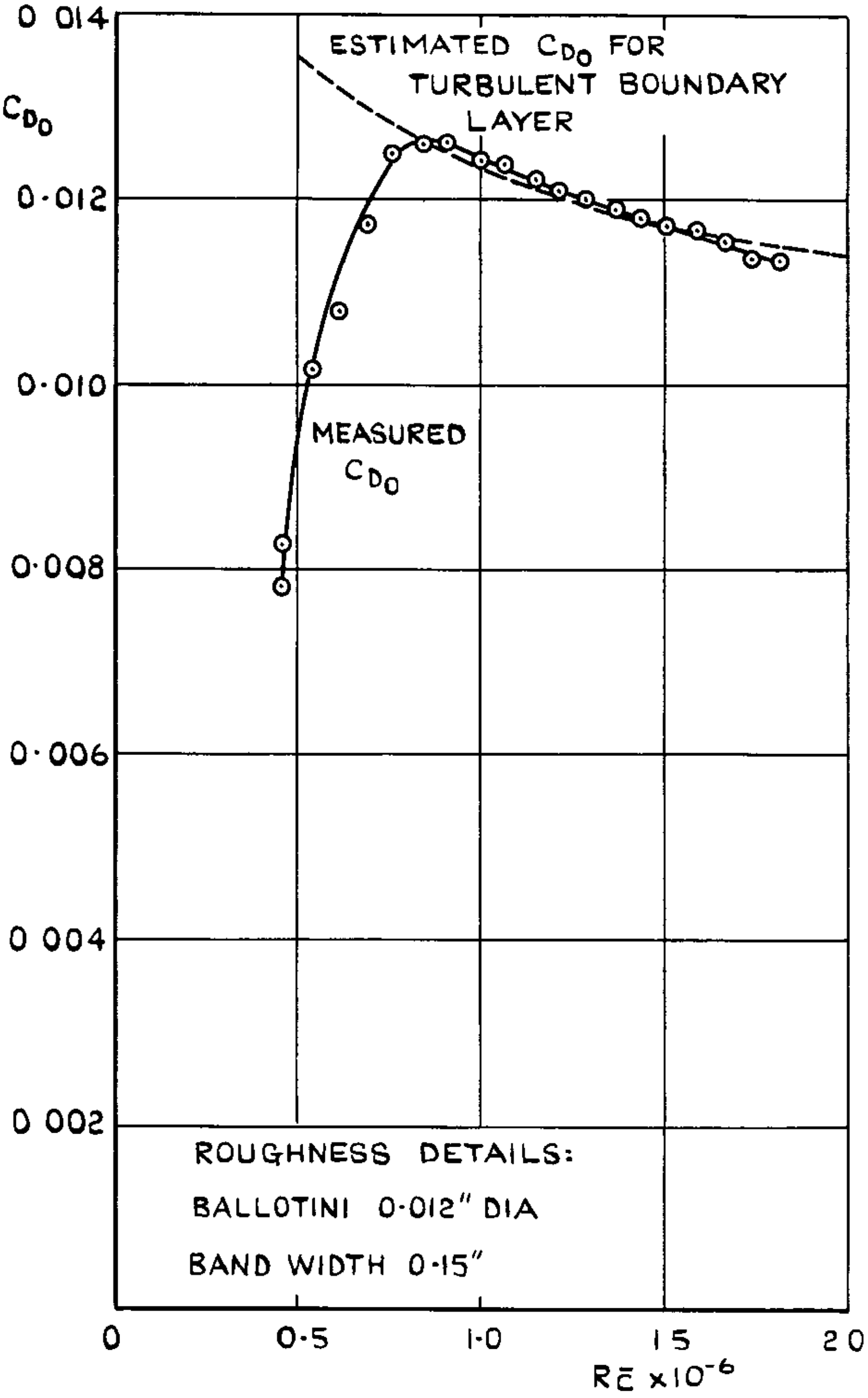
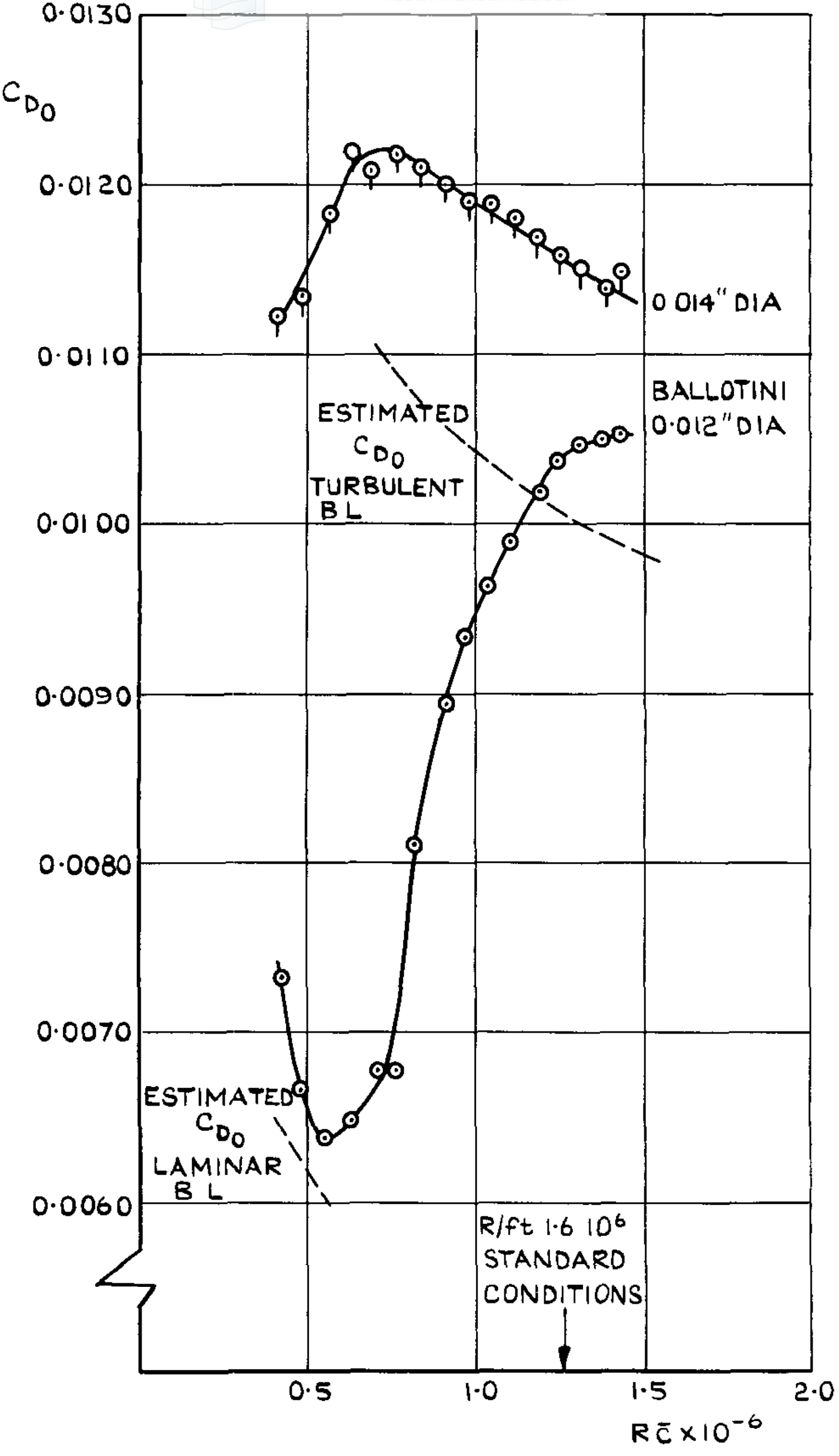
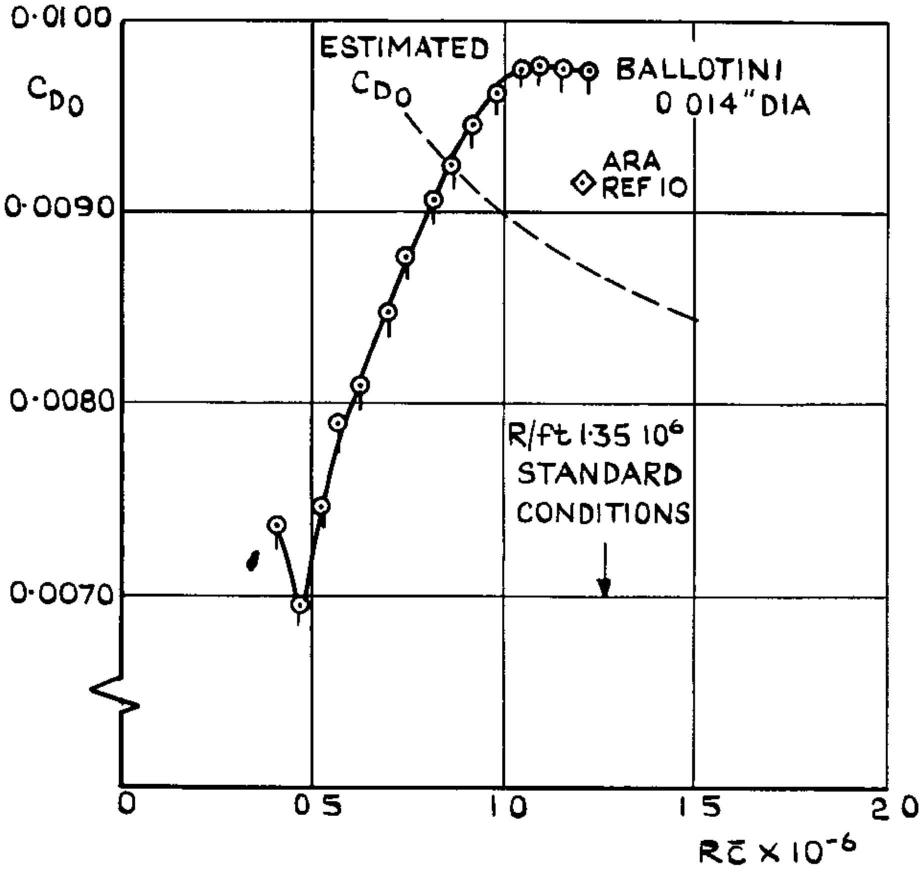


FIG. 9. VARIATION OF DRAG COEFFICIENTS WITH REYNOLDS NUMBER WING 9. M=1·4.



(a) M = 1·4.

FIG. 10. VARIATION OF DRAG COEFFICIENTS WITH REYNOLDS NUMBER AT CONSTANT MACH NUMBER. WING 15 0·15" BAND OF BALLOTINI



(b) M = 2·0

FIG. 10. (CONCLD.)

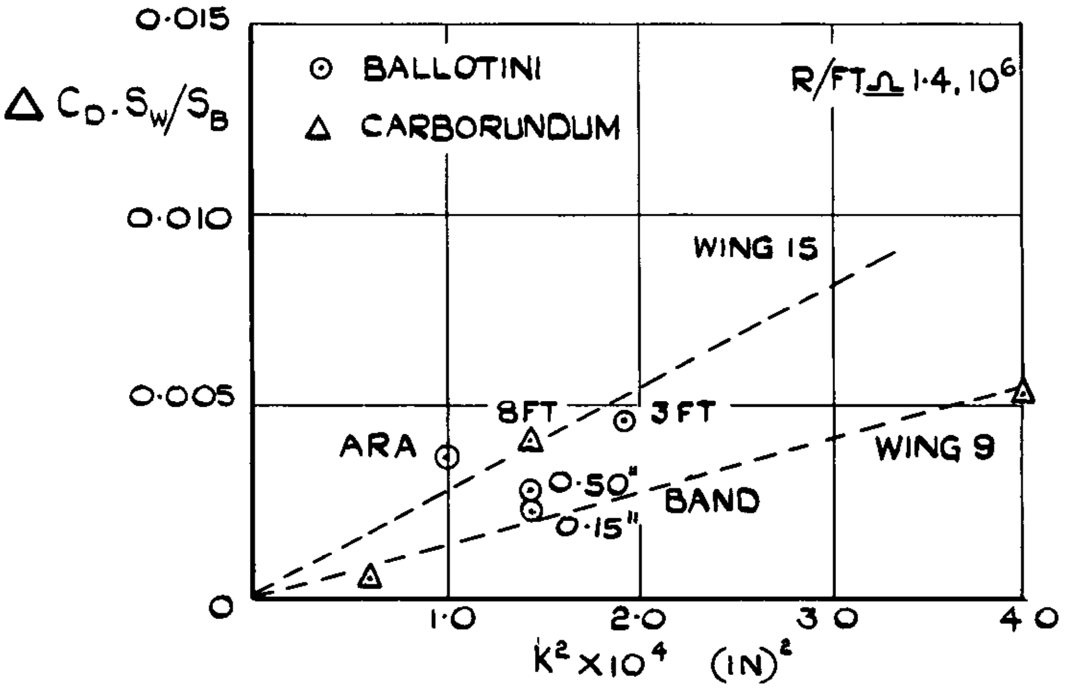


FIG. 11. VARIATION OF ROUGHNESS DRAG COEFFICIENT (BASED ON ROUGHNESS BAND AREA) WITH (ROUGHNESS HEIGHT)². M = 2·0.

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