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POSSIBILITIES FOR DRAG REDUCTION BY BOUNDARY LAYER CONTROL

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PREPARED BY Irven Naiman

SUPERVISED BY Roland J White

APPROVED BY

#4. I Naiman

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REFERENCES

1. Knight, Montgomery and Bamber, M.J.: Wind Tunnel Tests on Airfoil Boundary Layer Control using Backward Opening Slot. TN 323, NACA, October 1929.

2. Bamber, M.J.: Wind Tunnel Tests on Airfoil Boundary Layer Control using Backward-Opening Slot. Report No. 385, NACA, 1931.

3. Quinn, John H., Jr.: Tests of the NACA 65_3-018 Airfoil Section with Boundary-Layer Control by Suction. Confidential Bulletin No. L 4 H 10, NACA, October 1944.

4. Zalovcik, J.A., Wetmore, J.W., and vonDoenhoff, A.E.: Flight Investigation of Boundary-Layer Control by Suction Slots on an NACA 35-215 Low-Drag Airfoil at High Reynolds Numbers. Advance Confidential Report No. 4 B 29, NACA, March 1944.

5. Holstein, Horst: Widerstandsmessungen an einem Tragflügel mit durch Absaugung vergrösserter laminarer Laufstrecke. Bericht 40/1/3, AVA, January 23, 1940. (Drag Measurements on a Wing with Increased Laminar Region by Suction).

6. Holstein, Horst: Messungen zur Laminarhaltung der Reibungsschicht durch Absaugung a. einem Tragflügel mit Profil NACA 0012/64. Bericht 42/A/09, AVA, August 6, 1942. (Measurements on the laminarization of the friction layer by suction on an NACA 0012/64 wing.)

7. Schubauer, G.B., and Skramstad, H.K.: Laminar-Boundary-Layer Oscillations and Transition. Advance Confidential Report, NACA, April 1943.

8. Liepmann, Hans W.: Investigations on Laminar Boundary-Layer Stability and Transition on Curved Boundaries. Advance Confidential Report No. 3H30, NACA, August 1943.

9. Liepmann, H.W.: Investigation of Boundary Layer Transition on Concave Walls. Advance Confidential Report No. 4 J 28, NACA, February 1945.

10. Bussmann, K. and Münz, H.: Die Stabilität der laminaren Reibungsschicht mit Absaugung. Forschungsbericht Nr. 1567, AVA, March 31, 1942. (The stability of the Laminar friction layer with suction.)

11. Ras, Max: Contributions à l'étude de la couche limite aspiree. These, Universite de Paris, (No date). (Contributions to the study of boundary layer with suction.)

12. Fage, A., and Sargent, R.F.: Design of Suction Slots, Part I. F.M. 668, Ae. 2450, A.R.C., February 18, 1944.

13. Holstein, Horst, and Doneis, A.: Versuche zum Druckrückgewinn durch Formgebung der Absaugeschlitze bei der Absaugung laminarer Reibungsschichten. Forshungsbericht Nr. 1773, AVA, March 6, 1943. (Experiments on the pressure recovery of slots designed for suction of the laminar friction layer.)

14. Fage, A., and Sargent, R.F.: Effect on Aerofoil Drag of Boundary Layer Suction Behind a Shock Wave. R & M 1913, A.R.C., October 26, 1943.

15. Liepmann, H.W.: Investigations of the Interaction of Boundary Layer and Shock Waves in Transsonic Flow. Cal. Inst. of Tech. (No date).

16. Liepmann, H.W.: Further Investigations of the Interaction of Boundary Layer and Shock Waves in Transsonic Flow. Preprint. Cal. Inst. of Tech. (No date). Misc. Gen. 66.

SUMMARY

The existing literature on the mechanism of transition is reviewed. Oscillations in the laminar boundary layer are found to be amplified until the disturbance is so great as to cause a breakdown of the flow. This breakdown is known as transition. An analysis is made of the drag possibilities by means of boundary layer control assuming certain conditions of transition Reynolds Number, inlet loss, number of slots, blower efficiency and duct losses. The results appear to be highly favorable. However, experimental investigations on this matter give conflicting results, showing only small gains, and sometimes losses. An analysis of this data indicates that there is a lower limit to the quantity of air which must be removed at a slot in order to stabilize the laminar flow. The removal of insufficient air permits transition to occur. The removal of excessive amounts of air results in high power costs, with a net drag increase. With the estimated value of flow coefficient and duct losses equal to half the dynamic pressure, drag reductions of 50% may be obtained; with twice this flow coefficient, the drag saving is reduced to 25%. It is recommended, therefore, that further research be instigated in order to determine what amount of air must be removed at a slot in order to (1) stabilize the laminar flow, and (2) reestablish laminar flow; also further studies on slot design should be made. The recent work on boundary layer effects on compressibility shock should also be continued.

INTRODUCTION

While a considerable amount of work has been done on boundary layer removal, almost all of it has been concerned with improvement of maximum lift. Very little work has been done on reduction of drag. Reference 1 gives some information on drag reduction but this appears to be principally due to the jet effect of the discharged air. References 2 and 3, while primarily concerned with lift effects, also include some drag data. Few specific applications for drag reduction have been found. Reference 4 gives results of tests on a glove fitted to one part of the wing of a B-18 airplane. The drag and the nature of the flow was investigated for various numbers of slots and volumes of air flow. Laminar flow was maintained up to about 45% chord, the peak pressure position. The power cost was found to be less than the reduction in drag so that a net gain was obtained.

Reference 5 gives the results of some German tests on drag reduction which also show a net gain. Reference 6 gives some further tests but a net gain was not realized.

The body of this paper is divided into three sections: (1) a review of existing literature on the mechanism of transition and the means of boundary layer control for reduction of drag; (2) a theoretical analysis to determine the possibilities of drag reduction by boundary layer control; (3) analysis of existing experimental work on this matter.

The problem of reduction of drag has been narrowed to one of maintaining laminar flow as far as possible on the body. This means the delay of transition as long as possible. The understanding of the mechanism of transition has been advanced by research on the stability of the laminar boundary layer.

Stability of laminar boundary layer.--Early theoretical work by Tollmien and Schlichting (described in reference 7) on the stability of the laminar boundary layer indicated that amplification of oscillations was responsible for transition. Recent experimental studies by Schubauer and Skramstad (reference 7) and Liepmann (references 8 and 9) have confirmed this explanation. The phenomenon may be described briefly as follows.

Oscillations of some sort are always present in the airstream due to sound, surface vibrations, etc. In the laminar layer these vibrations are initially damped but after the boundary layer has grown to a certain thickness, depending upon the frequency of the disturbance, amplification occurs. The theory indicates that after further thickening of the boundary layer, a stable region is reached in which damping once more occurs. However, unless the disturbance is initially very weak, the amplification causes the oscillation to reach a magnitude so great as to cause a complete breakdown of the flow before the stable region is regained. This breakdown area is known as the transition region.

Important elements in this picture are the effects of pressure gradient and suction on transition. It has long been known experimentally that negative pressure gradient (accelerated flow) is favorable to maintenance of laminar flow, whereas positive pressure gradient (decelerated flow) is unfavorable. Recent German theoretical work (reference 10) confirms the effect of pressure gradient and also shows that suction has a marked stabilizing effect upon the laminar layer. Pressure discharge has great destabilizing effect causing transition to occur immediately. Ras (reference 11) has confirmed experimentally the stabilizing effect of suction.

Boundary layer control.-- The actual mechanical features of boundary layer control equipment may be considered as composed of inlets, manifolding, ducting, and discharge slots. The design of the ducting and discharge slots need not be further considered here as their design will be based only secondarily on aerodynamic requirements. Besides, these are well-known and nothing new is involved.

Very little work has been done on the inlet slot design for drag control. In reference 12 slots are described which were developed by smoke flow observations. Inasmuch as these tests were necessarily performed at very low velocities the validity of the results is questionable. Reference 13 gives quantitative results obtained at higher air speeds. Both references indicate that the direction of entry is not critical, (though backward slots tend to be inferior), that the edges should be rounded, and that the inner part of the slot should expand slowly as in a diffuser (see Figure 1). Under these circumstances the pressure in the inner chamber will be very nearly the same as the surface static pressure. Poorer designs may incur a considerable pressure loss. It appears, therefore, that for a good inlet slot, no pressure recovery is to be expected.

It is usually necessary to use more than one suction slot along the surface and in order to economize on ducting, several slots are manifolded. On wing surfaces difficulty usually arises, because the surface static pressure is not the same at each slot. The chamber pressure must be sufficiently low to assure that there is no outward flow at a low pressure slot with resulting breakdown of laminar flow. Under these circumstances a slot in a region of relatively high pressure may have too great a rate of flow unless throttling is resorted to. In any event, the power cost is increased.

Compressibility effects.— Research has been instituted recently to determine the effect of boundary layer upon the shock wave and the resultant drag effects (references 14 - 16). The preliminary results indicate that the shock wave characteristics are different in the presence of a laminar boundary layer than with a turbulent layer, though which is preferable is not yet known. It has also been found that at high velocities in the region of rapid drag increase boundary layer removal will allow a higher Mach Number to be reached before the drag coefficient reaches the same value. Further work is undoubtedly in progress on both these results.

SYMBOLS

x	position of suction slot
y	distance above surface
l	chord length
S	wing area
δ	boundary layer thickness
R_x	critical Reynolds number, Vx/ν
R_l	airfoil Reynolds number, Vl/ν
V	flight velocity
V'	discharge velocity of inducted air
q, q'	dynamic pressures
ν	kinematic viscosity
C_{D_x}	drag coefficient of flat plate at R_x
C_{D_W}	wing drag coefficient with boundary layer control assuming $V' = V$
C_{D_B}	equivalent drag coefficient for power expenditure of blower,
C_{D_T}	equivalent total drag, $C_{D_W} + C_{D_B}$
Q	volume of air inducted per unit time

C_Q volume coefficient, Q/SV

$C_{Q\delta}$ volume coefficient, $Q/V\delta$

P internal pressure of wing, referred to atmospheric static

$\overline{\Delta p}$ pressure loss in duct

C_P pressure coefficient, P/q

K duct loss coefficient, $\overline{\Delta p}/q$

η_B blower efficiency

Subscripts

$1, 2, 3, \cdots n$ number of suction slot

ANALYSIS OF POSSIBILITIES

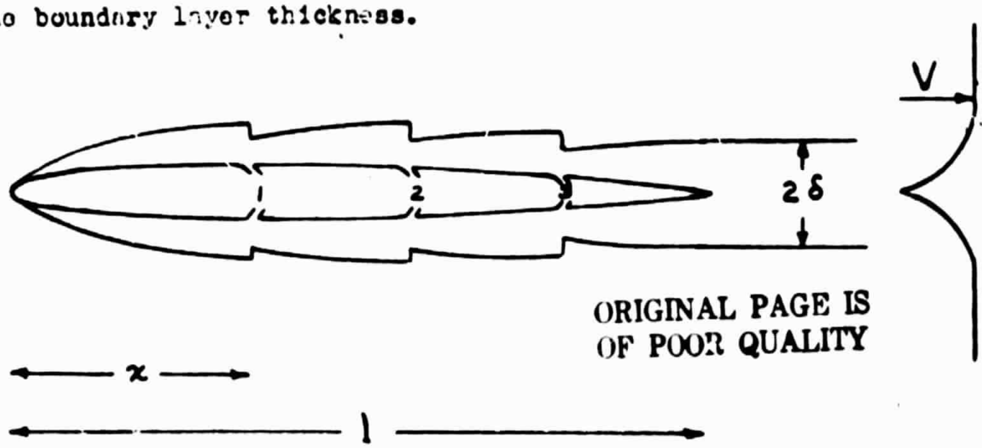
The analysis of drag reduction possible with boundary layer removal is necessarily based upon several assumptions. The assumptions used here are as follows:

1. The law of surface friction is that for a flat plate.

2. The laminar velocity profile is assumed to be parabolic.

Both of these assumptions introduce some error but the results of the analysis should be fairly close to the correct values.

Given certain initial conditions such as turbulance of the stream , vibrations, etc., transition from laminar to turbulent flow will tend to occur at a certain Reynolds Number. If a suction slot is placed at this point, so that air is removed just as transition is about to occur, then the boundary layer thickness will be reduced and the flow will continue laminar. When the thickness has again increased to that corresponding to transition, another suction slot again reduces the boundary layer thickness.

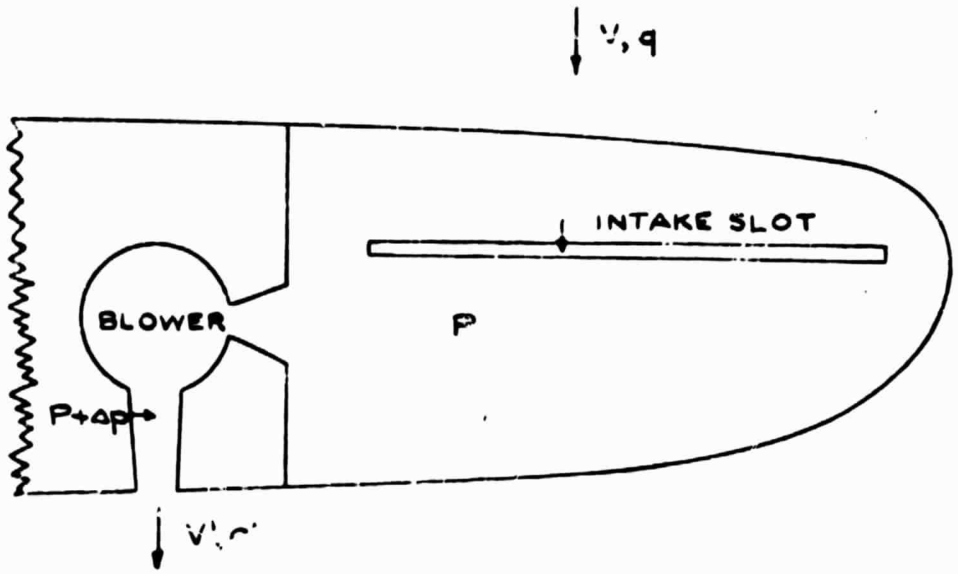


The above diagram illustrates three sets of intake slots, the first placed at a distance x corresponding to the critical Reynolds Number, $R_x = \frac{Vx}{\nu}$. The boundary layer in the wake is of width 2δ, the same as at the first slot. The velocity profile is indicated at the right of the figure. The inducted air is discharged elsewhere to the rear at stream velocity. The drag coefficient for laminar flow on a flat plate at Reynolds Number R_x may be designated as C_{D_x}.

The wing drag is the same as that accumulated up to the first slot and the drag coefficient is then given by

$$C_{D_W} = C_{D_x} \frac{x}{l} = C_{D_x} \frac{R_x}{R_l} \qquad (1)$$

To the above drag figure must be added the drag equivalent of the power expended by the blower. This power cost may be considered in two parts: the power to restore the stream total pressure to the inducted air, and the power to compensate for ducting losses.



In the literature the internal wing pressure is referred to the stream static in terms of dynamic pressure.

$$C_p = \frac{P}{q}$$

As stated earlier, experimentally it is found that very little energy is recovered upon induction of the air, and therefore, C_p is zero or negative. The inlet loss is given by q-P, or non-dimensionally

$$\text{Inlet loss} = 1 - C_p$$

The additional pressure loss in the ducting is a function of duct design, length, etc. and can be treated only generally here. This loss may be given as $\overline{\Delta p} = \kappa q$. The pressure added by the blower is Δp. The discharged air then has a dynamic pressure q' given by

$$q' = q - (q - P) - \overline{\Delta p} + \Delta p$$

$$= \Delta p + P - \overline{\Delta p}$$

If the air is discharged at stream velocity (as is usually assumed) then, with $q' = q$,

$$\Delta p = q - P + \overline{\Delta p}$$

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$$\text{or} \quad \frac{\Delta p}{q} = 1 - C_p + \kappa \tag{2}$$

The blower power required is given as $\frac{Q\,\Delta p}{\eta_B}$ where Q is the volume of air inducted per second and η_B is the blower efficiency. The equivalent drag coefficient is given by

$$C_{D_B} = \frac{1}{\eta_B}\frac{Q\Delta p}{qSV} = \frac{1}{\eta_B} C_Q (1 - C_p + \kappa) \tag{3}$$

The total drag as the result of application of boundary layer control is, therefore, given by

$$C_{D_T} = C_{D_W} + C_{D_B} \tag{4}$$

Figure 2 gives the drag possibilities with boundary layer control, assuming no duct losses, $\kappa = 0$. Transition Reynolds Number is assumed to be 4×10^6, inlet loss is equal to q, i.e. $C_p = 0$, exhaust velocity = V, $\eta_B = .75$. The figure gives the results for 1, 2, 3, 4, 5, 10, and ∞ number of slots. Contours of constant C_Q are indicated. Figure 3 gives the same results for $\kappa = .5$ and figure 4 for $\kappa = 1$. The method of computation is given in the Appendix. Examination of the figures indicate that for a given Reynolds Number there is a minimum number of slots required for drag reduction. The use of more slots with closer spacing reduces the total drag by reducing the volume requirements. The limiting condition is given by the curve representing an infinite number of slots. It would appear desirable, therefore, to use as many slots as possible so as to reduce the volume requirements and thereby reduce the losses and power requirements.

Note on optimum discharge velocity.— In the usual treatments on boundary layer control it is assumed that the air is discharged at stream velocity. This is done for convenience as it eliminates momentum questions. However, with a blower efficiency of less than unity, this is not the optimum condition.

The momentum condition gives

$$\Delta D_w = \rho Q (V - V')$$

where V' is the discharge velocity, or

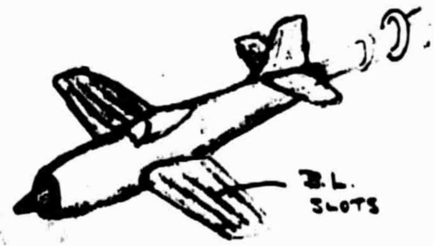
$$\Delta C_{D_w} = 2 C_Q \left(1 - \frac{V'}{V}\right).$$

The corrected energy equation gives

$$C_{D_B} = \frac{1}{\eta_B} \frac{Q \Delta p}{q S V} = \frac{1}{\eta_B} C_Q \left(\frac{q'}{q} - C_p + \kappa\right)$$

and the drag increment is

$$\Delta C_{D_B} = \frac{1}{\eta_B} C_Q \left(\frac{q'}{q} - 1\right)$$



The total drag increment is therefore

$$\Delta C_{D_T} = \Delta C_{D_W} + \Delta C_{D_B}$$

$$= C_Q \left\{ 2\left(1 - \frac{V'}{V}\right) + \frac{1}{\eta_B}\left[\left(\frac{V'}{V}\right)^2 - 1\right]\right\} \tag{5}$$

When V' = V, equation (5) reduces to zero. The optimum is obtained by setting the derivative equal to zero

$$\frac{d\Delta C_{D_T}}{d\frac{V'}{V}} = 2C_Q\left(\frac{1}{\eta_B}\frac{V'}{V} - 1\right) = 0$$

or $$\frac{V'}{V} = \eta_B$$

The optimum discharge velocity is therefore obtained when the ratio of discharge to stream velocity is equal to the blower efficiency.

With high blower efficiency this effect is small, but with low blower efficiencies it becomes important especially with large volume coefficients.

ANALYSIS OF EXPERIMENTAL WORK

Existing experimental results give conflicting results on the reduction of drag by boundary layer control. Some writers profess to have been successful, whereas others have not been. The previous analysis, as presented in figures 1 to 3, indicates that successful results should be obtained if the value of C_Q is kept small. Some further analysis is therefore indicated.

The published reports seldom give the individual slot pressure requirements and give no data on the boundary layer thickness. The volume coefficient for the individual slots is, however, reported. This information can be used to appraise the boundary layer condition at the first slot.

We may define $C_{Q\delta} \equiv \frac{Q_1}{V\delta} = \frac{Q_1}{Vl}\frac{l}{\delta} = \frac{C_{Q_1}}{\delta/l}$

Now if x_1 is the position of the first suction slot; and if it is assumed that the boundary layer has the same characteristics as for a flat plate; and again assuming a parabolic velocity distribution:

$$\frac{\delta}{x_1} = \frac{5.50}{\sqrt{R_{x_1}}}$$

Then

$$C_{Q\delta} = \frac{C_{Q_1}}{\delta/x_1}\,\frac{l}{x_1}$$

$$= \frac{C_{Q_1}}{5.50}\cdot\frac{\sqrt{R_{x_1}}}{x_1/l} \qquad (6)$$

In this manner the volume intake at the first slot of the various experiments may be placed upon a common basis, the boundary layer thickness δ.

In reference 4 are described flight tests upon a glove fitted on the B-18 airplane. The maximum test Reynolds Number, $R_l = 30 \times 10^6$; $x_1/l = .20$; C_{Q_1} max. $= .00004$. This gives $C_{Q_\delta} = .089$. Nine suction slots from $x = .20\,l$ to $.60\,l$

were fitted but laminar flow could not be maintained beyond the fifth slot, corresponding to the peak pressure point. Vibration difficulties were encountered which produced cracks in the airfoil surfaces. An attempt to utilize more slots by halving the spacing was unsuccessful, no laminar flow being obtained. However, with nine slots, at the optimum condition a total drag reduction, after allowance for blower power, was obtained equal to $\Delta C_{D_T} = -.00023$. The drag results were not obtained by wake measurements, but computed from surface measurements of pressure distribution, transition point, and velocity pattern. The magnitudes of the results are, therefore, questionable.

In reference 5 are described wind tunnel tests on an airfoil. The tests were made on single slots and combinations at several angles of attack. $R_l = 1.6 \times 10^6$; $x_4/l = .42$; $C_{Q_4} = .0004$ (slot 4 only) and $C_{Q_4} = .0002$ (slots 4 and 6). These values were at minimum total drag. This gives $C_{Q_\delta} = .142$ and $.071$, respectively. For slot 4 only at $C_{Q_4} = .0002$, $\Delta C_{D_T} = -.0006$ and at $C_Q = .0004$, $\Delta C_{D_T} = -.0009$; for slots 4 and 6, $C_{Q_4} = .0002$, $\Delta C_{D_T} = -.0009$. In both cases C_p was approximately -0.4, surface pressure coefficient $-.32$. Somewhat larger drag savings were accomplished with more slots and combinations.

In reference 6 are presented further wind tunnel tests on a model with 15 slots. The report presents results using only six slots; one presumes the selected six gave the optimum distribution. However, no reduction in total drag was obtained. The author ascribes this to the high Reynolds number and states that the slots were too far apart. $R_l = 3.2 \times 10^6$; $x_1/l = .075$; $C_{Q_1\,opt} = .00055$. This gives $C_{Q_\delta} = .655$, a figure much larger than in the two preceding references. Because the slots were not close enough, very large quantities of air were exhausted before the wing drag was reduced. The power cost was so high, because of the large quantities of air handled, that the total drag was increased by $\Delta C_{D_T} = .0007$.

The tests described in reference 3 were made primarily for lift increase, but measurements were also made at low lift coefficients. Only two slots were used, the first one being tested in two positions $x_1/l = 0.30$ and 0.45, and the second one at $x_2/l = 0.75$. At the forward position at low volume coefficients apparently all the air was inducted at the first slot. $R_1 = 1.9 \times 10^6$; $x_1/l = 0.30$; $C_{Q_1} = .0020$; therefore $C_{Q_\delta} = .915$. No measurements were made at lift coefficients less than 0.4 at this volume coefficient but the total drag was increased by .0035. For the other position tests were made at two Reynolds Numbers. At $R_1 = 1.9 \times 10^6$; $x_1/l = 0.45$; $C_{Q_1} = .0004$; $C_{Q_\delta} = .150$; $\Delta C_{D_T} = .001$. At $R_1 = 6 \times 10^6$; $x_1/l = 0.45$; $C_{Q_1} = .00067$; $C_{Q_\delta} = .443$; $\Delta C_{D_T} = .003$. The value of C_{Q_δ} at $R_1 = 1.9 \times 10^6$ is questionable because at higher volume coefficients, $C_{Q_1} = .00067$, the same as at higher Reynolds Number. If this correction is assumed C_{Q_δ} is found to be .250 instead of .150.

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The above results may be summarized as follows:

C_{Q_δ}	C_{D_T}	n	C_L	Extent of Laminar Flow
.071	-.0006	1	0	?
.071	-.0009	2	0	?
.089	-.00023	9	.2	To peak pressure point, .45 l
.142	-.0009	1	0	?
.150 (?) .250 (?)	+.001	2	0	?
.443	.003	2	0	?
.655	.0007	6	0	At least .9 l
.915	.0035	2	.4	?

It is evident that for small values of C_{Q_δ} drag reduction is possible. However, at too small a value it is not possible to maintain laminar flow against the pressure gradient. This is reasonable because adverse pressure gradient is destabilizing and suction is stabilizing. There is some point at which balance is achieved. With the meager amount of data on hand, it may be assumed that this value is, say, $C_{Q_\delta} = .150$. Assuming a parabolic velocity distribution for the laminar boundary layer, this value of C_{Q_δ} corresponds to $y/\delta = .42$. The value of $C_{Q_\delta} = 2/3$ represents complete removal of the boundary layer.

Theoretical and experimental investigations of the distribution across the boundary layer of the amplitude of the oscillations (reference 7) indicate that the peak value is reached at approximately $y/\delta = 0.2$. No disturbance exists at $y/\delta = 0.7$, at which point a phase shift occurs, the oscillations beyond this point being 180° out of phase with the oscillations close to the surface. At $y/\delta = .42$ the oscillation amplitude is approximately half the maximum. If the volume of the inducted air is too small, the large amplitude disturbances are not removed and transition is not delayed appreciably. The removal of this highly disturbed air is therefore necessary to preserve the laminar flow.

If it is assumed that a value of $C_{Q_\delta} = .150$ is sufficient for the purpose of stabilizing the flow, then a lower feasible limit is set. This value can be translated into C_Q and C_D values as before and is indicated in figures 2 to 4 by the dashed curve.

From the preceding discussion, it is now evident that some further research is necessary before drag reduction by boundary layer control can be attempted with any real hope of success. Specific work must be undertaken to provide the required information in the following categories: (1) the method of stabilizing the boundary layer so as to maintain laminar flow, (2) the method of reestablishing laminar flow when turbulence has arisen, and (3) further investigations on the design of intake slots.

Stabilizing the laminar flow. - The problem of stabilizing the laminar flow may be considered in two parts. The first part is the consideration of the amount of air that must be withdrawn in order to maintain stability. The experimental results indicate that there is some minimum quantity, apparently an amount sufficiently large so as to include the region in which the oscillations have reached their maximum amplitude. While this quantity has been tentatively set at $C_{Q\delta}$ = .150 (or about 22% of the boundary layer), the exact value is not known and further specific research is necessary to determine this quantity exactly. The second part of this problem is the spacing of the slots. Can the first slot and each succeeding slot be placed at the position where transition is just about to occur? Or is it necessary to place the slots somewhat ahead of this point, and, if so, how much?

Reestablishment of laminar flow. - Another problem closely allied to the above is the reestablishment of laminar flow after the boundary layer has become turbulent. How much of the turbulent layer must be removed for this purpose? It would seem reasonable to assume that the entire removal of the turbulent boundary layer is necessary to establish laminar flow. No definite information exists on this matter, however, and experiment may indicate a smaller or larger amount to be required. Specific research should be instituted to secure the answer to this question.

Design of intake slots. - Existing information on design of intake slots for drag reduction is very meager. The ideal slot will not produce a disturbance in the external flow and will reduce the inlet loss to a minimum value. There is some question as to the flow conditions in the slot under these circumstances. It has been suggested that it is necessary for transition to occur just within the entry so that the internal flow is turbulent. This again is a matter requiring complete investigation.

The above research should preferably be performed in a wind tunnel which is quite free of turbulence, such as the Bureau of Standards, the NACA, or the experimental tunnel at GALCIT. While some of this information could be obtained here, the question of spacing requires turbulent free air, perhaps flight tests.

Compressibility. - The research now in progress on the influence of the boundary layer on the nature of the shock wave should be continued. The delay of the critical region by means of boundary layer control also requires further investigation. This information is invaluable in order to appraise the possible gains at high Mach Numbers.

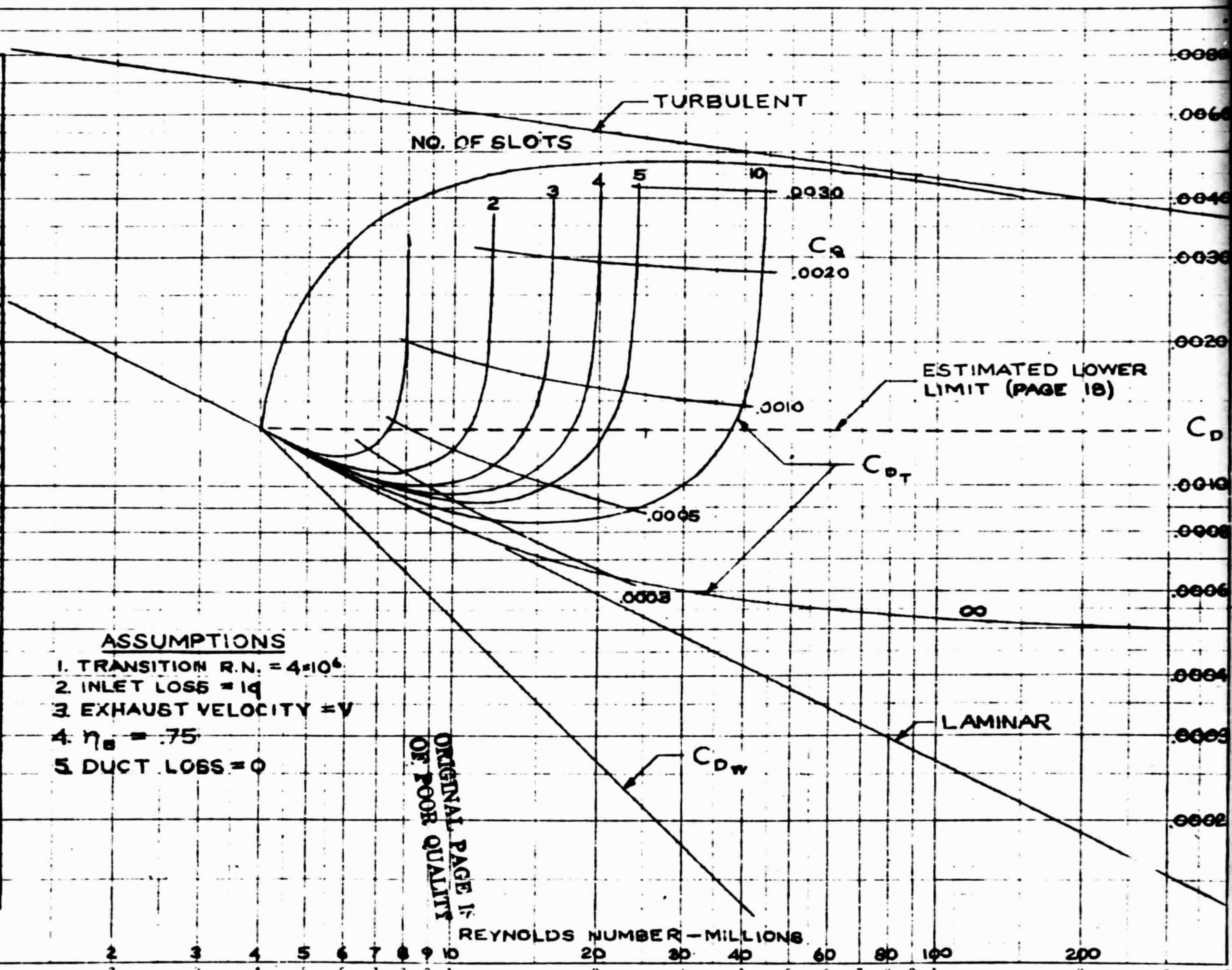

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			FIG. 2
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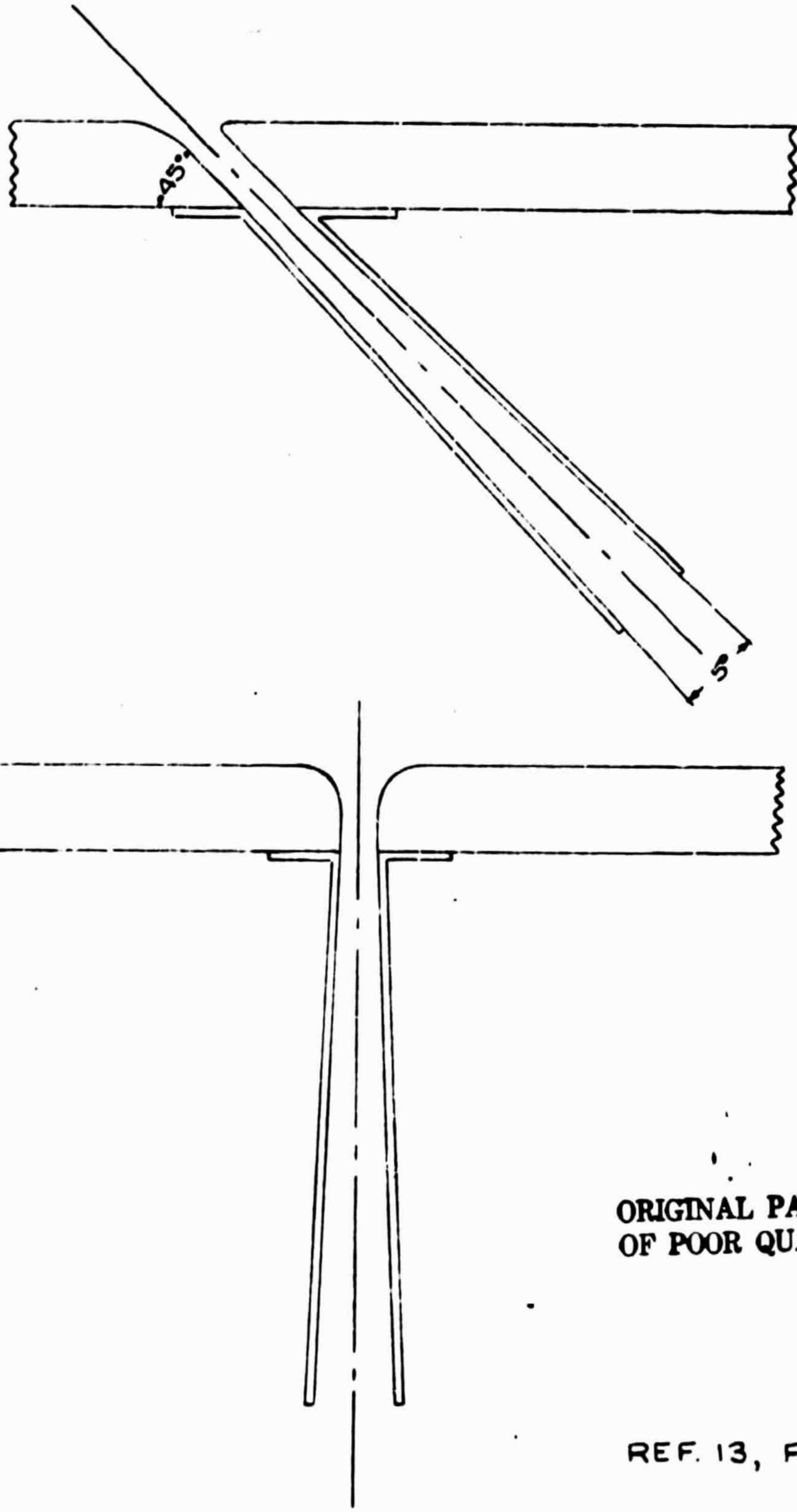

REF. 13, FIG. 2

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TYPES OF INTAKE SLOT

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FIG. 1

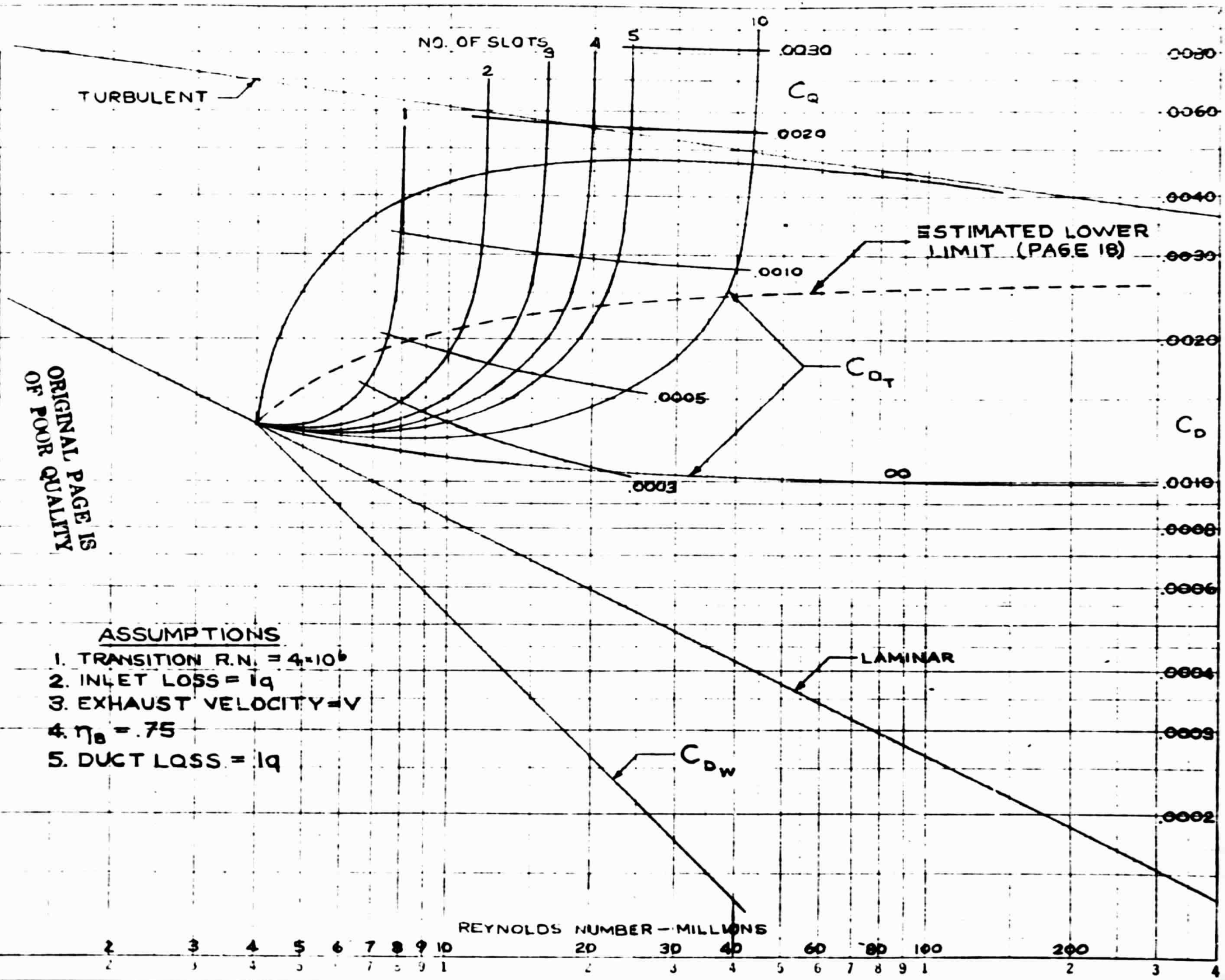

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		FIG. 4
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APPENDIX

COMPUTATIONAL METHOD

If the parabolic velocity distribution is assumed for the boundary layer, the ratio of local to stream velocity is given by

$$\frac{v}{V} = 1 - \left(1 - \frac{y}{\delta}\right)^2 \tag{7}$$

The quantity of air flowing per unit time in the strip between the surface and a distance y above the surface is given by

$$Q = \int_0^y v\,dy$$

or in coefficient form

$$C_{Q_\delta} \equiv \frac{Q}{V\delta} = \int_0^{y/\delta} \frac{v}{V}\frac{dy}{\delta}$$

$$= \left(\frac{y}{\delta}\right)^2\left(1 - \frac{1}{3}\frac{y}{\delta}\right) \tag{8}$$

The momentum loss per unit time in this space is given by

$$M\Big|_0^y = \rho\int_0^y (V-v)\,v\,dy$$

$$= \rho V^2\delta\left[\frac{2}{15} - \frac{1}{3}\left(1-\frac{y}{\delta}\right)^3 + \frac{1}{5}\left(1-\frac{y}{\delta}\right)^5\right] \tag{9}$$

The drag is given by

$$D = M\Big|_0^\delta = \frac{2}{15}\rho V^2\delta$$

and the momentum thickness is given by

$$\theta = \frac{M}{\rho V^2} = \frac{2}{15}\delta$$

With boundary layer control a certain amount of air, C_{Q_δ}, is removed at a slot corresponding to a layer of width y. The momentum loss in the remaining boundary layer is given by

$$M\Big|_y^\delta = \rho\int_y^\delta (V-v)\,v\,dy$$

$$= \rho V^2\delta\left[\frac{1}{3}\left(1-\frac{y}{\delta}\right)^3 - \frac{1}{5}\left(1-\frac{y}{\delta}\right)^5\right] \tag{10}$$

Further downstream there exists a new boundary layer with a thickness greater than that normally created in the distance from the slot, because of the presence of the unremoved boundary layer. It is assumed that immediately after the slot the unremoved air is rearranged into a parabolic velocity distribution having a new thickness δ' but with the same momentum as that represented by equation (10). That is,

$$M\Big|_y^{\delta} = M\Big|_0^{\delta'} = \frac{2}{15}\rho V^2 \delta'$$

then

$$\frac{\delta'}{\delta} = \frac{5}{2}\left(1-\frac{y}{\delta}\right)^3 - \frac{3}{2}\left(1-\frac{y}{\delta}\right)^5 \qquad (11)$$

The boundary layer develops along a flat plate, with the parabolic law as follows:

$$\delta = 5.50\sqrt{\frac{\nu x}{V}}$$

and the thickness δ' is equivalent to a reduction of local surface Reynolds Number to a value R_x', then

$$\frac{R_x'}{R_x} = \frac{x'}{x} = \left(\frac{\delta'}{\delta}\right)^2 \qquad (12)$$

Using y/δ as parameter, C_{Q_δ} can be computed as a function of R_x'/R_x using equations (8), (11), and (12). This function is presented in figure 5.

Now if a wing is to be operated at a design value R_l, the minimum number of slots required is the integer in the ratio R_l/R_x. If it is decided to use n slots the required value of R_x' is given by

$$R_x' = R_x - \frac{R_l - R_x}{n}$$

or

$$\frac{R_x'}{R_x} = 1 - \frac{R_l/R_x - 1}{n} \qquad (13)$$

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and from figure 4 the required value of C_{Q_δ} may be determined.

The total number of slots is 2 n, allowing for both surfaces, and the total volume coefficient is therefore

$$C_Q = 2n\, C_{Q\delta} \frac{\delta}{l}$$

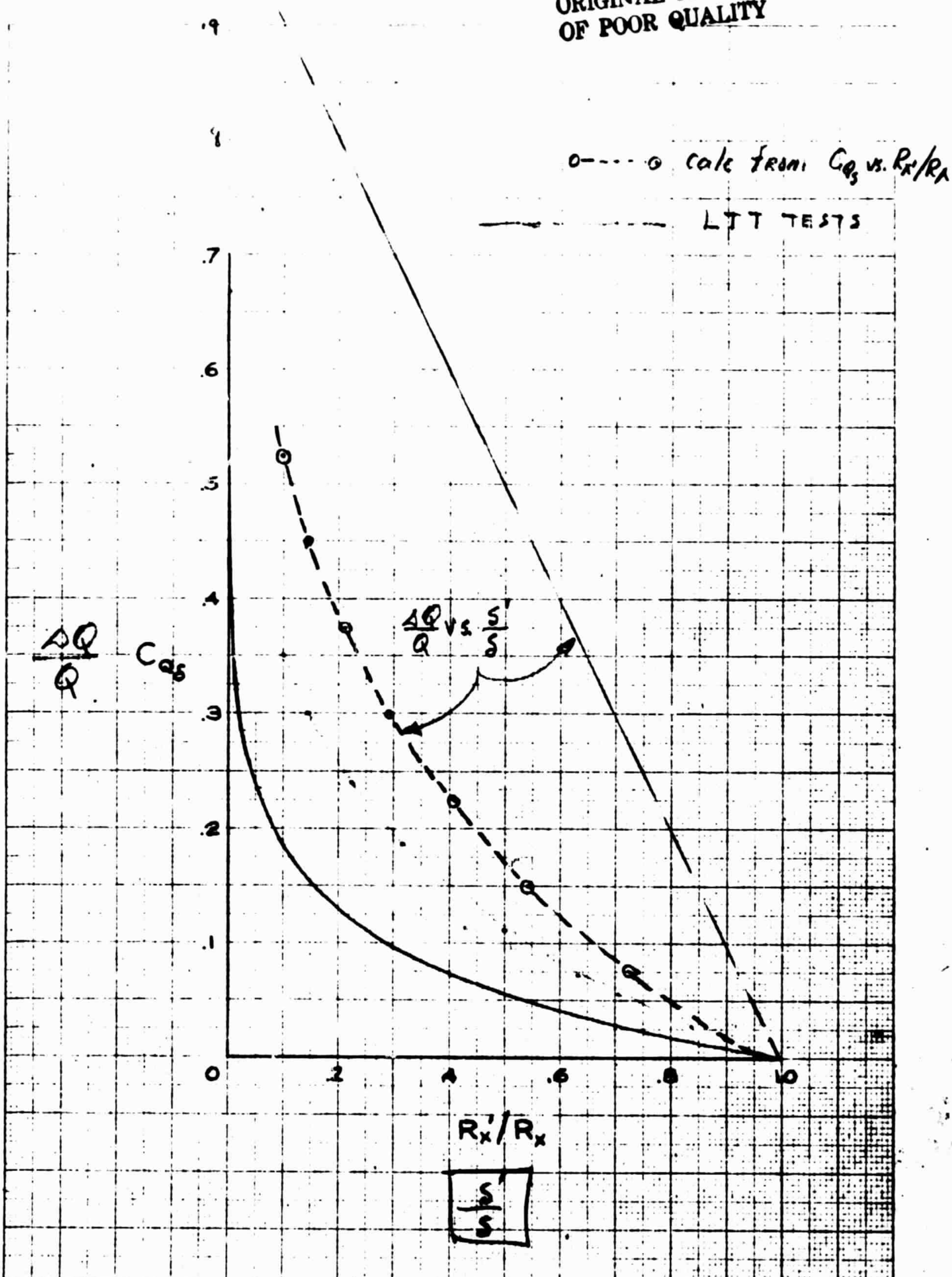
$$= 2n\, C_{Q\delta} \frac{\delta}{x} \frac{x}{l}$$

$$= 11n \frac{C_{Q\delta}}{\sqrt{R_x}} \frac{R_x}{R_l} \qquad (14)$$

The equivalent drag coefficient for the power expended by the blower is by equation (3)

$$C_{D_B} = \frac{1}{\eta_B} C_Q (1 - C_P + K)$$

which assumes the discharge velocity to be equal to flight velocity. Figures 1 to 4 were constructed by assuming the inlet loss to be equal to q, i.e. $C_P = 0$, and using duct loss coefficients of $K = 0$, .5, and 1., with $\eta_B = 0.75$.



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C_{Q_δ} vs. R_x'/R_x

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FIG. 8
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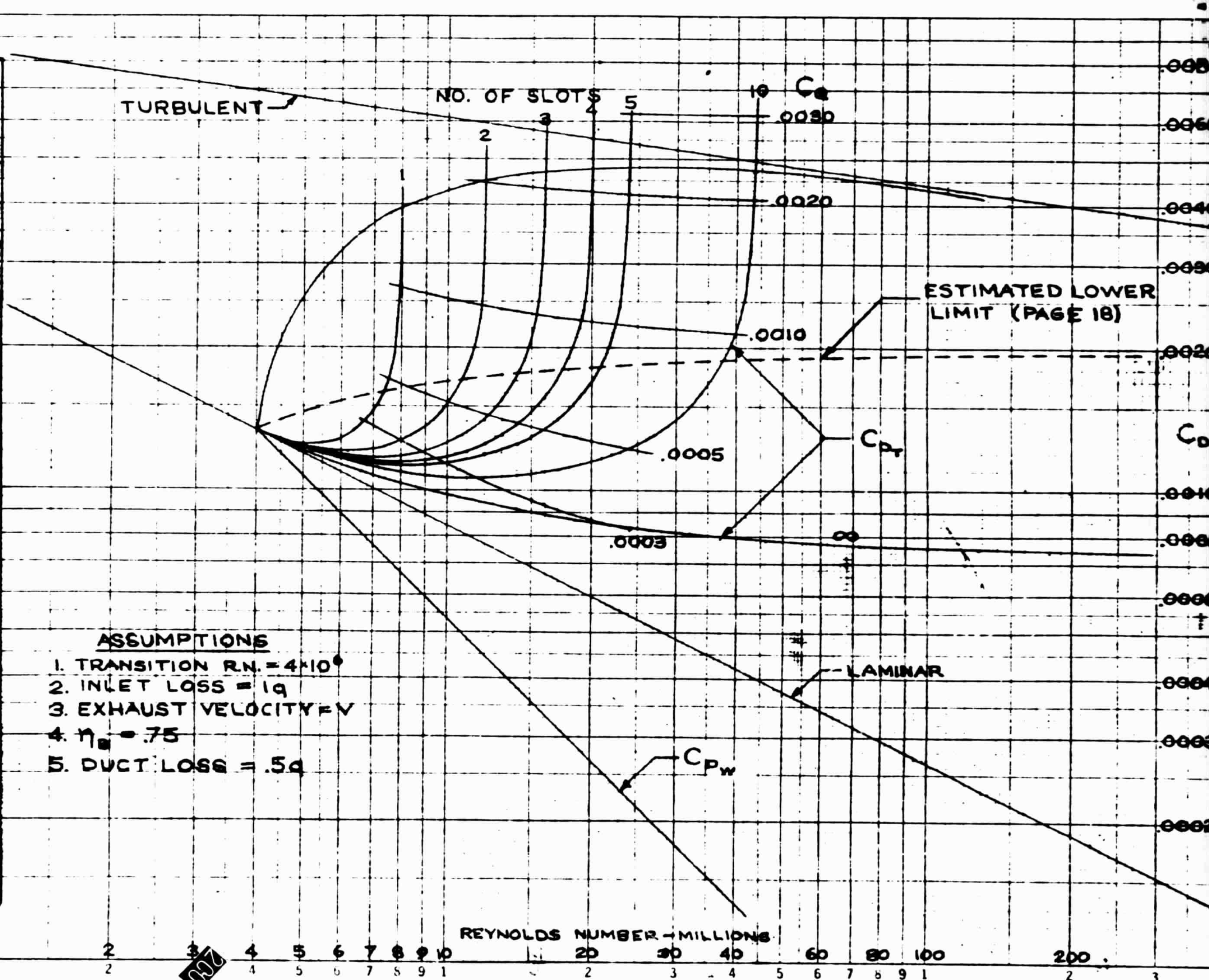
CONTRACT NO.

NO. 319 MILLIMETERS 180 BY 22? DIVISIONS



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DRAG POSSIBILITIES WITH BOUNDARY LAYER CONTROL

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FIG. 8

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