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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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WIND-TUNNEL INVESTIGATION OF RECTANGULAR AIR-DUCT ENTRANCES IN THE LEADING EDGE OF AN NACA 23018 WING

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SUMMARY

A preliminary investigation of a number of duct entrances of rectangular shape installed in the leading edge of a wing was conducted in the NACA 20-foot tunnel to determine the external drag, the available pressure, the critical Mach numbers, and the effect on the maximum lift.

The results showed that the most satisfactory entrances, which had practically no effect on the wing characteristics, had their lips approximately in the vertical plane of the leading edge of the wing. This requirement necessitated extending the lips outside the wing contour for all except the small entrances. Full dynamic pressure was found to be available over a fairly wide range of angle of attack. The critical Mach number for a small entrance was calculated to be about as high as that for the plain wing but was slightly lower for the larger entrances tested.

INTRODUCTION

The National Advisory Committee for Aeronautics conducted in 1938 a preliminary investigation of a radial-engine cooling system that admitted cooling air into air ducts located in the leading edge of wing roots in the propeller slipstream. These tests showed considerable promise, provided that suitable and efficient entrances could be made. These tests being a preliminary investigation of a complete cooling system, only a limited amount of attention could be given to the various components of the system. A program was therefore started to test duct entrances of various size and shape to provide design information that could be used not only in connection with a wind-duct cooling system but also with any duct system requiring entrances in the leading edge of the wing.

Duct entrances in the leading edge of a wing should have the following properties: (a) low external drag; (b) no adverse effect on the stalling characteristics of the wing; (c) maximum pressure available throughout the take-off, climb, and high-speed flight conditions; and (d) high critical Mach number for high-speed airplanes.

This paper presents the results of preliminary tests made to study these features. In order to simplify this investigation, most of the tests were made with the limiting condition of no air flow in the duct. This condition is believed to have the highest external drag that would be obtained with any internal flow condition.

APPARATUS AND METHODS

The tests were conducted in the NACA 20-foot wind tunnel. A wing of 5-foot chord and 15-foot span of NACA 23018 section was used as the basic model; to this wing were added various rectangular leading-edge duct entrances. (See figs. 1 and 2.) The various entrances tested are identified by sketches in the figures which present the tests results.

The lift and the drag of the wing with duct entrances were measured on the usual force balance system. Pressures within the entrances were measured to determine the total pressure available and the velocity of flow for these tests in which internal air flow existed. Pressure-distribution surveys were made over the outer surfaces of several entrance lips to determine critical Mach numbers.

Most of the polar tests, for which only lift, drag, and available pressure were measured, were made with no cooling air allowed to flow through the duct. In the tests for which the effect of cooling-air flow on the external drag was investigated and in all tests to determine the critical Mach numbers of the entrance lips, air was allowed to flow through the duct and out through a variable-area exit located in the lower surface of the wing.

At the beginning of the program, some of the entrances were found to have no appreciable effect on the wing characteristics as determined from the force balance system. Several check tests were therefore made with the wake-survey method described in reference 1 to determine the drag more accurately. A wake-survey comb (similar to the one described in reference 1) was mounted on a carriage behind the wing and was capable of traversing the central part of the span. (See fig. 3.)

The wake-survey method was also used to isolate the external drag of the entrance for the few tests in which air was allowed to flow through the duct. The wake from the cooling air, which emerged from the lower surface of the wing, was restrained from mixing with the wake from the upper surface of the wing by a thin plate fastened to the trailing edge of the wing and extending behind it to the survey comb. The increased drag of the upper surface obtained in this manner was assumed to be proportional to the external drag of the entrance with air flowing through the duct.

The critical Mach numbers of several entrances were calculated by the method given in reference 2 from measurements of peak negative pressures over the upper and the lower lips.

RESULTS AND DISCUSSION

The results are presented in the following nondimensional units:

$C_L = \dfrac{\text{wing lift}}{qS}$, lift coefficient

$C_D = \dfrac{\text{total drag}}{qS}$, drag coefficient

$C_{D_d} = \dfrac{\text{total drag} - \text{drag of wing alone}}{q \times \text{entrance area}}$, duct entrance drag coefficient

C_{L_s} lift coefficient at point of local stall

p/q total pressure ratio within entrance

M Mach number (V/a)

M_{cr} Mach number at which compressibility occurs where q dynamic pressure

S wing area

p total pressure in duct entrance

V velocity

and a velocity of sound in air

V_1 velocity within entrance

c wing chord

t wing thickness

α uncorrected angle of attack

In figures 4 to 13 the results are presented for the tests of the entrances having no internal air flow. Figure 6 also shows the effect of flow on the pressure distribution. The computed critical Mach numbers are given for several entraces in figures 14 to 18.

Although curves of lift, drag, and pressure plotted against angle of attack or in the form of polars are ideal methods of presenting the results, the amount of data involved makes these methods too cumbersome. The results are therefore presented for the most part in the form of summary tables with the figures showing the entrance profiles.

Typical Curves Showing Results

In figure 4 the polar curve for the wing alone is given together with the polar curves for a typical "good" entrance and a typical "poor" entrance. It may be noted that the drag of the wing was scarcely affected by the presence of entrance ON at a lift coefficient 0.2 but that entrance AE increased the wing drag about 10 percent. Entrance ON had little effect on the lift coefficient at the stall; but entrance AE precipitated a stall at a lift coefficient of only 0.55.

Figure 5 shows curves of the total pressures available in the duct entrance in terms of dynamic pressure plotted against the angle of attack of the wing. Full dynamic pressure is available for both entrances up to an angle of attack of about 6°, beyond which the pressure gradually decreases. The pressure criterion used in this analysis is the angle-of-attack range at which at least 0.9 dynamic pressure is available. This angle range is from −4° to 11° for duct ON. Of further interest is the effect of the stall on the pressures for entrance AE. The pressure within entrances, in general, gradually decreases after a certain angle of attack is reached, but it may be noted that the pressure remains fairly high for high angles of attack after the entrance precipitates a local stall.

The pressure-distribution plot shown in figure 6 is only an intermediate step in calculating the critical Mach number; the principal points of interest are the shape of the curves and the magnitude of the peak negative pressures; the values of the peak negative pressures determine the critical speeds.

Entrance

Characteristics, No Cooling-Air Flow

In figures 7 to 13 are tabulated the values of the lift, the drag, and the pressure criteria for the entrances tested under the condition of zero cooling-air flow. This condition of zero flow is probably more severe than any flight condition obtainable from all considerations because the flow of cooling air lessens spillage and the need for large curvature lips. It should be pointed out that entrances which appear good from these tests will probably be good under all conditions and that entrances which appear poor may not be necessarily poor under more favorable flow conditions.

Figure 7 gives the results of the flush-entrance tests. A progressive cutting into either the lower or the upper surfaces of the wing as a means of increasing the entrance size is seen to increase the drag coefficient of the entrance rapidly, particularly for the upper surface. With the upper surface cut back to B or A, the lift coefficient at point of local stall was greatly decreased because of an early separation at the upper lip.

Figure 8 shows the effect of progressively moving the lower lip forward. The effect was generally beneficial from drag considerations but had very little effect on the lift coefficient at the point of local stall.

In figures 9 and 10, the results are given for the series of tests covering the progressively forward movements of both the upper and the lower lips for two sizes of entrance. Although the lip thickness was varied in some cases, the results show that the optimum location for the plane of opening is near the leading edge of the wing. The flush entrance AE, which had a high drag and a low lift coefficient at local stall C_{L_s}, was greatly improved by being moved slightly forward and by increasing the curvature of the upper lip. Although the effects of entrance location and of the lip curvature are not isolated in figure 9, they are in figure 10, in which figure the location is shown to be the most important variable.

In figure 11, the results are given for a series of entrances of different width. The drag per unit of entrance area slightly decreased as the width was increased. This result suggests that the sides of the entrance were prominent sources of drag. The wake-survey results also show a high concentration of energy loss at each side of the entrances. These tests show the need for more careful design of the transition from the entrance to the wing at each end of the opening. Entrances with more gradual transition of the end of the opening into the wing would probably have less drag than the square ends used for these tests.

Wake-survey drag tests were made to check the force tests for three of the entrances. The results (fig. 11) are in fair agreement with C_{D_d} at $C_{D_{min}}$.

In figure 12, a comparison is made between two large entrances, CP and ON, that differ chiefly in their vertical location. Entrance ON, the lips of which are about equidistant from the chord line, is better than entrance CP, which has lower lips. The smaller entrance CN has a lower drag per unit of area than either of the other two.

Figure 13 shows the effect of variations in upper-surface curvature. Little effect in either the drag or the maximum lift coefficient was found by changing the curvature of the upper lip of the largest entrance, but the drag of the smaller entrance was definitely increased by adding thickness to the upper lip. Check drag tests with the wake-survey apparatus indicate a somewhat higher drag than that obtained with the force balance; the drag measured was small, however, when either method was used.

Effect of Cooling-Air Flow on the External Drag

In order to determine the effect of flow on the external drag of one of the best entrances tested, air was allowed to flow into entrance RL' and out through a bottom exit, as shown in figure 1. The drag of the upper portion of the entrance, which is an unknown fraction of the total external drag of the entrance, was separated from the drag associated with the internal flow by making a wake survey of the flow over only the upper surface of the wing. The results, which are only qualitative, show that the external drag of this entrance remains about constant for internal-flow velocities between the values of 0 and 0.6 free-stream velocity but that it rapidly decreases at higher values of internal velocities. In other research at the laboratory on entrances of different shape, the external drag has been found to decrease with increasing internal flow but not necessarily in the same manner as was found in this investigation.

Critical-Speed Determination

Several surface-pressure surveys were made to determine the Mach numbers at which the local speed of sound over the entrance lips would be obtained; this value is known as the critical Mach number. The surveys were made over the outer surfaces of several representative entrances; the results are given in figures 14 to 18. Critical Mach numbers computed with the use of figure 22 of reference 2 are presented for several values of cooling-air velocity and angles of attack of the wing that are representative of high-speed flight.

In figure 14(a) the critical Mach numbers are given for the flush lip C of entrance CL'. The critical speed is slightly higher for the lip than for the wing alone except for a small range of flow and angle-of-attack values. The critical speed for the lower lip L' (fig. 14(b)) is higher than for the wing alone except for a range of small flow and low angle-of-attack values, which are probably out of the useful range. Entrance CL' is therefore seen to have a critical speed that is a little, if any, lower than that of the wing within the probably useful range of the flow coefficient and the angle of attack.

Figures 15 to 17 give the critical Mach numbers for a series of entrances that have variations in the curvature and the thickness of only the top lip. (See figs. 11 and 13 for the shape of lips.) Lip I' has critical Mach numbers exceeding those of the wing alone for a limited range of low angles of attack and high flow velocities. The critical speeds are very low for low flow velocities and relatively high angles of attack. The thicker lips R and Q have somewhat higher critical speeds than lip I'. The critical speed for lip Q, for example, is 3 to 11 percent lower, in the useful range, than for the wing alone. The lower lip L' is satisfactory over the useful range in that the critical Mach number is higher than for the wing alone.

Figure 18 gives the results for entrance H'L' and shows that this entrance has a critical speed 13 to 27 percent below that for the wing in the useful range.

CONCLUDING REMARKS

The result of these tests, which were of a preliminary nature in that they covered a wide range of entrance sizes and shapes with a simplified test procedure, indicates that duct entrances with their lips approximately in the vertical plane of the wing leading edge had only a slight effect on the maximum lift, the minimum drag, and the critical speed of an NACA 23018 wing . Satisfactory pressures within the ducts were also found to be available. Moving the upper or the lower lip in the rearward direction had, in general, an adverse effect on the wing characteristics.

Further tests intended to perfect a few of the best entrances are planned in which a more refined test procedure will be followed.

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2. Stack, John, Lindsey, W. F., and Littell, Robert E.: The Compressibility Burble and the Effect of Compressibility on Pressures and Forces Acting on an Airfoil. Rep. No. 646, NACA, 1938.

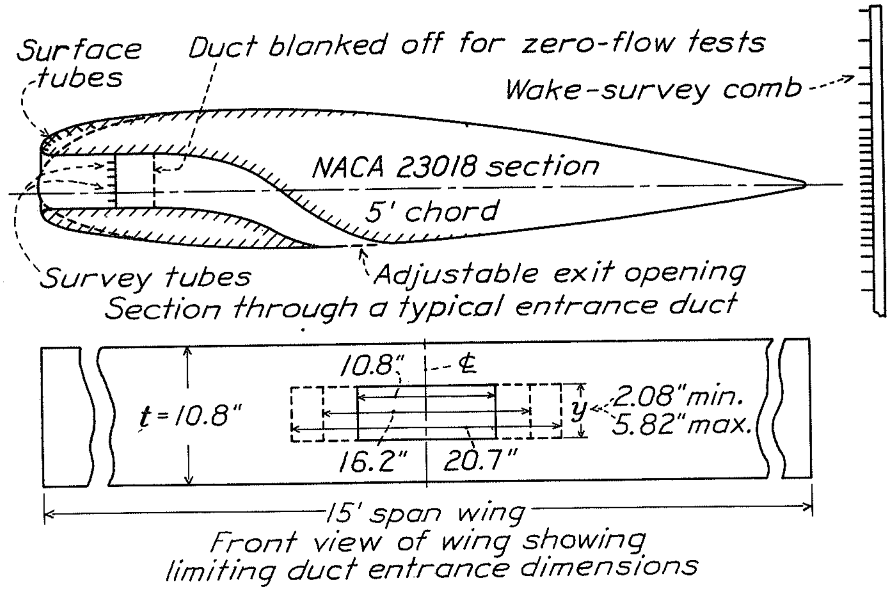


Figure 1.- Details of wing-duct set-up.

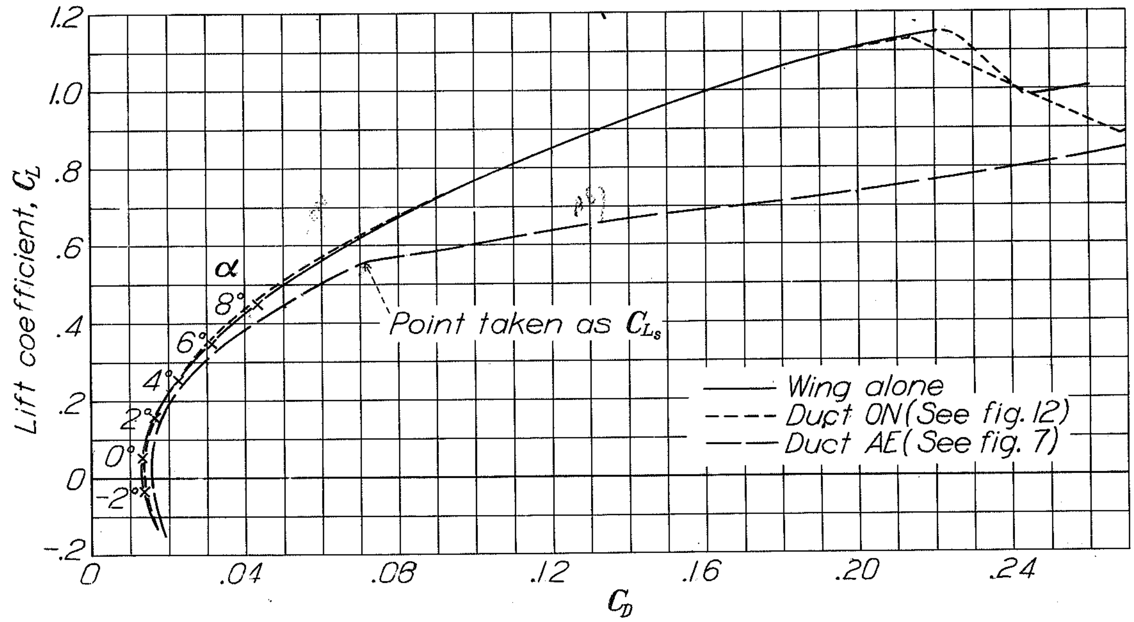


Figure 4.- Typical polars of wing showing the effect of the presence of two duct entrances.

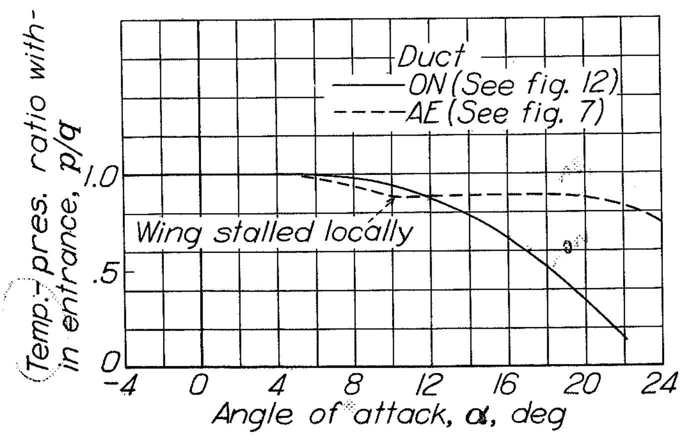


Figure 5.- Typical curves of available pressure for two duct entrances.

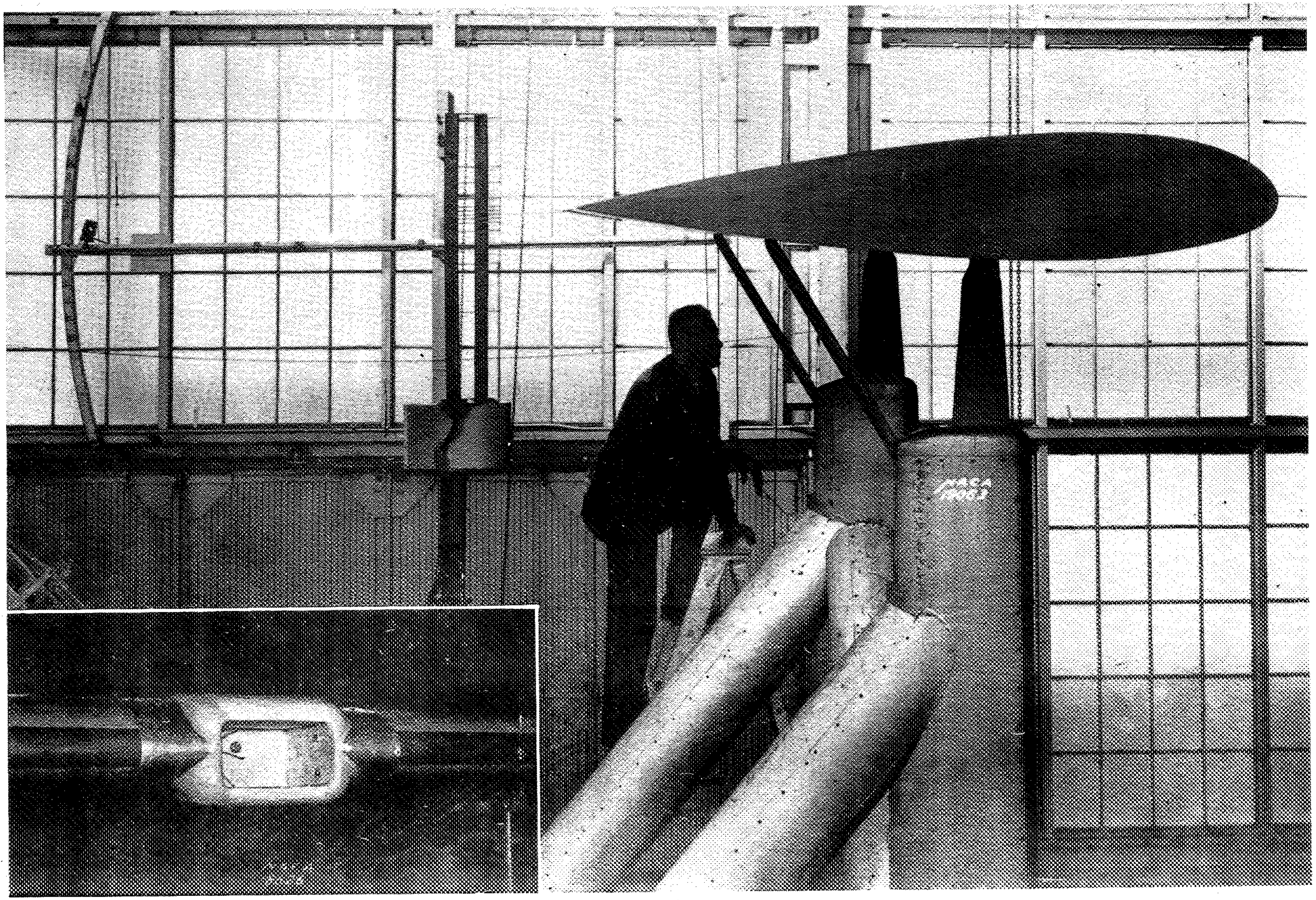


Figure 2.- Close-up of
typical entrance.

Figure 3.- Wing mounted for wake-survey tests.

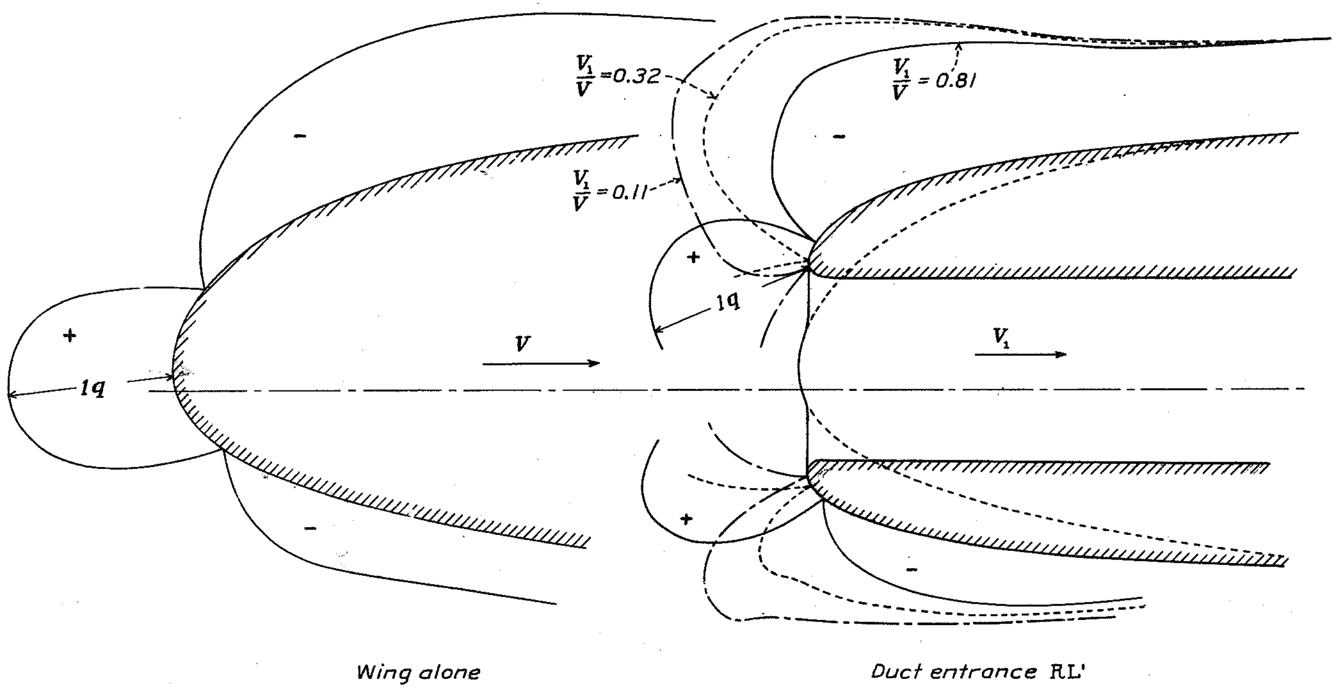
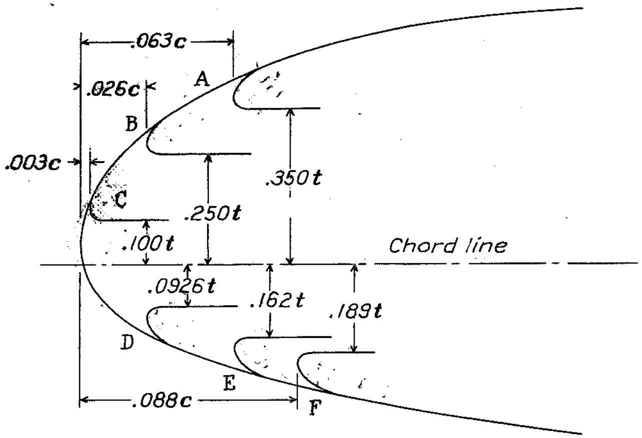
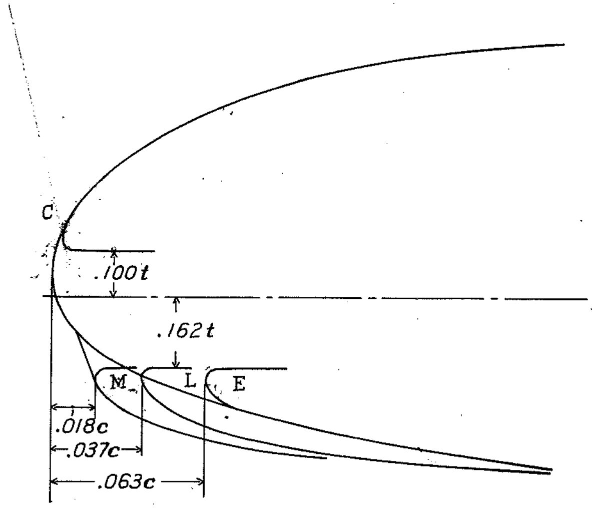


Figure 6.- Typical pressure distribution.
Angle of attack, 1°.



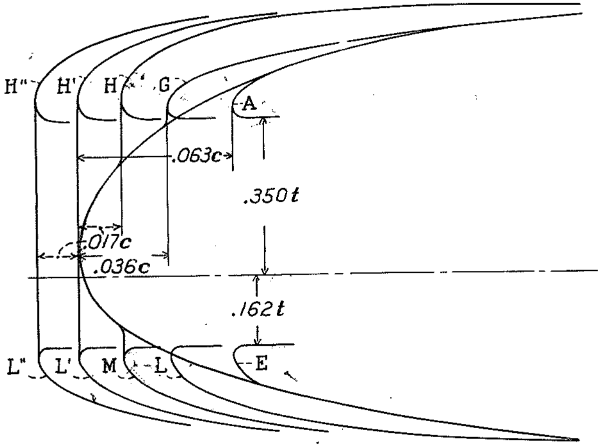
Duct	AF	AE	BF	BE	BD	CF	CE	CD
C_{D_d} ($C_{D_{min}}$)	.40	.35	.28	.18	.23	.24	.12	.13
C_{D_d} (C_L=0.2)	.44	.35	.19	.20	.22	.22	.07	0
C_{L_S}	.42	.54	.66	.69	.95	1.12	1.11	1.13
Range of α for .9q pressure, deg	-4 to 22	-4 to 22	-4 to 22	-4 to 22	-4 to 9	1 to 22	1 to 22	-1 to 15
Entrance area, sq ft	.441	.413	.362	.332	.275	.242	.212	.156

Figure 7.- Results of flush-entrance tests. Zero flow; entrance width equal to wing thickness.



Duct	CE	CL	CM
C_{D_d} ($C_{D_{min}}$)	.12	.06	.04
C_{D_d} (C_L=0.2)	.07	.02	.02
C_{L_S}	1.11	1.15	1.16
Range of α for .9q pressure, deg	1 to 22	-1 to 18	-4 to 13
Entrance area, sq ft	.212	.212	.212

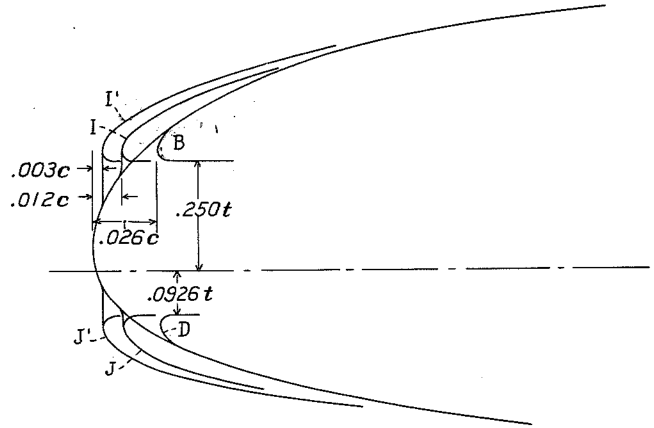
Figure 8.- Effect of lower lip, fore-and-aft locations. Zero flow; entrance width equal to wing thickness.



Duct	AE	GL	HM	H'L'	H"L"
C_{D_d} ($C_{D_{min}}$)	.35	.23	.07	.05	.06
C_{D_d} (C_L=0.2)	.35	.14	.05	.02	.02
C_{L_S}	.54	.59	1.14	1.14	1.16
Range of α for .9q pressure, deg	-4 to 22	-4 to 9	-4 to 10	-4 to 11	-4 to 11
Entrance area, sq ft	.413	.413	.413	.413	.413

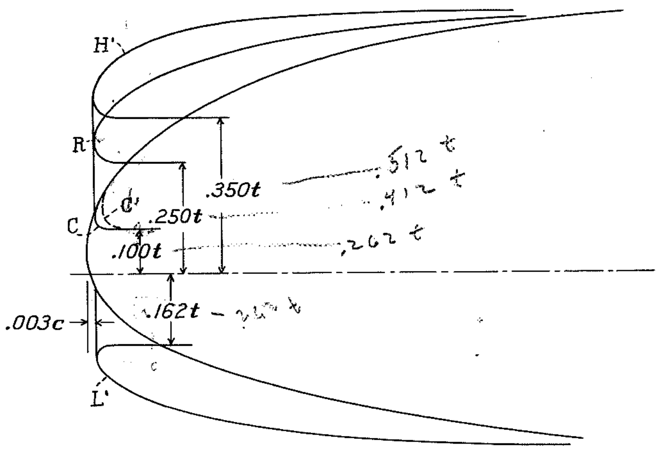
.0001

Figure 9.- Entrance at various fore-and-aft locations. Large entrances; zero flow; entrance width equal to wing thickness.



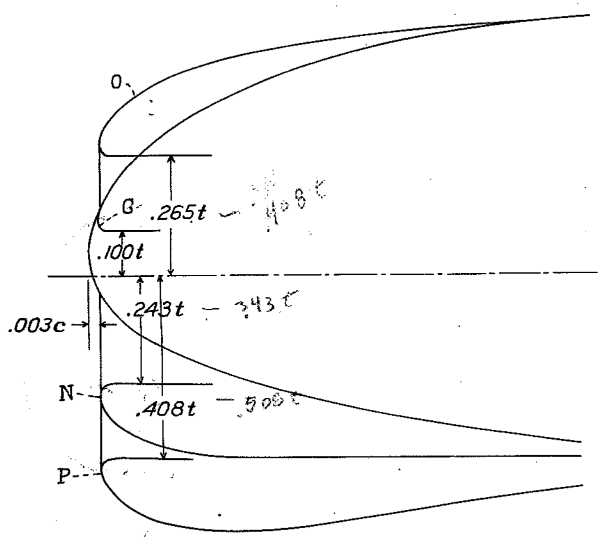
Duct	BD	IJ	I'J'
C_{D_d} ($C_{D_{min}}$)	.23	.08	.05
C_{D_d} (C_L=0.2)	.22	.05	.05
C_{L_S}	.95	1.13	1.14
Range of α for .9q pressure, deg	-4 to 8	-4 to 9	-4 to 9
Entrance area, sq ft	.275	.275	.275

Figure 10.- Entrances at various fore-and-aft locations. Small entrances; zero flow; entrance width equal to wing thickness.



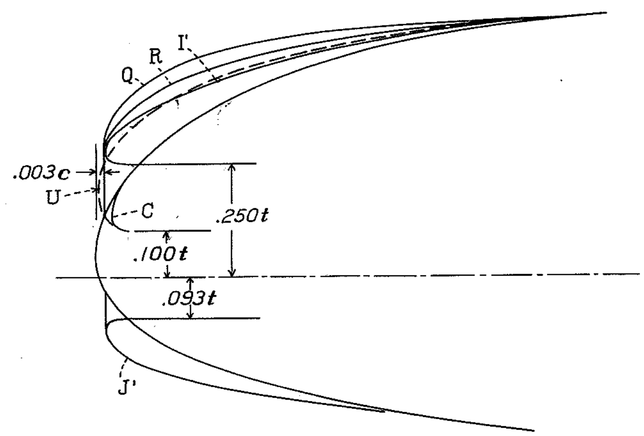
Duct width	t			1.50t			1.92t		
Duct	CL'	RL'	H'L'	CL'	RL'	H'L'	C'L'	RL'	H'L'
C_{D_d} ($C_{D_{min}}$)	.06	.06	.06	.05	.05	.05	.04	.04	.04
C_{D_d} (C_L=0.2)	.07	.05	.07	.06	.03	.05	.05	.06	.04
C_{L_S}	1.15	1.12	1.14	1.14	1.13	1.14	1.13	1.13	1.13
Range of α for .9q pressure, deg	-4 to 10	-4 to 11	-4 to 11	-4 to 10	-4 to 11	-4 to 11	-4 to 11	-4 to 11	-4 to 11
C_{D_d} from wake survey tests	.08	.07	.06	-	-	-	-	-	-
Entrance area, sq ft	.212	.332	.413	.318	.497	.620	.407	.637	.793

Figure 11.- Effect of entrance proportions. Zero flow.



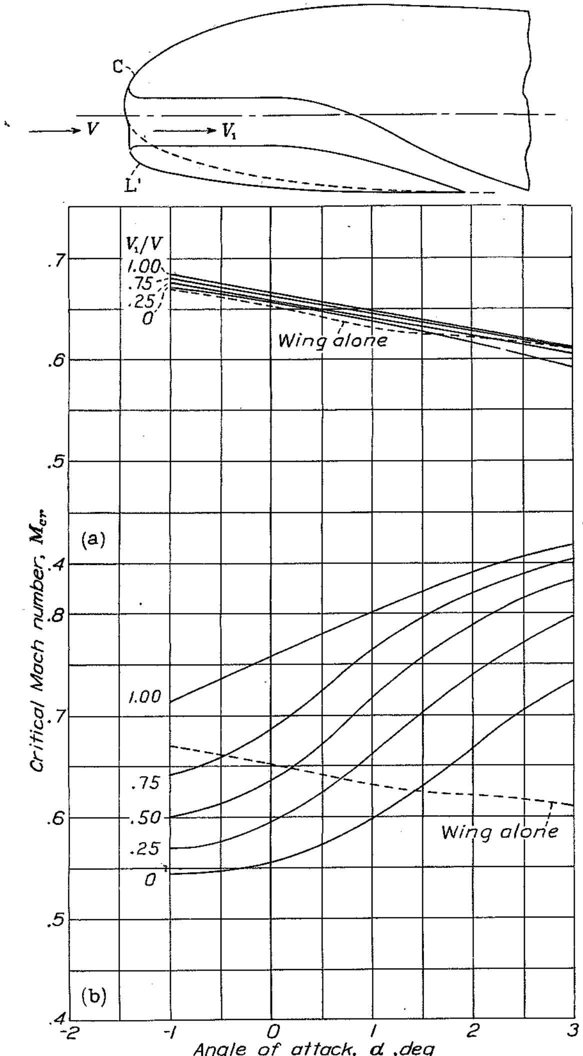
Duct	CP	CN	ON
C_{D_d} ($C_{D_{min}}$)	.12	.05	.09
C_{D_d} (C_L=0.2)	.07	.03	.05
C_{L_S}	1.12	1.07	1.13
Range of α for .9q pressure, deg	-4 to 14	-4 to 12	-4 to 12
Entrance area, sq ft	.413	.272	.413

Figure 12.- Effect of vertical location of upper and lower lips. Zero flow; entrance width equal to wing thickness.

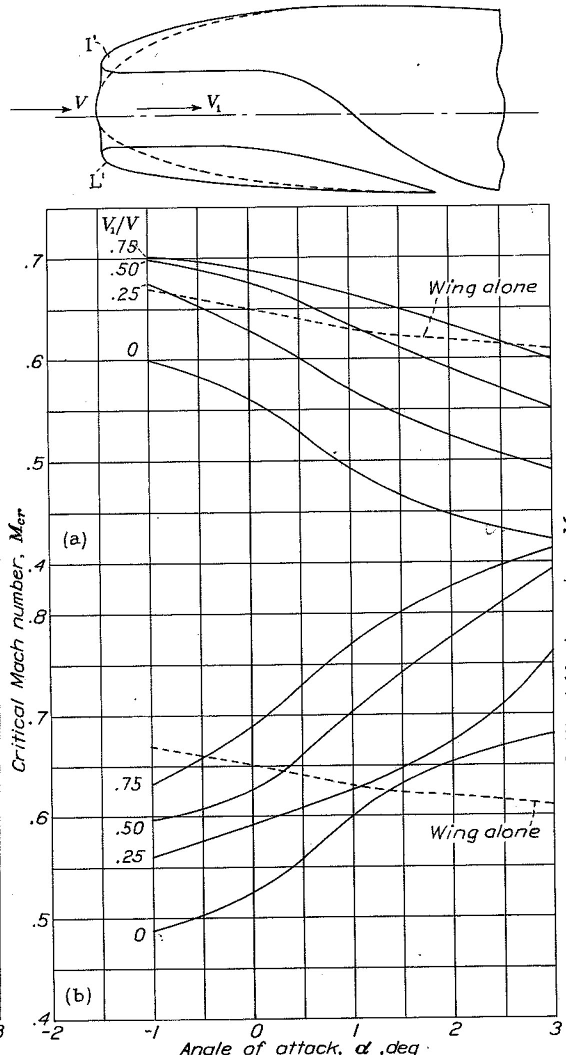


Duct width	t			1.92t	
Duct	Q J'	R J'	I' J'	C J'	U J'
C_{D_d} ($C_{D_{min}}$)	.05	.05	.05	.05	.09
C_{D_d} (C_L=0.2)	.06	.05	.05	.07	.10
C_{L_S}	1.13	1.12	1.11	1.13	1.15
Range of α for .9q pressure, deg	-4 to 13	-4 to 13	-4 to 12	-4 to 10	-4 to 12
C_{D_d} from wake survey tests	.07	.07	.07	-	-
Entrance area, sq ft	.275	.275	.275	.325	.325

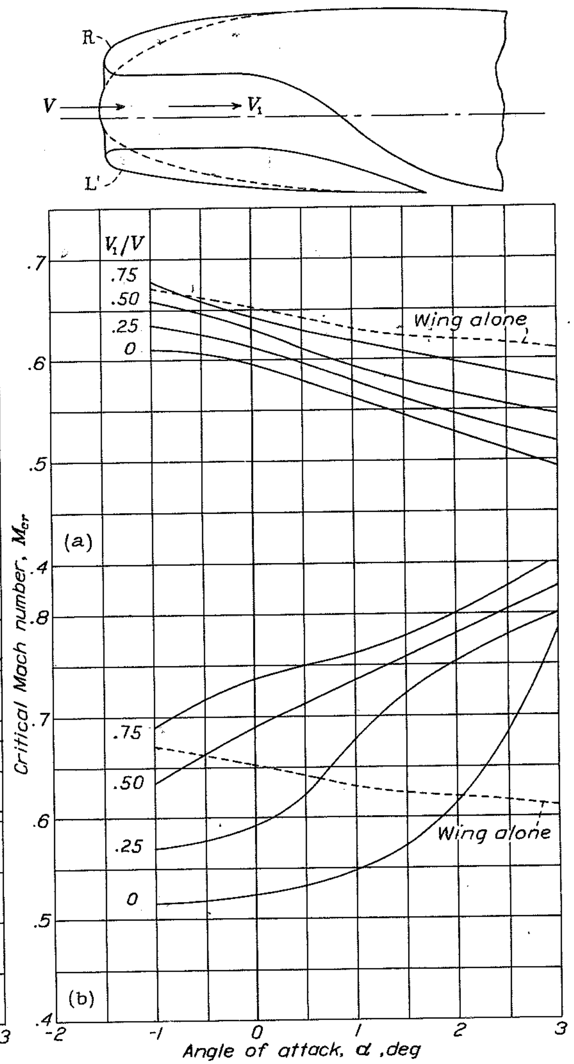
Figure 13.- Effect of variations in upper surface curvature. Zero flow.



(a) Lip C of entrance CL' (b) Lip L' of entrance CL'
Figure 14

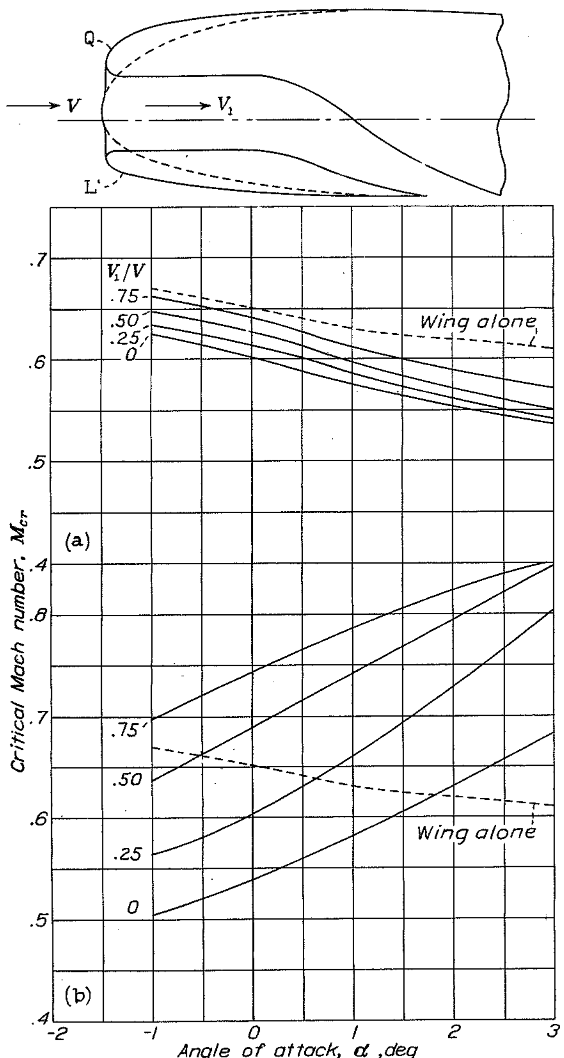


(a) Lip I' of entrance I'L'. (b) Lip L' of entrance I'L'.
Figure 15

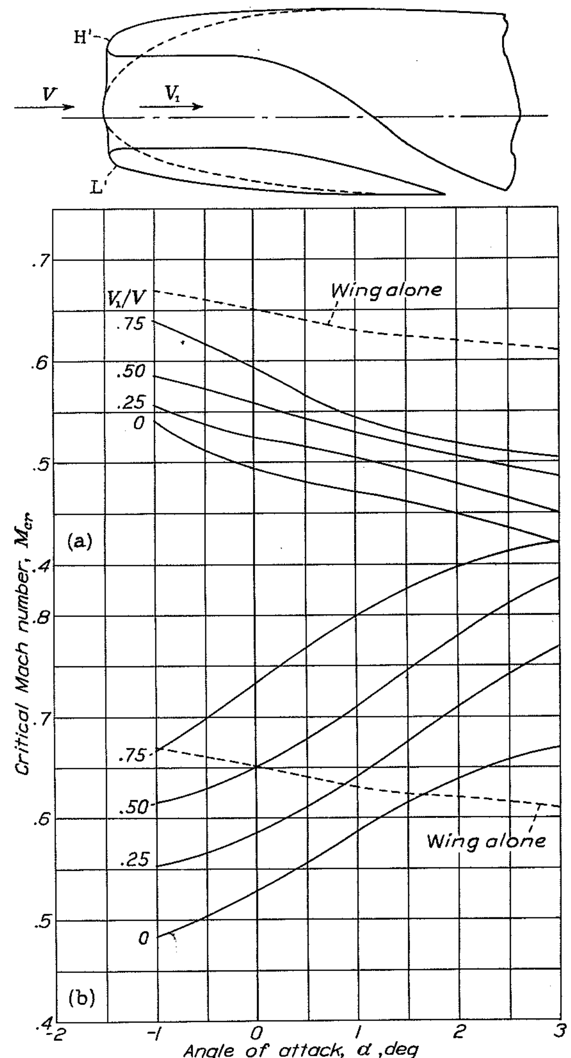


(a) Lip R of entrance RL'. (b) Lip L' of entrance RL'
Figure 16

Figures 14,15,16.- Critical Mach numbers obtained from surface-pressure surveys over outer surfaces of representative entrances.



(a) Lip Q of entrance QL'. (b) Lip L' of entrance QL'.
Figure 17.



(a) Lip H' of entrance H'L'. (b) Lip L' of duct H'L'.
Figure 18

Figures 17,18.- Critical Mach numbers obtained from surface-pressure surveys over outer surfaces of representative entrances.