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EXPERIMENTAL INVESTIGATION OF AN NACA 64A010 AIRFOIL SECTION WITH 41 SUCTION SLOTS ON EACH SURFACE FOR CONTROL OF LAMINAR BOUNDARY LAYER

By Dale L. Burrows and Milton A. Schwartzberg

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

An investigation has been made of boundary-layer suction through flush surface slots as a means for increasing the extent of laminar flow on the NACA 64A010 airfoil section. The 3-foot-chord model was designed according to an analysis presented herein to maintain nearly full-chord laminar flow at Reynolds numbers up to 25×10^6 with the use of 41 suction slots on each surface.

Laminar flow was maintained over at least 0.91 chord on one surface up to a Reynolds number of 10×10^6. A like extent of laminar flow on the other surface would have resulted in a net drag saving of about 50 percent over the plain smooth airfoil at Reynolds numbers as high as 10×10^6. This result was obtained only after the expenditure of a great amount of effort in forming slot-entry contours that would not cause transition and in maintaining the surfaces of the model and the edges of the slots sufficiently smooth. Extensive laminar flow was not obtained at higher Reynolds numbers because of the increasing sensitivity of the flow to minute surface irregularities and slight inaccuracies of slot-entry contour.

INTRODUCTION

The advantages resulting from the attainment of extensive laminar flow over an aerodynamic surface are well-known. The extent of laminar flow may be limited because of high Reynolds number, surface imperfections, stream turbulence, adverse pressure gradient, or some combination of these factors.

The possibility of increasing the extent of laminar flow (by removal of air from the boundary layer) has received appreciable attention. Two methods for such removal are continuously distributed suction through a porous surface and suction through a number of spanwise slots. Both of these methods serve to delay laminar separation and also limit the growth of the laminar boundary layer so that the adverse effect of increasing wing Reynolds number on transition is decreased. In addition, according to laminar stability theory, continuous suction increases the stability of the boundary layer to small disturbances. The results of an experimental investigation of continuous suction are reported in references 1 and 2.

Several investigations have been made of suction slots as a means of increasing the chordwise extent of the laminar boundary layer on an airfoil surface. The primary purpose of such investigations was to determine if the combined wake and suction drag of a slotted laminar-flow airfoil could be appreciably reduced in comparison with the drag of a plain airfoil. Pfenninger, reference 3, reported that full-chord laminar flow could be obtained at Reynolds numbers up to 2.2×10^6 on a 10.5-percent-thick slightly cambered airfoil model which, for the best test arrangement, had 12 slots on the upper surface and 10 slots on the lower surface. A large reduction in total drag was reported for Reynolds numbers up to 2.2×10^6 above which the drag began to increase. Holstein, reference 4, also reported drag tests of a slotted airfoil on which total drag savings were obtained at Reynolds numbers up to about 3×10^6. The results of a slot investigation (reference 5) indicated that slots were effective in extending the laminar boundary layer in an adverse pressure gradient for a 0.50 chord distance at a Reynolds number as high as 7.5×10^6. A flight investigation (reference 6) demonstrated that suction through slots could increase the extent of laminar flow by about 12 percent of the chord at a Reynolds number of 26.5×10^6.

The purpose of the present investigation was to determine whether approximately full-chord laminar flow could be maintained over a slotted airfoil for Reynolds numbers much higher than those of previous investigations. Since previous wind-tunnel investigations may have been limited by stream turbulence it was thought that with a wind tunnel of low turbulence and with a model having a suction-slot arrangement designed to operate at high Reynolds numbers, increases in the extent of laminar flow could be obtained at relatively high Reynolds numbers.

A 3-foot-chord NACA 64A010 airfoil section was selected for investigation in order that the results obtained might be directly comparable to those presented in references 1 and 2 for the NACA 64A010 section with continuously distributed suction. The model was constructed with 41 suction slots of approximately 0.005 inch width on each surface.

This arrangement was designed on the basis of the methods derived in reference 5 with a view toward obtaining full-chord laminar flow at Reynolds numbers up to 25×10^6. The slot-entry geometry was based on the work of references 3 and 7, and the slot size was based on the work of reference 5.

The tests were made in the Langley two-dimensional low-turbulence pressure tunnel with the model at zero angle of attack. The data obtained included not only the wake drag and boundary-layer profiles, but also the suction-flow quantity and suction-pressure loss for each slot. The flow coefficient based on the total quantity of flow removed from all slots varied from 0 to 0.0026. The investigation was made for Reynolds numbers from 3×10^6 to 10×10^6.

SYMBOLS

x	distance along airfoil chord
y	distance perpendicular to airfoil surface
c	airfoil chord
s	distance from airfoil leading edge measured along surface
l	distance along surface between slots
w	slot width (see fig. 8)
d	chordwise length of suction region measured along surface
α	section angle of attack
U	local velocity outside boundary layer
u	local velocity inside boundary layer
U_o	free-stream velocity
ΔH	total pressure loss of suction air
ρ	mass density
q	local dynamic pressure $\left(\frac{1}{2} \rho V^2\right)$

q_o	free-stream dynamic pressure $\left(\frac{1}{2}\rho V_o^2\right)$
S	pressure coefficient (q/q_o)
ΔQ	suction flow quantity per unit span through single slot
Q_{bl}	flow quantity per unit span in boundary layer out to $\frac{u}{U} = 0.997$ at a station just forward of a slot
$\Delta Q/Q_{bl}$	fraction of flow removed from boundary layer at a particular slot
ΔC_Q	single-slot flow coefficient $(\Delta Q/U_o c)$
C_Q	total flow coefficient for all slots in use $\left(\sum \Delta C_Q\right)$
C_P	suction-pressure-loss coefficient $(\Delta H/q_o)$
Δc_{d_s}	drag coefficient equivalent of single-slot suction power $(\Delta C_Q C_P)$
c_{d_s}	drag coefficient equivalent of suction power for all slots in use $\left(\sum \Delta C_Q C_P\right)$
c_{d_l}	airfoil suction-drag coefficient based on slot spacing $\left(2\ \Delta c_{d_s}\ \frac{d/c}{l/c}\right)$
c_{d_w}	airfoil wake-drag coefficient
c_{d_T}	airfoil total drag coefficient $(c_{d_w} + c_{d_s})$
δ	boundary-layer thickness defined as distance perpendicular to surface at which $\frac{u}{U} = 0.707$
δ^*	boundary-layer displacement thickness $\left(\int_0^\infty \left(1 - \frac{u}{U}\right)dy\right)$

θ boundary-layer momentum thickness $\left(\int_0^\infty \frac{u}{U}\left(1 - \frac{u}{U}\right)dy\right)$

ν kinematic viscosity

R free-stream Reynolds number based on wing chord $(U_o c/\nu)$

R_δ boundary-layer Reynolds number $(U\delta/\nu)$

R_{δ^*} boundary-layer Reynolds number $(U\delta^*/\nu)$

R_θ boundary-layer Reynolds number $(U\theta/\nu)$

K slot total pressure-loss correlation coefficient

Subscripts:

1, 2, 3 refer to stations employed in slot analysis (see fig. 3)

SLOT-ARRANGEMENT ANALYSIS

Maximum boundary-layer Reynolds number.- The investigation presented in reference 5 suggested the possibility that a slotted airfoil might be designed to maintain extensive laminar flow up to some desired wing Reynolds number if the boundary-layer Reynolds number was prevented by suction from exceeding a limiting value. The choice of a limiting value of boundary-layer Reynolds number depends upon a number of conflicting requirements.

From an aerodynamic point of view, it is desirable to maintain a high value of boundary-layer Reynolds number in order to minimize skin friction, reduce the suction quantity, and increase the boundary-layer stability to surface projections and roughness (reference 8). From the practical viewpoint of construction simplicity, it is also desirable to have a thick boundary layer in order that the slot widths and spacings can be as large as possible, as is discussed subsequently.

On the other hand, the boundary layer must not be too thick or else it will be susceptible to transition by amplification of small disturbances such as are dealt with in the laminar stability theory. An upper limit for a maximum permissible boundary-layer Reynolds number is suggested by reference 9, which shows that, for no slots and a smooth surface, laminar flow can be obtained for values of R_{δ^*} up to about 6000. In the belief that the presence of slots and possible surface irregularities

might cause transition for such high values of the Reynolds number, a smaller value, 2635, was arbitrarily chosen for the present analysis.

Slot arrangement.- The location of the first slot is simply determined by the criterion of $R_{\delta^*} = 2635$ and a knowledge of how the laminar boundary layer will develop along the forward part of a given surface. In the absence of laminar separation, the boundary-layer growth may be determined with a fair degree of accuracy by the following equation:

$$(R_{\delta^*})^2 = 3\,\frac{U_o c}{\nu}\left(\frac{1}{S}\right)^{3.58}\int_0^{s/c}(S)^{4.08}\,d(s/c) \tag{1}$$

which is a slightly different form of the equation of reference 10. For the NACA 64A010 airfoil, the pressure distribution and profile of which are shown in figure 1, the calculated suction region and the position of the first slot was found to vary with Reynolds number as shown in figure 2.

With regard to the spacing of the subsequent slots, an obvious upper limit to the spacing is the distance required for the boundary-layer Reynolds number to grow from zero to the maximum allowable value; such a condition could exist if all the boundary layer were removed at each slot. Too large a slot spacing, however, requires excessive suction power as is shown subsequently. Too small a slot spacing, on the other hand, is impractical, so that the choice of slot spacing must be some compromise between suction drag and construction complexity.

The determination of the suction drag resolves into the determination of the quantity of suction flow required to overcome the boundary-layer growth between slots and the pressure loss associated with the flow removed. If the boundary layer is assumed to have a Blasius profile, then the required reduction in boundary-layer thickness at each slot in terms of the boundary-layer Reynolds number may be predicted by an application of the following rearrangement of equation (1):

With the assumption that

$$R_{\delta^*_1} = R_{\delta^*_3} \text{ (see stations 1, 2, and 3 of fig. 3)}$$

then

$$\left(\frac{R_{\delta^*2}}{R_{\delta^*1}}\right)^2 = \left(\frac{R_{\delta^*2}}{R_{\delta^*3}}\right)^2 = \frac{3R\left(\frac{1}{S_2}\right)^{3.58}\left[\int_0^{(s/c)_3} (S)^{4.08}\, d(s/c) - \int_{(s/c)_2}^{(s/c)_3} (S)^{4.08}\, d(s/c)\right]}{3R\left(\frac{1}{S_3}\right)^{3.58}\int_0^{(s/c)_3} (S)^{4.08}\, d(s/c)}$$

$$= \left(\frac{S_3}{S_2}\right)^{3.58} - \frac{3R}{\left(R_{\delta^*1}\right)^2}\left(\frac{1}{S_2}\right)^{3.58}\int_{(s/c)_2}^{(s/c)_3} (S)^{4.08}\, d(s/c) \tag{2}$$

For a given pressure distribution S, free-stream Reynolds number R, airfoil chord c, and the assumption of a maximum allowable value of the boundary-layer Reynolds number R_{δ^*} at positions just ahead of two slots, distance l apart, the required reduction in R_{δ^*} at the first of the two slots may be deduced by equation (2) as a function of l.

The suction flow and the suction total pressure loss for different assumed distances l between slots were determined for 90° slots by the equations of reference 5:

$$\frac{R_{\delta^*2}}{R_{\delta^*1}} = \frac{R_{\delta_2}}{R_{\delta_1}} = 1 - 1.6\,\frac{\Delta Q}{Q_{bl}} \quad \left(\text{for } \frac{\Delta Q}{Q_{bl}} < 0.275\right) \tag{3}$$

and

$$\frac{\Delta H}{q} = 1 + \frac{\Delta Q}{Q_{bl}}\,(2.26K - 1.26) \tag{4}$$

where K varies with $\left(\frac{1.33\delta^*_1}{w}\right)^2 \frac{\Delta Q}{Q_{bl}}$ for a 90° slot as shown in figure 3 (from reference 5).

The increment of suction drag for each slot is

$$\Delta c_{d_s} = \Delta C_Q C_P$$

and for a Blasius profile becomes

$$\Delta c_{d_s} = 2.19 \left(\frac{\Delta Q}{Q_{b_l}}\right)\left(\frac{R_{\delta^*_l}}{R}\right)\left(\frac{\Delta H}{q}\right) S_l \tag{5}$$

The suction drag was calculated according to the foregoing equations for several choices of slot spacing l and for several representative values of local dynamic pressure and dynamic-pressure gradient on the NACA 64A010 airfoil at zero angle of attack and at Reynolds numbers of 25×10^6 and 10×10^6. The slot width w was taken equal to $1.33\delta^*$, which is approximately as wide as can be used without inducing transition (reference 5.) The theoretical plain-airfoil pressure distribution (fig. 1) was used. Actually, as shown by Pfenninger, reference 3, the suction tends to produce a somewhat more favorable pressure gradient in regions just forward and rearward of the slot. For this analysis, such a suction sink effect on the pressure distribution was neglected.

The calculated variation of the single-slot suction-drag coefficient with slot spacing is shown in figure 4 for three representative chordwise positions on the airfoil at a Reynolds number of 25×10^6 and for one chordwise position at a Reynolds number of 10×10^6. Figure 4 shows that, even for somewhat widely varied flow conditions, the drag varies almost linearly for low values of slot spacing l/c. Extreme forward and rearward slot positions, $\frac{x}{c} = 0.088$ and $\frac{x}{c} = 0.90$, have similar drag variations with spacing because of the compensating effects of pressure coefficients and gradients of pressure coefficients. Suction-drag calculations at a Reynolds number of 25×10^6 for other positions on the airfoil indicated that all variations of suction drag with l/c lie between the curves shown in figure 4.

Values of approximate total airfoil suction drag, shown in figure 5, were obtained by assuming that all slots contribute the same increment of suction drag (fig. 4) and multiplying the individual slot drag by the number of slots corresponding to a given l/c. Such variations of

$$c_{d_l} = 2\left(\Delta c_{d_s}\right) \frac{d/c}{l/c}$$

permit approximate predictions of the total suction drag to be expected for a chosen slot spacing. Comparison of the drag curves for the two different Reynolds numbers demonstrates the desirability for decreasing the slot spacing as the Reynolds number is increased. Figure 5 also indicates that the suction drag decreases continuously with decreasing slot spacing. The variation becomes small, however, for a slot spacing

less than 0.02c and in view of the increasing difficulties of construction with decreasing slot spacing, a slot spacing of 3/4 inch or 0.0208c was chosen.

Before the slot spacing was finally decided upon, the possibility of laminar separation occurring between the slots in the adverse pressure gradient had to be considered. By the method of reference 11, it was determined that because the maximum boundary-layer Reynolds number is held constant by suction, the tendency toward separation becomes less marked as the wing Reynolds number is increased. At the design Reynolds number of 25×10^6 the slot spacing of $\frac{x}{c} = 0.0208$ was well within the limits required to prevent laminar separation. As shown in figure 2, 91 percent of the surface must be controlled by suction at a Reynolds number of 25×10^6 (no slots over the first 9 percent of the model), which means that, with an l/c of 0.0208, 44 slots would be required per surface. Only the first 41, however, were constructed in the model because of the extreme difficulty of locating suction ducting in the thin trailing-edge section. The criterion of $w = 1.33\delta^*_1$ when applied to the NACA 64A010 airfoil at a Reynolds number of 25×10^6 resulted in values of the slot width that lay in the range of 0.0045 to 0.0052 inch. For construction convenience, 0.005 inch was chosen as the slot width to be incorporated in the 3-foot-chord model.

Calculated suction-drag coefficients.- For the conditions of slot width $w = 0.005$ inch, slot spacing $\frac{l}{c} = 0.0208$, a maximum value of R_{δ^*} of 2635 at each slot, and 41 slots on each surface, suction-flow coefficients as shown in figure 6 were calculated for each slot for the NACA 64A010 airfoil at zero angle of attack and a Reynolds number of 25×10^6. The summation of the calculated flow coefficients for the individual slots resulted in a total flow coefficient of 0.00082 for one surface of the airfoil or 0.00164 for both surfaces. The total suction-drag coefficient for both surfaces was calculated to be about 0.0021.

Calculations were also made to determine the low Reynolds number suction-drag performance of the slot arrangement which had been designed for a Reynolds number of 25×10^6. The suction distributions, total suctions, and suction drags are presented in figure 6 for Reynolds numbers of 6.25×10^6, and 10×10^6, and 25×10^6. It was assumed, at the lower Reynolds numbers, that the forward slots would be filled so that suction would only be applied in the region indicated in figure 2. The use of 0.005-inch slots at Reynolds numbers of 10×10^6 and 6.25×10^6 with the maximum boundary-layer Reynolds number still held to 2635 meant that w/δ^*_1 would be decreased to about 0.55 and 0.33, respectively, with a

corresponding increase in slot velocity and total pressure loss in the suction air. The present design is, consequently, not well adapted to lower Reynolds numbers. Nevertheless, the elimination of an appreciable number of forward slots at low Reynolds numbers is of sufficient consequence to permit the attainment of suction drags below that calculated for a Reynolds number of 25×10^6.

MODEL AND APPARATUS DESCRIPTION

The profile chosen for these slotted airfoil tests was the NACA 64A010 airfoil. The photograph presented as figure 7(a) shows the two-dimensional, 3-foot-chord, 3-foot-span model in the condition in which it was tested. The coordinates of the airfoil are given in reference 12 and the theoretical pressure-coefficient distribution of the airfoil without suction and at zero angle of attack is presented in figure 1. In accordance with the results of the model-design analysis the 82 spanwise suction slots, 41 on each surface, had a chord spacing of 3/4 inch and a slot width of approximately 0.005 inch. The slots were located between 0.088 chord and 0.92 chord and extended over $21\frac{1}{2}$ inches of the model span (fig. 7(b)). For all tests, in order to allow for a normal spanwise spread of the turbulent boundary layer and to avoid suction in a turbulent area, both ends of each slot were plugged and glazed in an area outside of lines extended from the span ends of the first slot and inclined $7\frac{1}{2}^{\circ}$ inward from the stream direction as shown in figure 7(b). The span distance on each side of the slotted part was completed with dummy ends made to airfoil profile and used to house pressure and suction-flow tubing as shown in figures 7(c) and 7(d), respectively.

The first 32 slots, which extended from 0.088 to 0.733 chord, were formed by attaching, to an inner-base casting, a series of $\frac{1}{4}$-inch-thick aluminum slabs which were machined separately to form the $\frac{3}{4}$-inch slot spacing and spaced on assembly to form the 0.005-inch slot-gap width. The remaining slots were formed of brass to permit soldering of the suction-air-collector chambers in the very close-quartered trailing-edge section. The detailed slot construction is shown in figure 8. Measurements of the completed slots showed that no slot width varied by more than 0.0005 inch from the design value of 0.005 inch. The spanwise variation of each slot width was even less. The slot passages were constructed with a short section having straight parallel sides which led into a straight-sided section expanded on a 5° angle to form a diffuser that was about 0.2 inch in length. (See fig. 8.) The slots

were inclined upstream and formed a 60° angle with the model surface in accordance with the best results of reference 3. Each slot opened into a rectangular-shaped collection chamber which extended the length of the slot. The collection chambers were made large in cross section to insure low velocities in an effort to avoid spanwise variations of static pressure which would cause spanwise variations in the suction flow.

At the outset of the investigation the forward and rearward edges of the slot entrances were sharp-edged as shown by solid lines in figure 8. During the course of the first group of tests, efforts were made to enlarge progressively the slot-inlet radii without exceeding the radii shown by the dashed lines in figure 8, that is, 0.010- and 0.0025-inch radii for the forward and rearward edges, respectively. These radii were chosen according to the results of reference 7. Representative slot-entry contours, typical of those that gave the best results, are shown by the photomicrographs of figure 9. The indicated contours were obtained from solder impressions of the slot. Because of this method of obtaining the photomicrographs, the slot width and angle and minute scratches and ridges may not have been well reproduced, but the general shape of the inlet contour is satisfactorily indicated.

In preparation for a second group of tests, the whole airfoil was sanded down on one side so that all of the slot radii were eliminated. The forward radii of the first 32 slots of one surface were cold-formed very accurately to 0.01 inch with a contoured roller and the rearward radii of the same 32 slots were sanded to approximately 0.002 inch with No. 600 emery cloth. Slots 33 to 41 were left with sharp edges because the trailing-edge slots could not be disassembled.

As a result of the sanding operation, the contour of the airfoil was thinned by about 0.05 percent of the chord which represents a negligible decrease in the original 10 percent thickness.

The model was tested in the Langley two-dimensional low-turbulence pressure tunnel described in reference 13. The test arrangement of suction tubes, flow orifices, and pressure measuring tubes is sketched in figure 10 (also see figs. 7(c) and 7(d)). Each suction tube was provided with a calibrated orifice equipped with a static-pressure tube to indicate the quantity of suction flow through each slot. The pressure measuring tubes used to measure the loss in total pressure in the suction air extended to the span center line of the slot collector chambers. Since velocities in the collector chambers were small, the static pressure was assumed to be equal to total pressure. Ducting losses beyond the slot collectors were not measured.

The external drag of the model was measured with the tunnel wake-survey rake and the boundary-layer measurements were made with a conventional multitube pressure rake (reference 14).

Slot 41 on the upper surface was completely closed off to suction because of an inaccessible pinched-off suction duct which remained closed throughout all tests.

RESULTS AND DISCUSSION

Extent of laminar flow.- With the original sharp-edged suction slots, as shown in figure 8, extensive laminar flow could not be maintained at Reynolds numbers higher than about 4×10^6. Boundary-layer surveys indicated that transition moved forward to the first slot at a Reynolds number of about 6×10^6; whereas for the smooth airfoil with no slots, a much larger extent of laminar flow would be expected. Once the entrances were rounded on the first slot, transition moved to the second slot. It was concluded, therefore, that the slots themselves were causing transition due to the sharp edges. This result suggested that a smoothing and rounding of the slot entrances might permit the attainment of laminar flow over at least 0.90 chord (position of the last slot) at Reynolds numbers higher than 4×10^6. After a very careful smoothing and rounding of all the slot entrances with a hand hone, laminar flow was obtained on 91 percent of the upper surface (as mounted in the tunnel) at a Reynolds number of 10×10^6. (See fig. 11.) This value was the highest Reynolds number at which extensive laminar flow was obtained. The transition point jumped suddenly from a position just rearward of the last slot to a position in the region of the forward slots as the Reynolds number was increased above 10×10^6. Because of the practical difficulty of modifying the slots in the lower surface to conform closely to the upper-surface slots, extensive laminar flow on the lower surface was not obtained at Reynolds numbers above 5.5×10^6. The transition point on the lower surface moved forward progressively with further increases in the Reynolds number.

With the hope of increasing the maximum Reynolds number at which laminar flow could be obtained up to 0.91 chord, the slot entrances were very carefully tool-formed in an effort to improve further upon the smoothness of the slot inlets. Contrary to expectations, however, the maximum Reynolds number at which laminar flow could be obtained over the tool-formed slots was only 8.8×10^6 as compared to 10×10^6 for the hand-honed slots.

Although laminar flow was obtained over 0.91 chord at a Reynolds number of 10×10^6, it is stressed that this result was obtained only after the expenditure of appreciable effort in smoothing and modifying the slots and in keeping the surface of the model itself in a smooth

condition. The results just discussed constitute essentially the main results of the tests. In the following discussion, there will be described the various observations with regard to slot shape, suction flow, and drag.

Slot modifications.- A detailed investigation to determine the most desirable slot shape was not attempted because of the extremely small size of the slots. A discussion of some of the difficulties encountered with the slots and of the slot modifications, however, may be of some interest.

In forming the slot-entrance radii by the hand-honing process, extensive boundary-layer surveys were made with the pressure rake to locate transition regions, and thereby determine where the slot entrance required some further change in shape, and to determine the amount of suction necessary to prevent transition. This necessarily tedious procedure was followed in a forward to rearward order for all slots on both surfaces and most of the boundary-layer surveys were made at a span station $\frac{1}{2}$-inch from midspan as shown in figure 7(b). Once full-chord laminar flow was established at some low Reynolds number, it was somewhat less difficult to determine the slots that prevented full-chord laminar flow at higher Reynolds numbers. Those slots that caused transition at the higher Reynolds numbers would cause transition at slightly lower Reynolds numbers when the suction-flow rate was altered slightly. Identification of the troublesome slots involved advancing the Reynolds number to just below the value at which the wake-survey rake indicated a large increase in drag and then gradually opening, closing, and returning each slot-flow control valve to its original low Reynolds number setting during which procedure the malfunctioning slots were clearly indicated by an appreciable increase in the wake size. Some re-forming and smoothing was then done on each critical slot in order to increase the value of the critical Reynolds number.

For the second group of tests, the first 32 upper-surface slots had been accurately formed before the model was mounted in the tunnel and no attempt was made to alter the entry shapes during the tests.

In general, the slots in the favorable pressure gradient over the forward part of the airfoil required more care with regard to formation of contour and degree of smoothness; whereas the slots in the adverse pressure gradient performed efficiently with very little more than beveled edges. A similar effect was noted in reference 5. The photographs of slots 2 and 3 in figure 9 may be taken as fairly representative of the forward 18 slots on the upper surface of the model (as mounted in the tunnel). For these cases, the slot forward edges had radii of about 0.004 inch and the rearward edges had radii of about 0.002 inch. The forward edges of the lower-surface slots had radii of about 0.008 inch

and the rearward edges had radii varying from 0.004 to 0.006 inch. As shown in figure 9, slot 12 on the upper surface (also slot 5, not shown) had unintentionally enlarged inlet radii which fortunately did not prevent laminar flow at the higher Reynolds numbers as might have been expected from the experience with the poorer performing lower-surface slots where the inlets generally had large radii.

Although surface roughness was not measured, an indication of the size of roughness which produced early transition was given by the observation that the ability of the slot to maintain laminar flow was limited by small ridges left on the slot entrances by the hand-honing process and by the even smaller ridges left by the tool-forming process. Such ridges were hardly discernible to the unaided eye and could be effectively reduced by honing with a soft-lead pencil such that the appearance of the inlet was changed from mat to burnished finish. This process enabled the maximum Reynolds number for full-chord laminar flow to be advanced from 8.5×10^6 to 10×10^6 on the hand-honed slots and from 8.3×10^6 to 8.8×10^6 on the tool-formed slots. A further indication of the degree of sensitivity of the flow to foreign particles on the surface was obtained when it was found that above a Reynolds number of about 4×10^6 a small piece of lint from a model cleaning cloth would cause transition when left protruding from a slot entrance.

Aside from the sensitivity of the flow to slot-inlet radii there was an indication that the contour immediately upstream and downstream of each slot had some marked effect on the slot performance. The slab forming the rearward edge of slot 12 for the tool-formed-radii condition had unintentionally been tilted such as to inset the rear edge of the slot an estimated 0.001 inch below the forward edge. For this slot it was observed that the flow was considerably less sensitive through a wider range of suction quantities than could be tolerated on the other slots where high suction rates seemed to increase the destabilizing effect of slot-inlet roughness and poor contour. A similar effect was noted in reference 3.

Suction distribution.- The calculated suction distributions (fig. 6) indicate that no slots are required ahead of slot 9 for a Reynolds number of 10×10^6. The forward eight slots were not sealed for any of the tests because of the difficulty of unsealing and cleaning such small slots. It was thought, however, that the boundary layer over the forward eight slots would have less tendency to become turbulent if a small amount of air were withdrawn at each slot instead of providing no suction and leaving the slot open. For this reason, most of the tests were made with at least a small amount of suction on all the slots and no attempt was made to test the model with the suction distribution exactly as calculated.

The amount of suction in each slot was varied through a wide range in order to determine the distribution which would give extensive laminar flow at the highest possible Reynolds number. The distribution of minimum suction flow for which extensive laminar flow could be obtained with the hand-honed slots at a Reynolds number of 10×10^6 is shown in figure 11. In comparison with the calculated results of figure 6, much less total suction flow was required to maintain laminar flow over the first sixteen slots in the favorable gradient than was indicated by the calculations despite the condition in the calculated results that the forward eight slots were sealed and despite the excessive flow required through slots 5 and 12 in the experimental case. Comparison of the calculated results of figure 6 and the data of figure 11(a) indicates that toward the end of the region of adverse pressure gradient, relatively more total flow removal was required than the calculations indicated. The minimum total quantity of suction flow for the whole upper surface $\frac{C_Q}{2} = 0.00054$, as determined from the tests, however, was of the same order as the calculated minimum total quantity $\frac{C_Q}{2} = 0.00077$.

The reasons for the discrepancies between the calculated and experimentally determined minimum-suction-flow distributions are not entirely clear. Perhaps laminar flow can be maintained across suction slots in a region of favorable pressure gradient for values of $R_{\delta*}$ greater than 2635 or perhaps the assumptions of Blasius profile and boundary-layer reduction across the slot, equation (3), made in calculating the effect of suction on the boundary layer are not entirely justified. The lack of detailed boundary-layer measurements over the entire airfoil surface with suction prevents a satisfactory answer to these questions at the present time. The measurements made of the boundary layer at 0.91 chord for the best condition of the hand-honed model (fig. 11(b)) indicate that the choice of $R_{\delta*} = 2635$ used in the slot-design analysis may be somewhat high in the region of adverse pressure gradient. Because the measured profile differs in shape from the Blasius profile, comparison of the two profiles becomes more valid on the basis of R_θ rather than $R_{\delta*}$. On the basis of R_θ, the Blasius profile of $R_{\delta*} = 2635$ is seen to have a value of R_θ somewhat lower than the value of R_θ of the thickest measured profile corresponding to minimum suction for laminar flow over 0.91 chord. The condition of $R_\theta = 1034$ rather than $R_{\delta*} = 2635$ may have been a better criterion for the maximum allowable boundary-layer Reynolds number.

In general, laminar flow could not be maintained across individual slots if the suction flow through the slot was either too high or too low. The range of flow rates through which laminar flow could be

maintained was, however, rather wide as can be seen from the comparison in figure 11(a) of the distributions of minimum suction and maximum suction for 0.91-chord laminar flow. The slots in the favorable gradient were much more sensitive to flow rate than those in the adverse gradient. In subsequent tests, laminar flow could be maintained over 91 percent of the upper surface up to Reynolds numbers of about 9.5×10^6 with no suction pressure applied to the first four slots but with a suction distribution on the rest of the slots similar to the minimum suction shown in figure 11(a). The slots were left unsealed but the ducts were closed.

Drag results.- Because upper and lower surfaces did not have the same extent of laminar flow at a given Reynolds number, the wake-survey method of obtaining drags did not indicate the drag coefficients that might have been expected if both surfaces had operated with equal effectiveness. It was necessary, therefore, to use a less direct approach in order to obtain an indication of the profile drag of an airfoil having extensive laminar flow on both surfaces. The wake drags shown in figure 11(b) for the hand-honed model at $R = 10 \times 10^6$ were calculated in the first case on the assumptions that transition occurred slightly rearward of the last slot $\left(\frac{x}{c} = 0.91\right)$ and that the momentum loss associated with the measured laminar profile was equal to that of a turbulent profile. The development of 0.09 chord of turbulent flow was calculated according to reference 15 and converted to drag by the method of reference 16. In the second case, the wake drags were calculated by a similar procedure but with the assumption that the boundary-layer development on the last 0.09 chord was laminar. Inasmuch as the position of transition in the last 0.09 chord was not established, the two calculations serve to bracket the wake drags that might be expected for two surfaces having similar extents of laminar flow.

For the minimum suction case of figure 11, the total drag coefficient (measured drag equivalent of the suction power plus calculated wake drag) for 91-percent laminar flow on two surfaces at $R = 10 \times 10^6$ was 0.0023 and for 100-percent laminar flow was 0.0018 as compared to a drag coefficient of 0.0042 for the solid smooth airfoil at the same Reynolds number. For the maximum suction case, the total drag coefficients were 0.0038 for 91-percent laminar flow and 0.0034 for 100-percent laminar flow. These results for the maximum suction case indicate the necessity from a consideration of low total drag of providing as little suction as possible to maintain extensive laminar flow.

Because wake drags may be of some interest in spite of the differences in performance of the upper and lower surfaces, the various drag quantities are presented in figures 12 to 15. Figure 12 shows that the total drag (wake drag plus suction drag) is less than that of the smooth unslotted

airfoil up to a Reynolds number of about 8×10^6. The suction distributions (fig. 13) used to obtain these drags are in general similar to the distribution used on the upper surface for the low-drag condition at $R = 10 \times 10^6$. The general patterns, of the variations of c_{d_W}, c_{d_S}, and c_{d_T} with C_Q are shown in figure 14 for a Reynolds number of 7.4×10^6. Spanwise wake surveys are presented in figure 15 from which some indication may be had of the difficulty of obtaining uniformity of slot performance in spite of the seeming uniformity of slot shape and smoothness.

CONCLUDING REMARKS

An experimental investigation of an NACA 64A010 airfoil section equipped with 82 boundary-layer suction slots (41 per surface) indicated that laminar flow could be maintained over 0.91 chord up to Reynolds numbers as high as 10×10^6. This result was obtained on only one surface of the model where the slot radii forward and rearward, respectively, were approximately 1.0 and 0.5 times the slot width, 0.005 inch. The drag coefficient equivalent of the suction power required to obtain this result was as low as 0.0006 (for the one surface) which when multiplied by 2 and combined with an estimated wake drag indicated that a drag coefficient of 0.0024 or less might be obtained for an airfoil having two sides that operated with equal effectiveness, as compared to 0.0042 for the plain smooth airfoil. It was found that the total suction-flow quantity and the suction drag required to obtain the results at a Reynolds number of 10×10^6 were of the same order as the values predicted by the analysis presented herein.

Perhaps the most significant observation of the investigation was the increasing difficulty encountered in obtaining full-chord laminar flow at higher Reynolds numbers. The degree of the difficulty was indicated by the extreme amount of care required to provide slot-entry contours and a smoothness of surface that would not cause transition. At the higher Reynolds numbers the roughness which seemed to prevent laminar flow was so small that a soft-lead pencil used as a hone was found to be effective in further reducing the roughness and advancing the Reynolds number for extensive laminar flow.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., November 13, 1951

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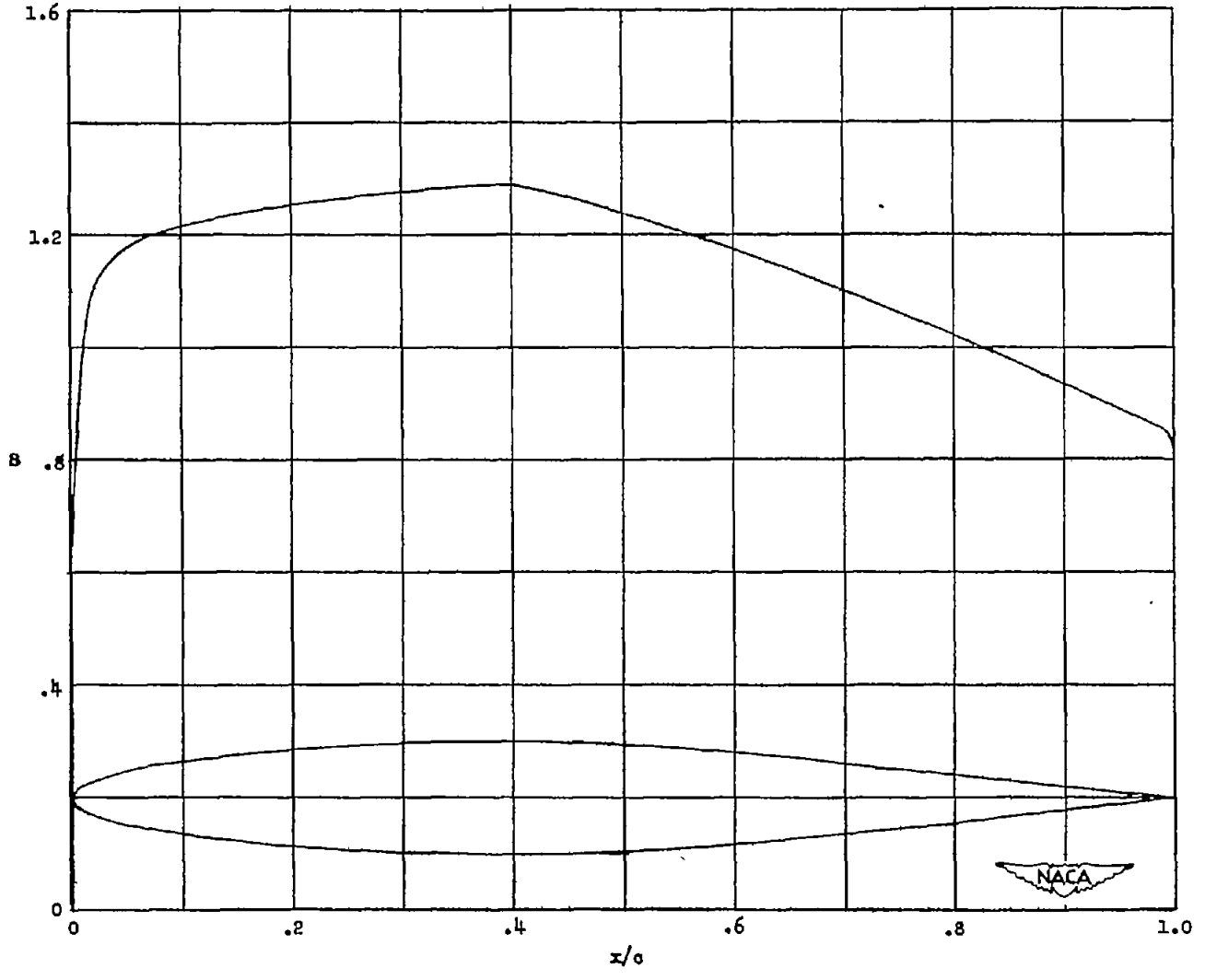


Figure 1.- Theoretical pressure-coefficient distribution over either surface of the NACA 64A010 slotted airfoil; $\alpha = 0^{\circ}$.

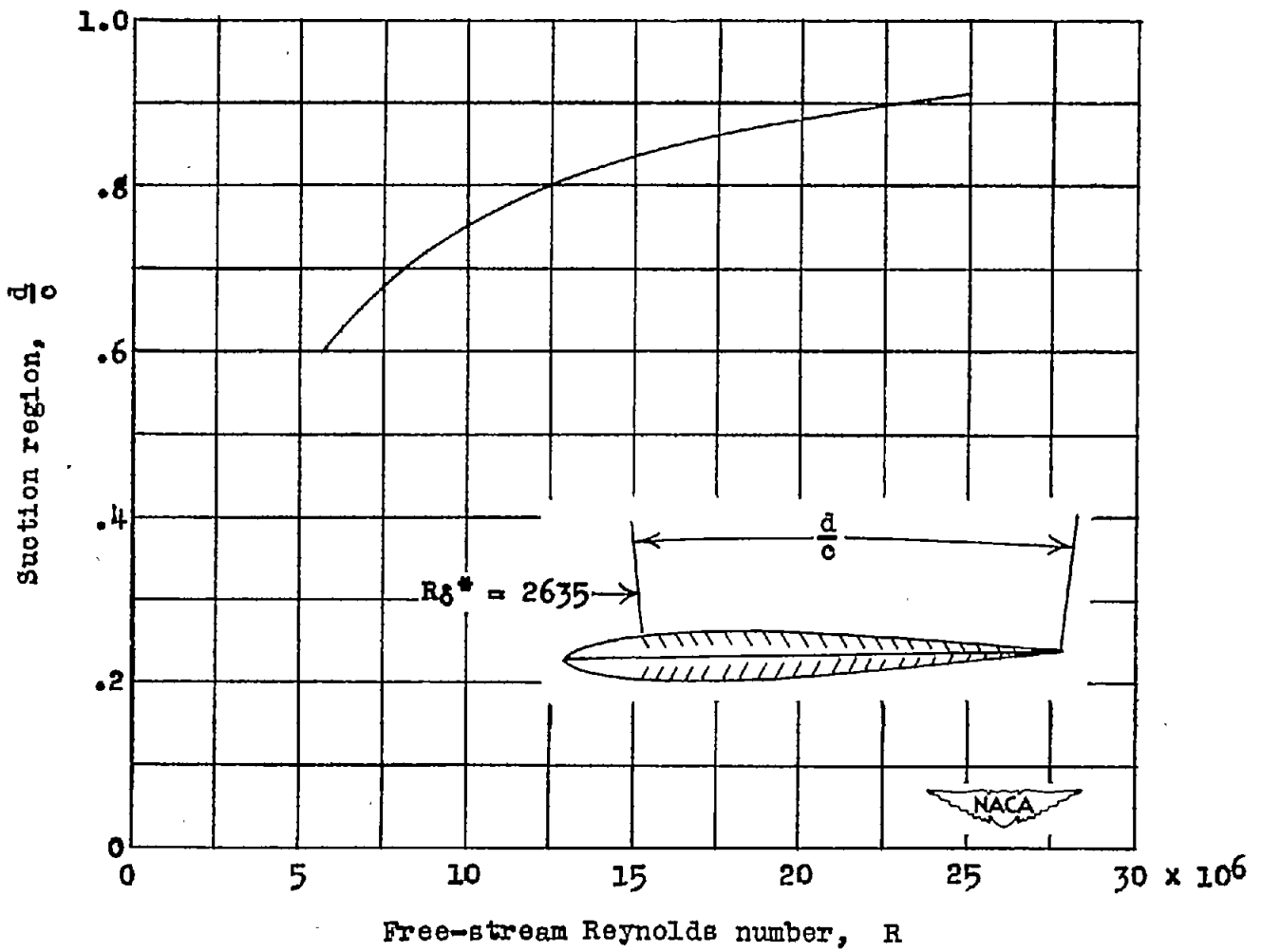


Figure 2.- Calculated chordwise region requiring suction to maintain laminar flow over the NACA 64A010 slotted airfoil for Reynolds numbers up to 25×10^6 with the first slot position at the station where R_{δ^*} first reaches 2635. $\alpha = 0^\circ$.

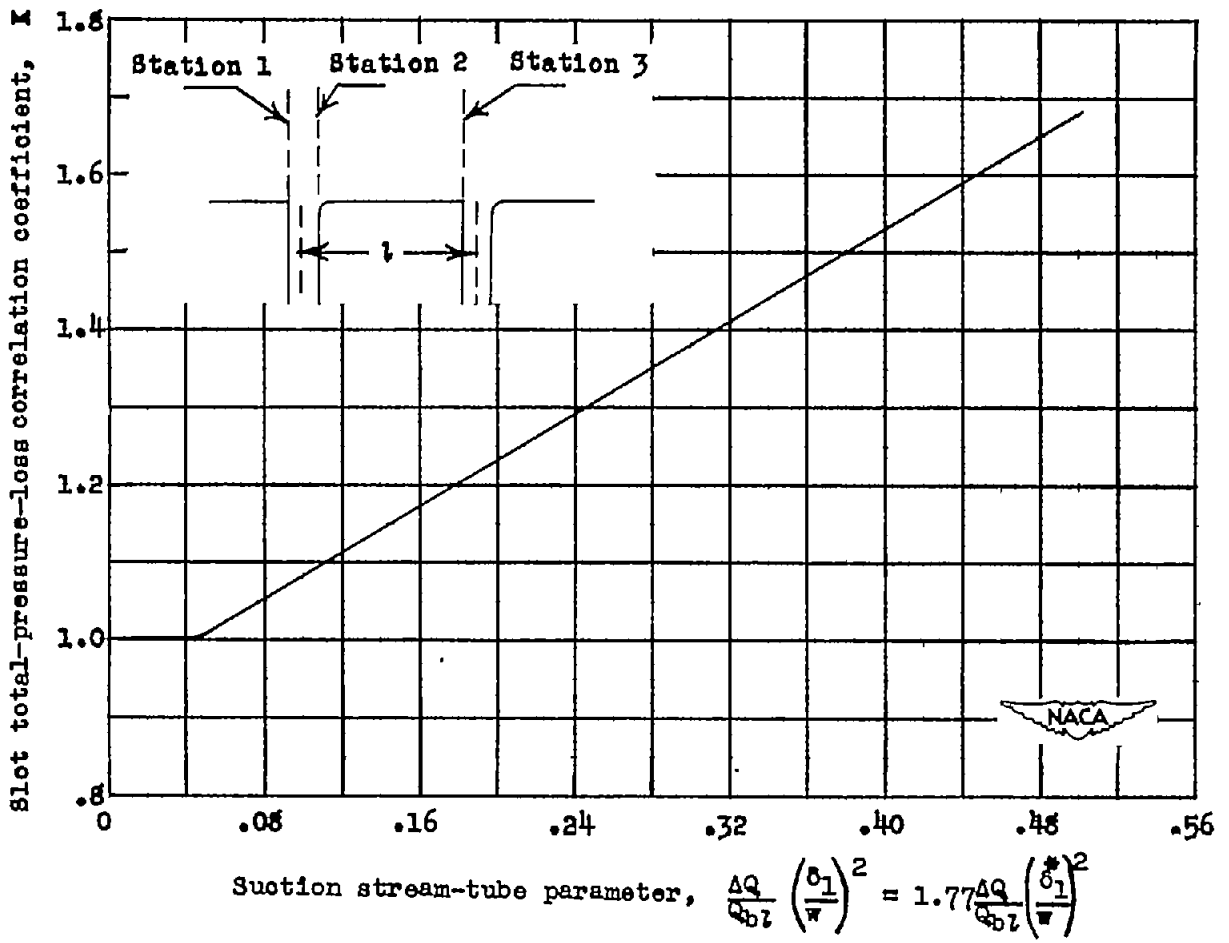
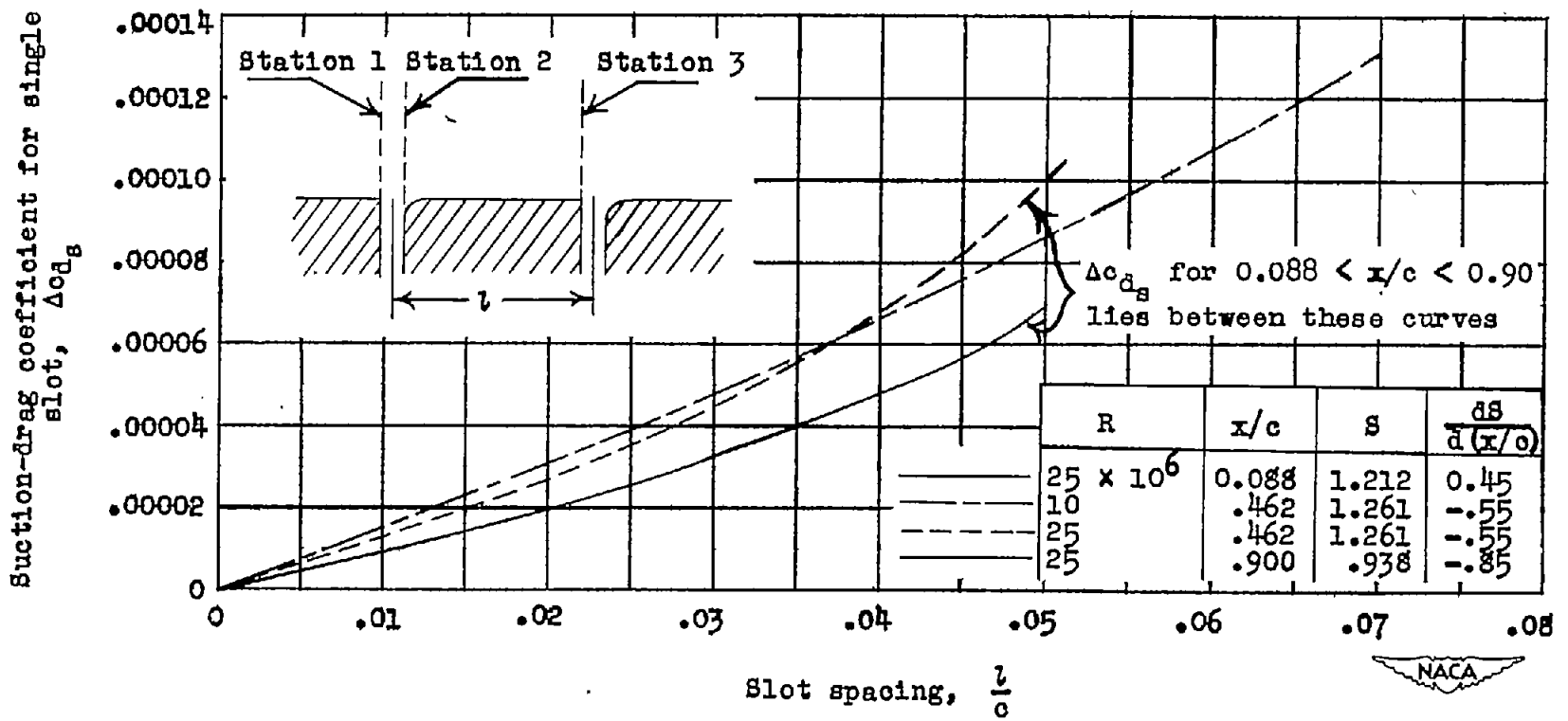


Figure 3.- Calculated variation of the slot total-pressure-loss correlation coefficient with the suction stream-tube parameter as taken from reference 5. Curve is used in relation:

$$\frac{\Delta H}{q} = 1 + \frac{\Delta Q}{Q_{bl}}(2.26K - 1.26).$$



R	x/c	S	$\frac{dS}{d(x/c)}$
25×10^6	0.088	1.212	0.45
10	.462	1.261	-.55
25	.462	1.261	-.55
25	.900	.938	-.85

Figure 4.- Calculated variation of single-slot suction-drag coefficient with slot spacing for sample slots on the NACA 64A010 airfoil at two Reynolds numbers. $\alpha = 0^{\circ}$; $R_{\delta_1}{}^* = R_{\delta_3}{}^* = 2635$; $\frac{\delta_1{}^*}{w} = 0.752$.

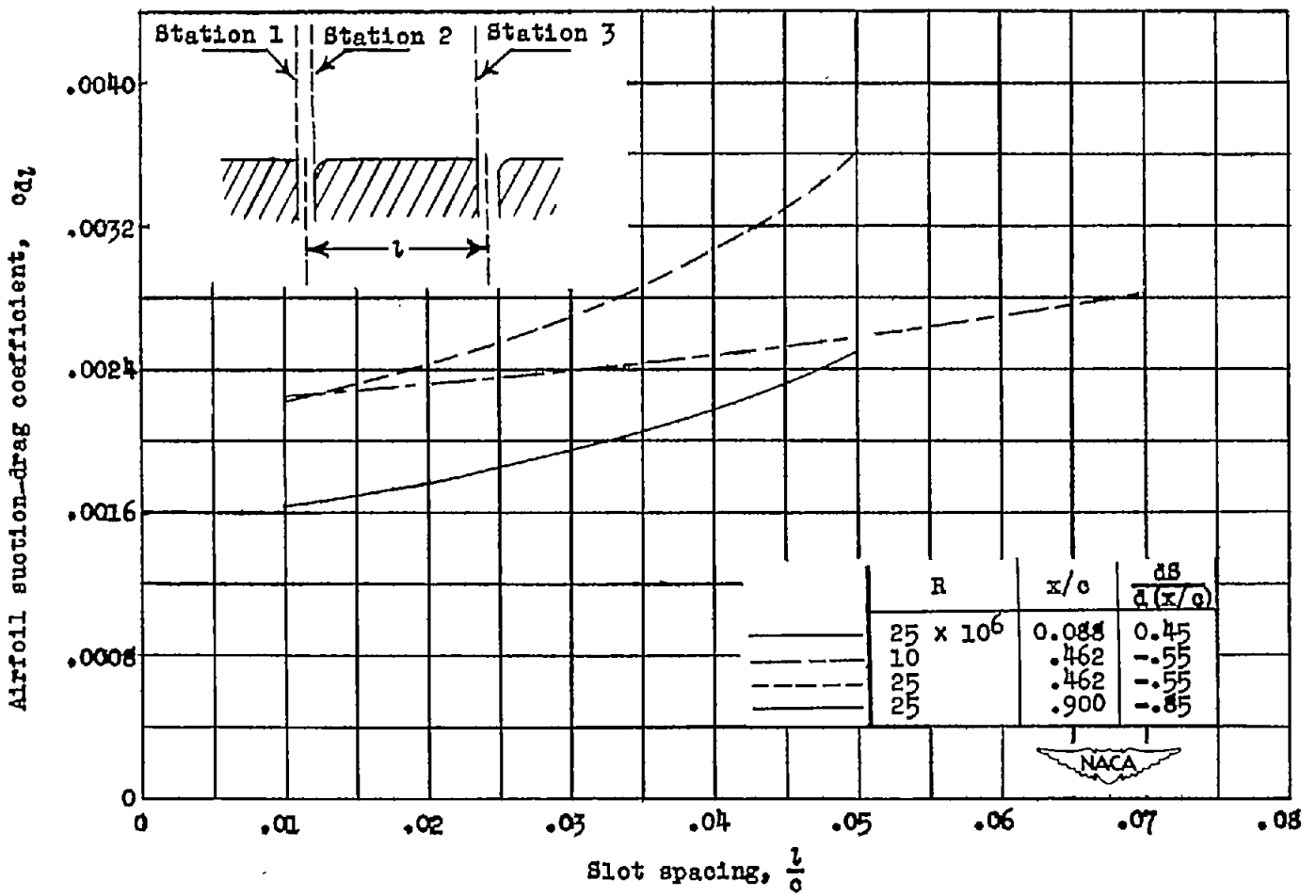


Figure 5.- Calculated variation of total airfoil suction-drag coefficient with slot spacing at two Reynolds numbers and with all slots contributing the same increment of drag as the sample slot. $\alpha = 0^{\circ}$; $R_{\delta_1}{}^* = R_{\delta_3}{}^* = 2635$; $\frac{\delta_1{}^*}{w} = 0.752$.

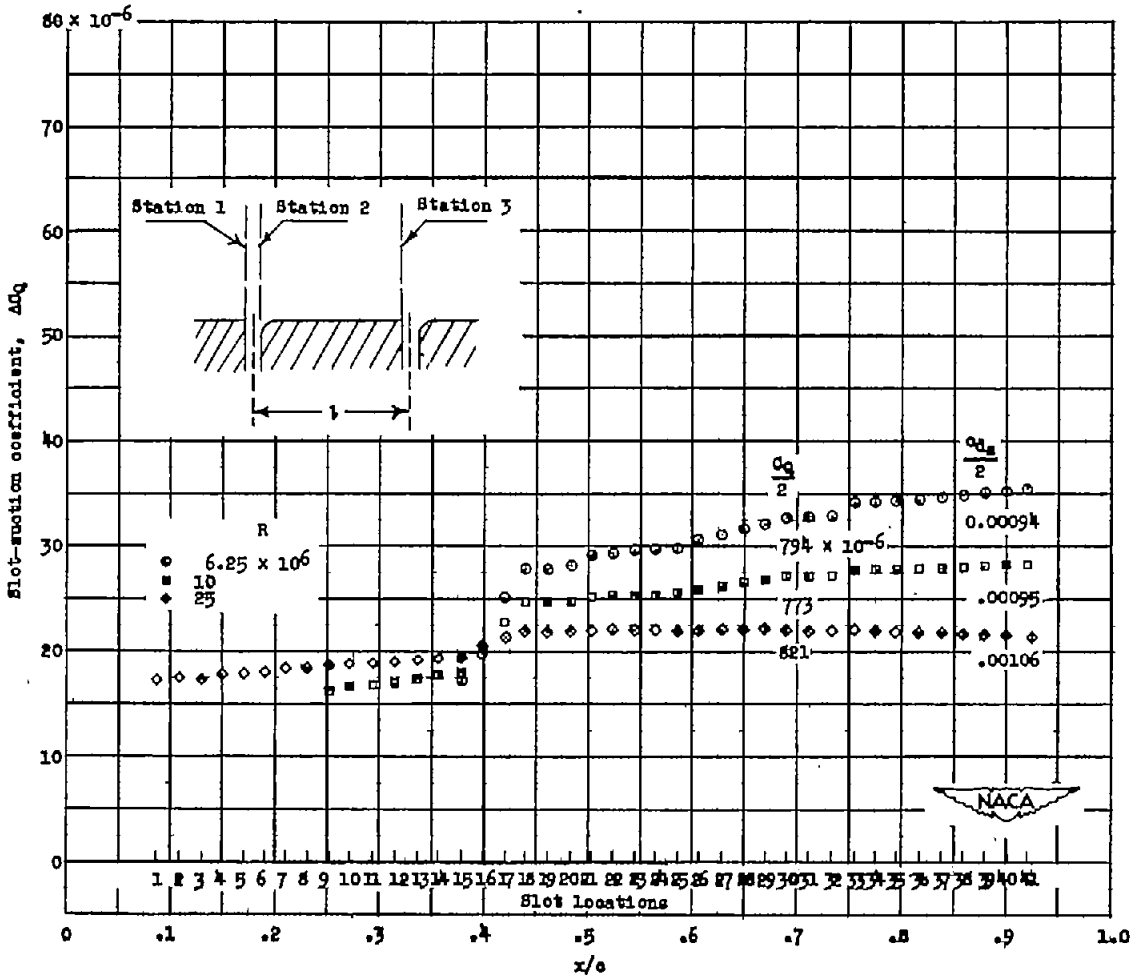
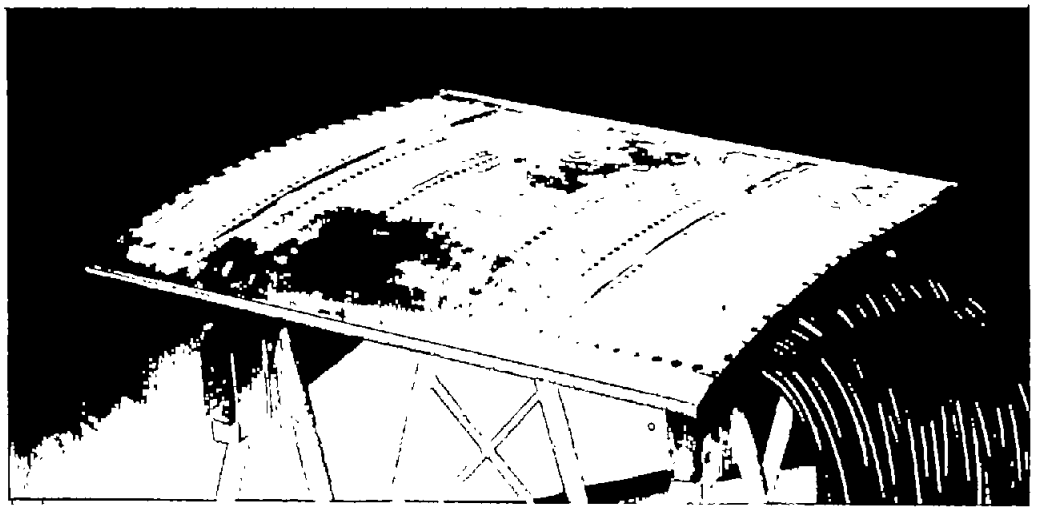


Figure 6.- Calculated slot-suction-coefficient distribution and suction-drag coefficients for the NACA 64A010 slotted airfoil at three values of the free-stream Reynolds number; w = 0.005 inch; $R_{\delta_1}^* = R_{\delta_3}^* = 2635$; $\alpha = 0^\circ$.



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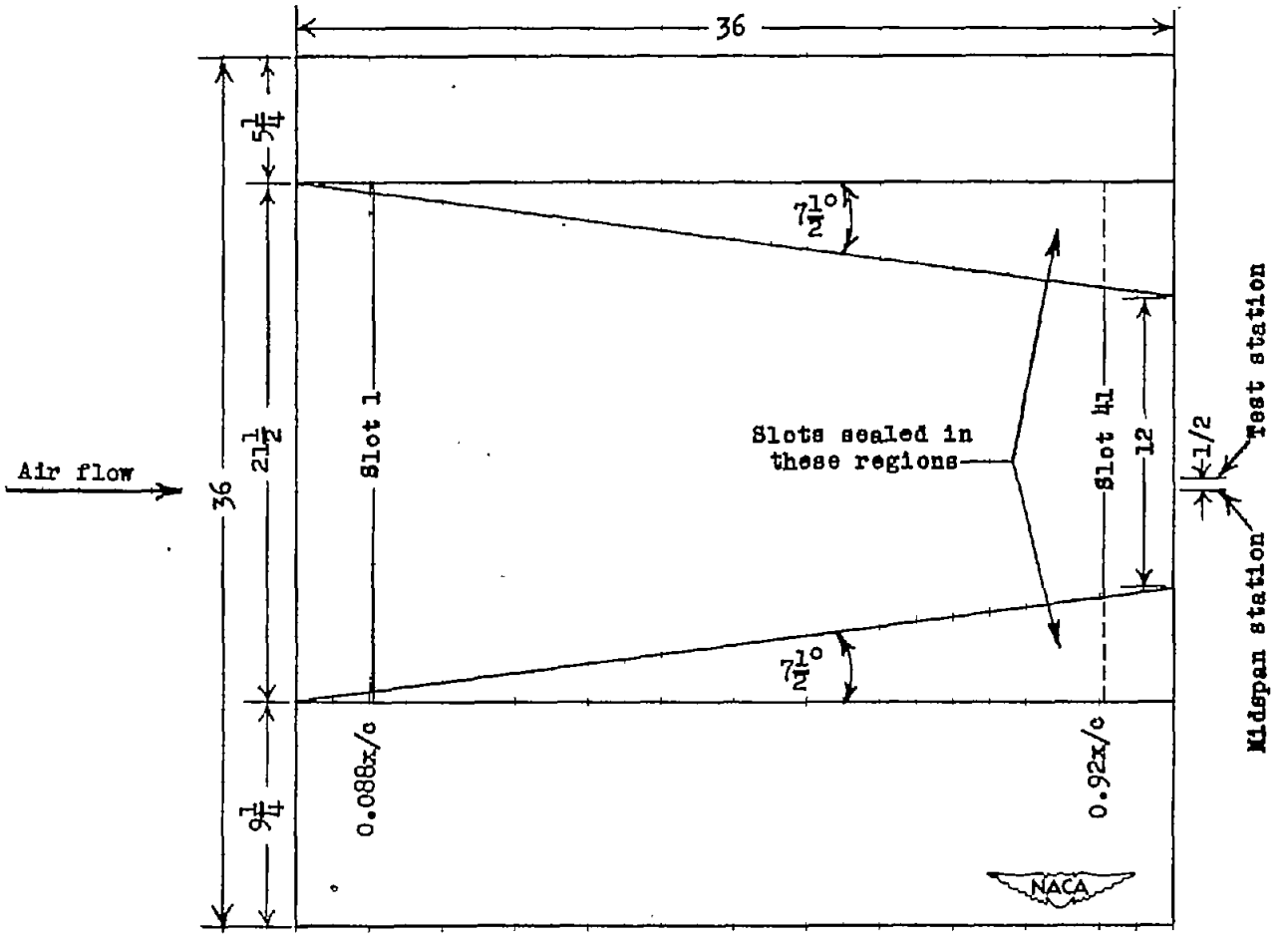
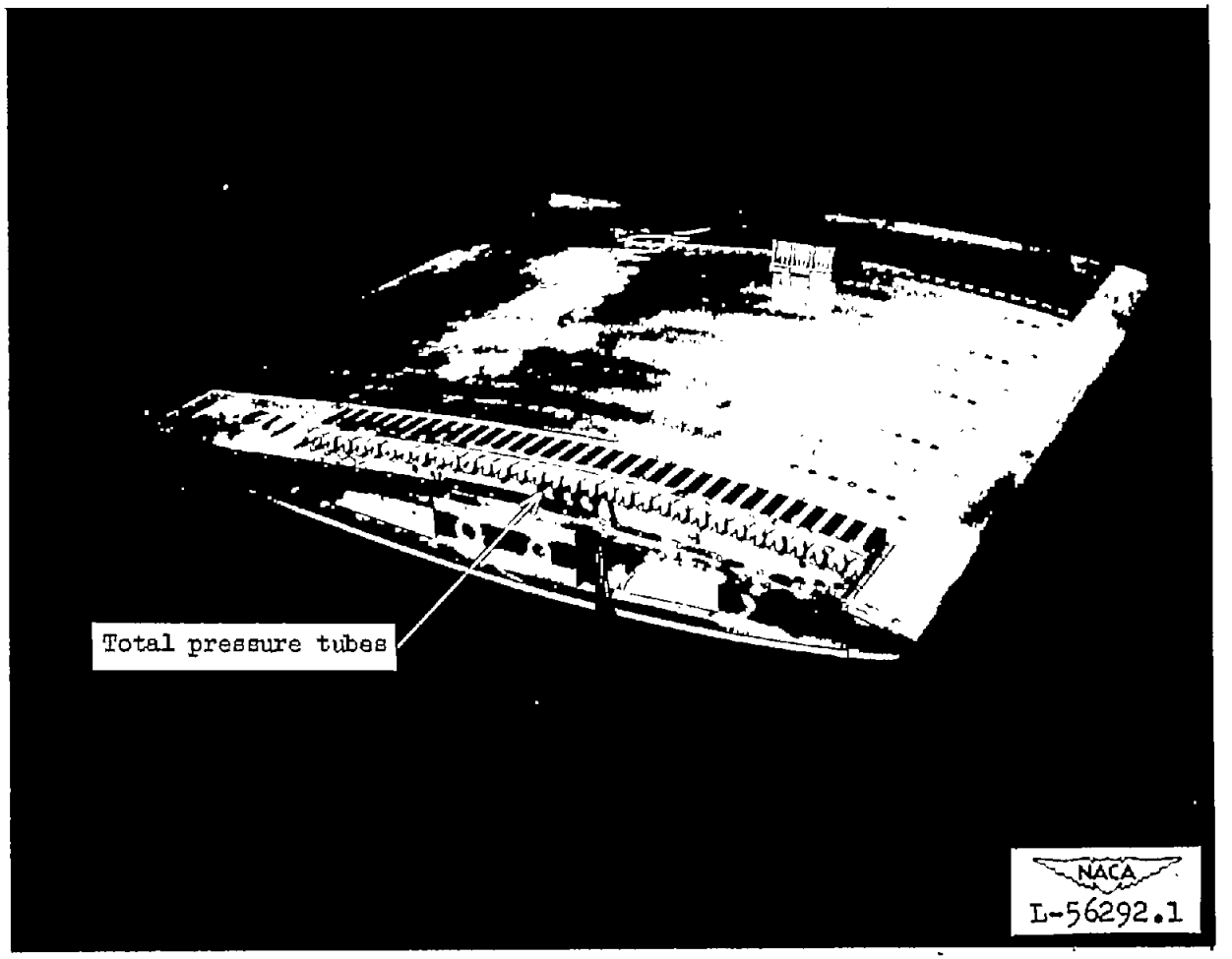
(a) Three-quarter left view of completely assembled airfoil.

Figure 7.- NACA 64A010 airfoil with boundary-layer suction slots.



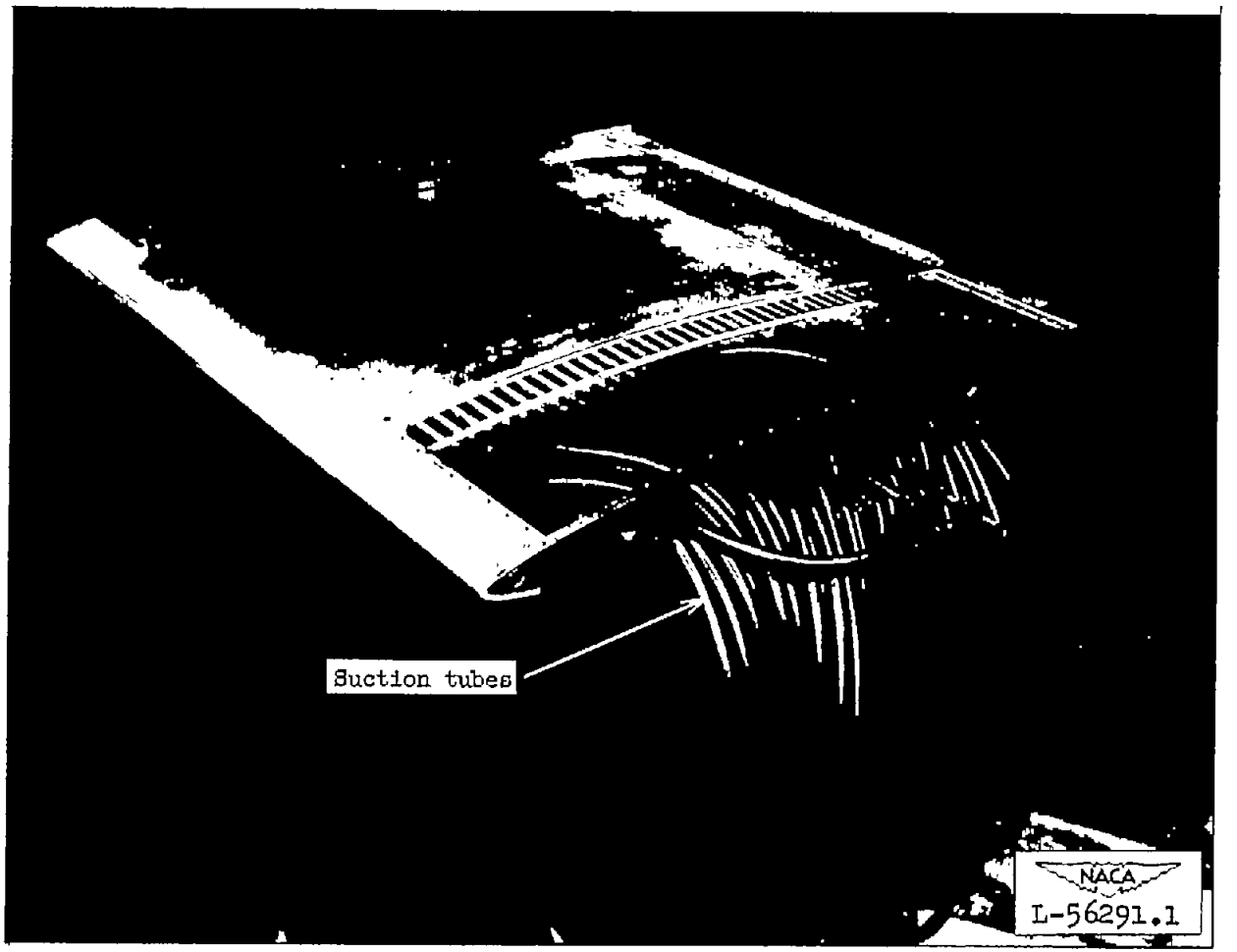
(b) Sketch of airfoil upper surface.
(All dimensions are in inches.)

Figure 7.- Continued.



(c) Right-side view of airfoil with dummy ends removed to show total pressure-tube connections to suction-slot chambers.

Figure 7.- Continued.



(d) Left-side view of airfoil with dummy end sections removed to show suction-tube connections to slot chambers.

Figure 7.- Concluded.

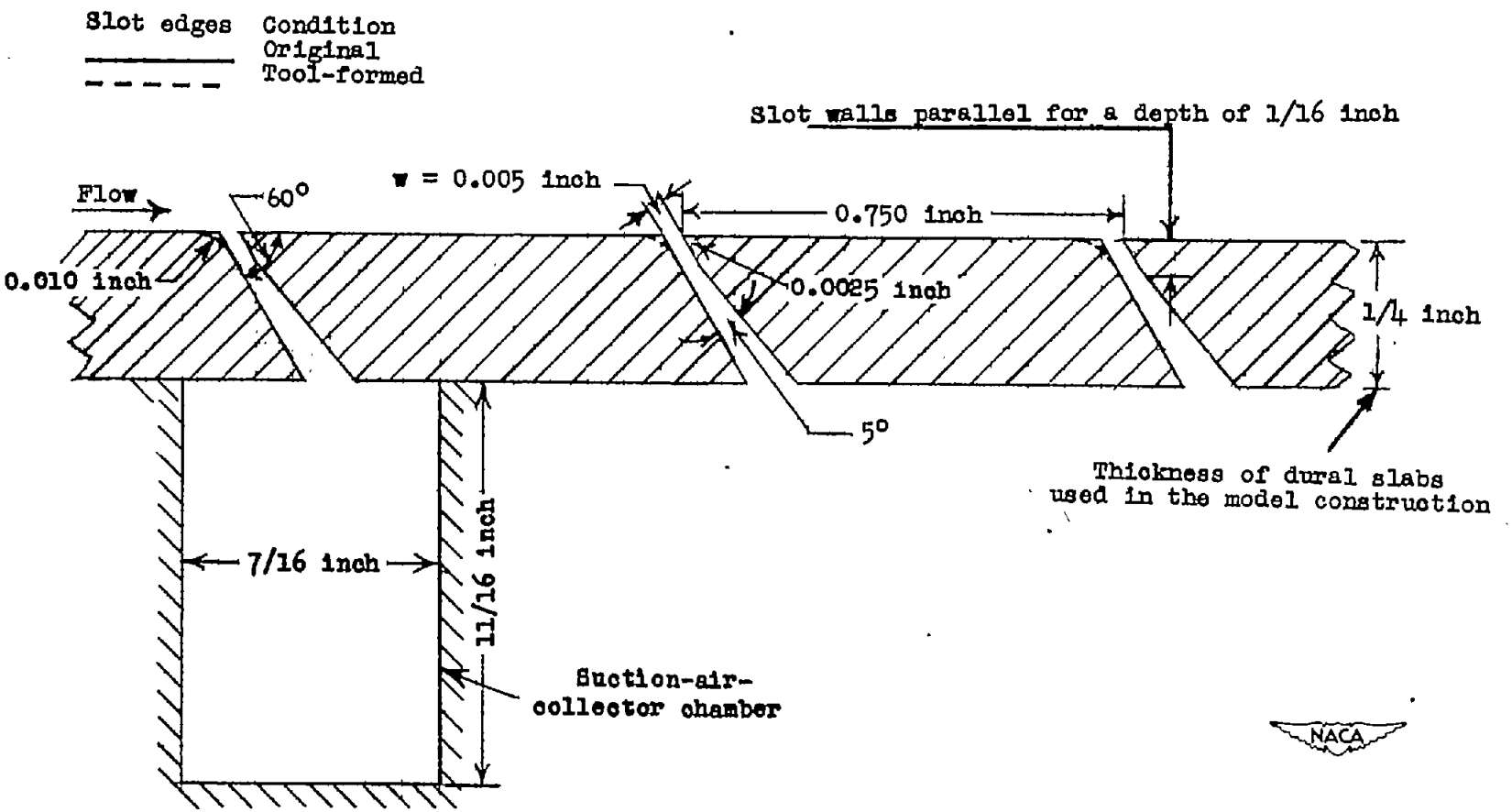
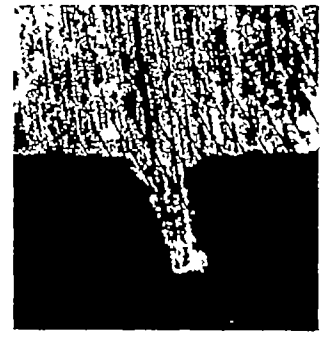


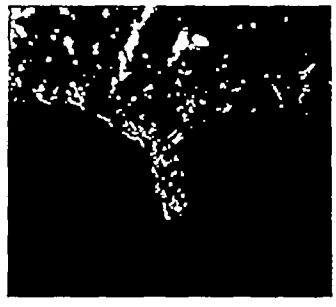
Figure 8.- Design of boundary-layer suction slots for the NACA 64A010 slotted airfoil.

Slot 2



Slot 3

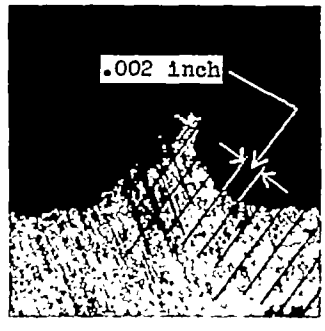
Upper Surface



Slot 12

Slot 19

Upper Surface



Slot 10

Slot 20

Lower Surface

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Figure 9.- Photomicrographs of several slots on each surface of the NACA 64A010 slotted airfoil that show examples of the hand-formed slot radii as they existed for the low-drag condition. The dark regions represent the model profile and the dark lines are a superimposed scale.

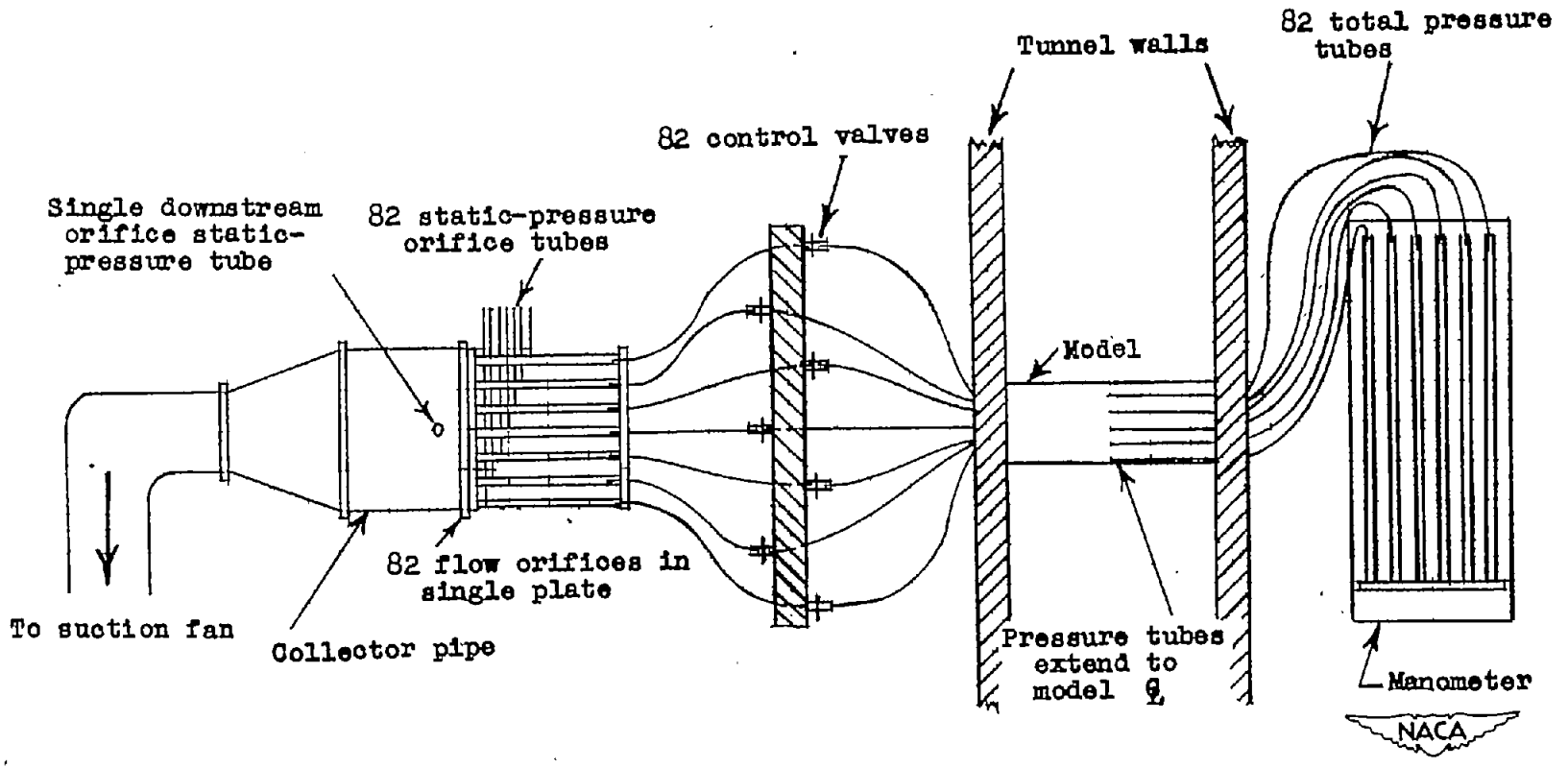

Figure 10.- Arrangement of test apparatus for the NACA 64A010 slotted airfoil as set up in the Langley two-dimensional low-turbulence pressure tunnel.

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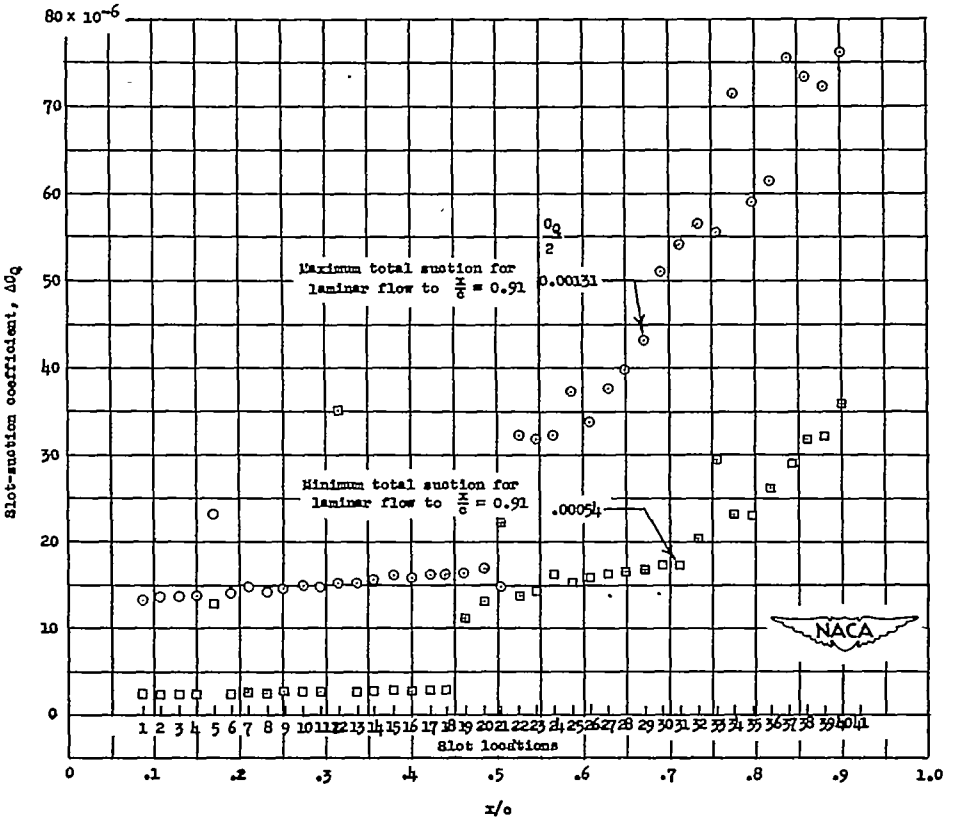
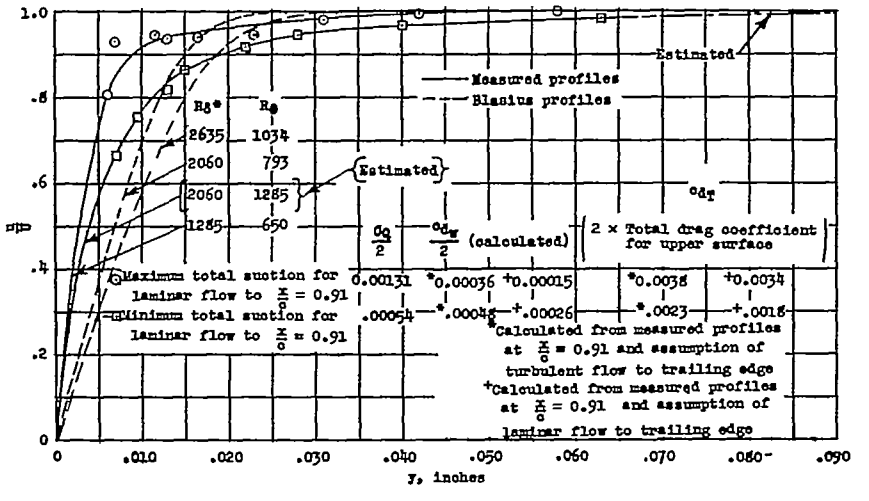


(a) Suction-coefficient distributions for boundary-layer measurements of figure 11(b).



(b) Boundary-layer profiles at $\frac{x}{c} = 0.91$ and spanwise station 0.5 inch right of model center line.

Figure 11.- Boundary-layer and suction quantity measurements for the upper surface of the NACA 64A010 slotted airfoil at the maximum Reynolds number for extensive laminar flow. Slots hand-honed; $R = 10 \times 10^6$; $\alpha = 0^\circ$.

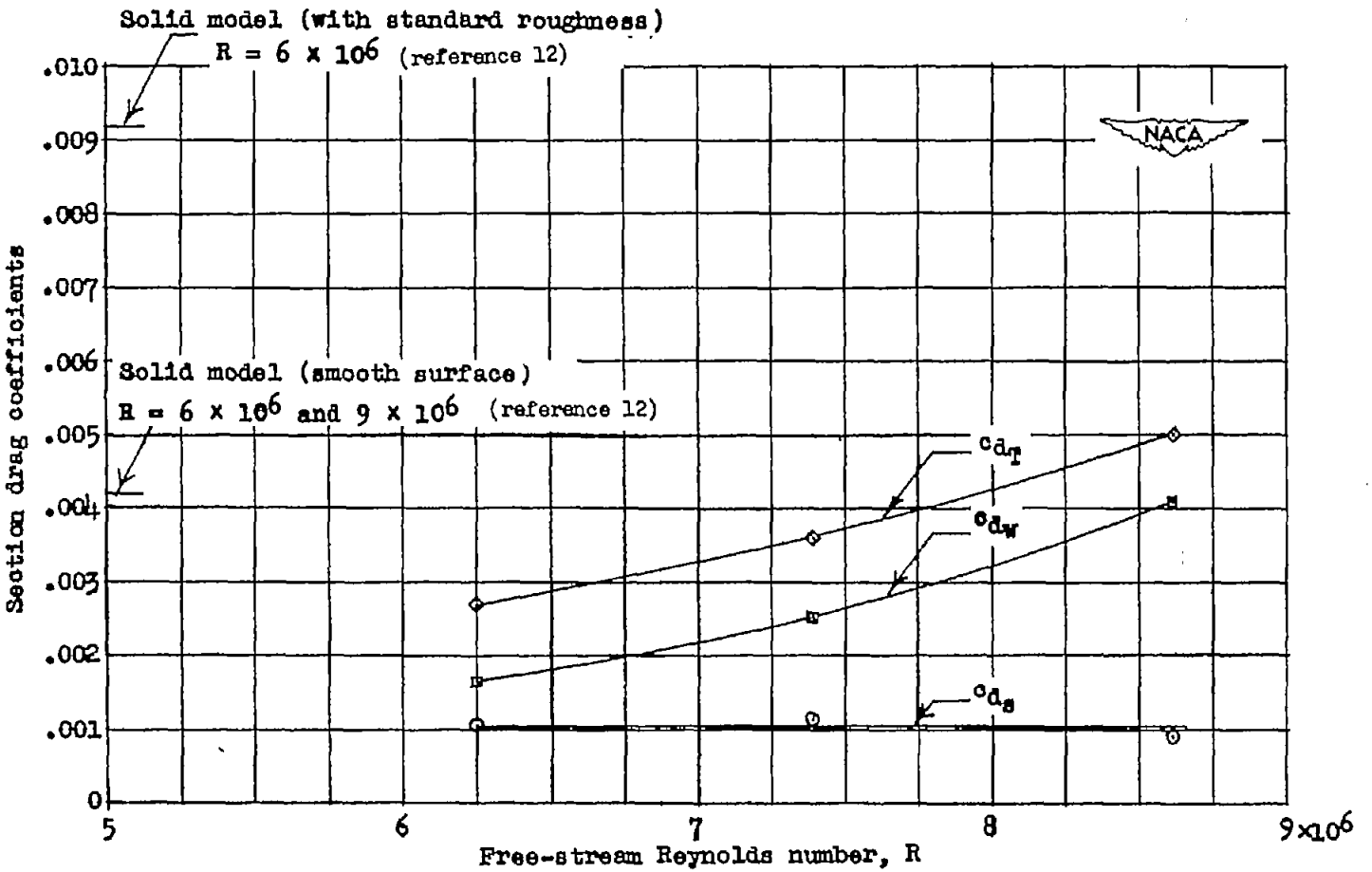


Figure 12.- Suction, wake (measured 0.5 inch right of span center line), and total drag coefficients at Reynolds numbers from 6.25×10^6 to 8.62×10^6 for the NACA 64A010 slotted airfoil with hand-formed slot radii. Average $C_Q = 0.0009$; $\alpha = 0^\circ$; same suction control valve settings as used to obtain data in figure 13.

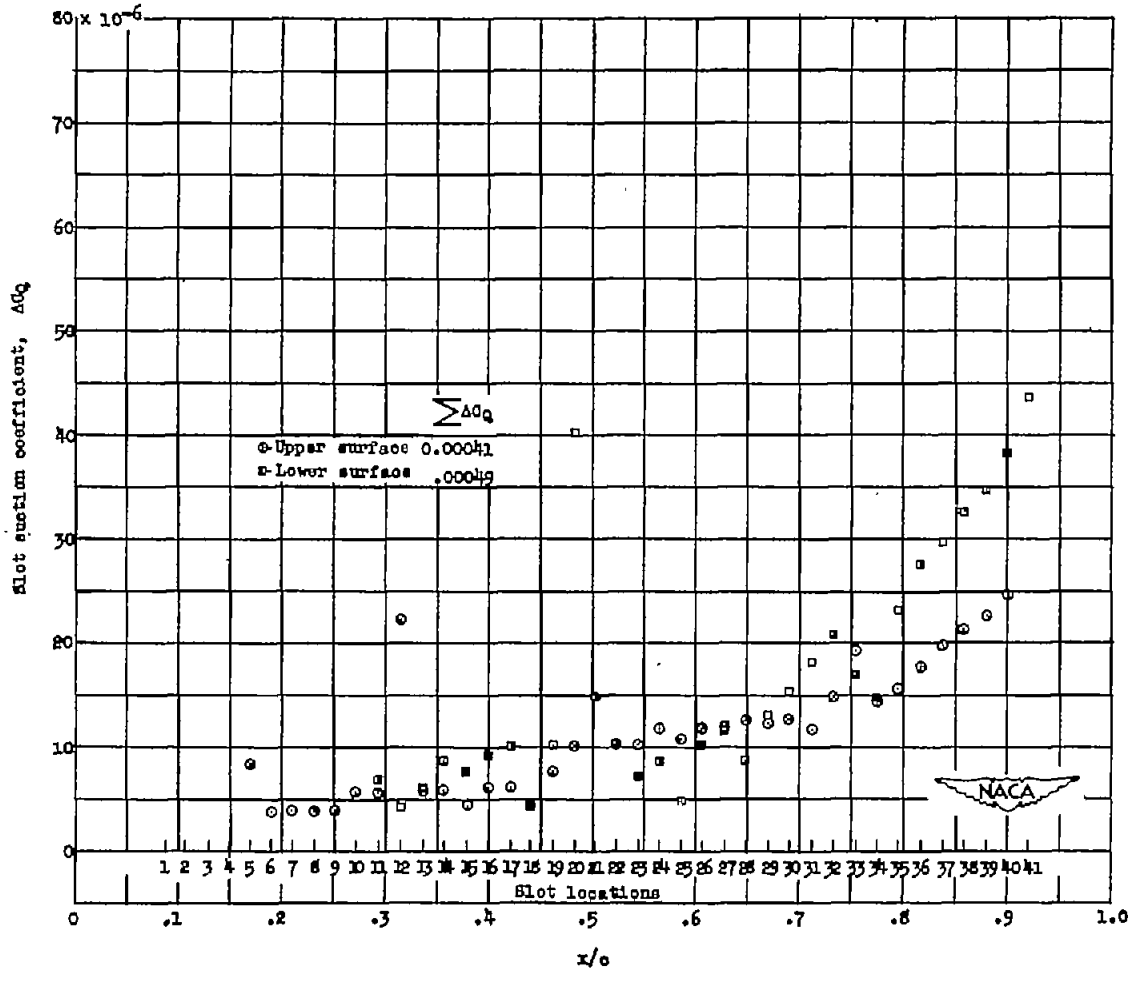


Figure 13.- Experimental distribution of slot-suction coefficients, on both surfaces of the NACA 64A010 slotted airfoil with hand-formed slot radii; $R = 6.25 \times 10^6$. This valve setting used for all drag data in figures 12, 14, and 15. $C_Q = 0.0009$; $\alpha = 0^\circ$.

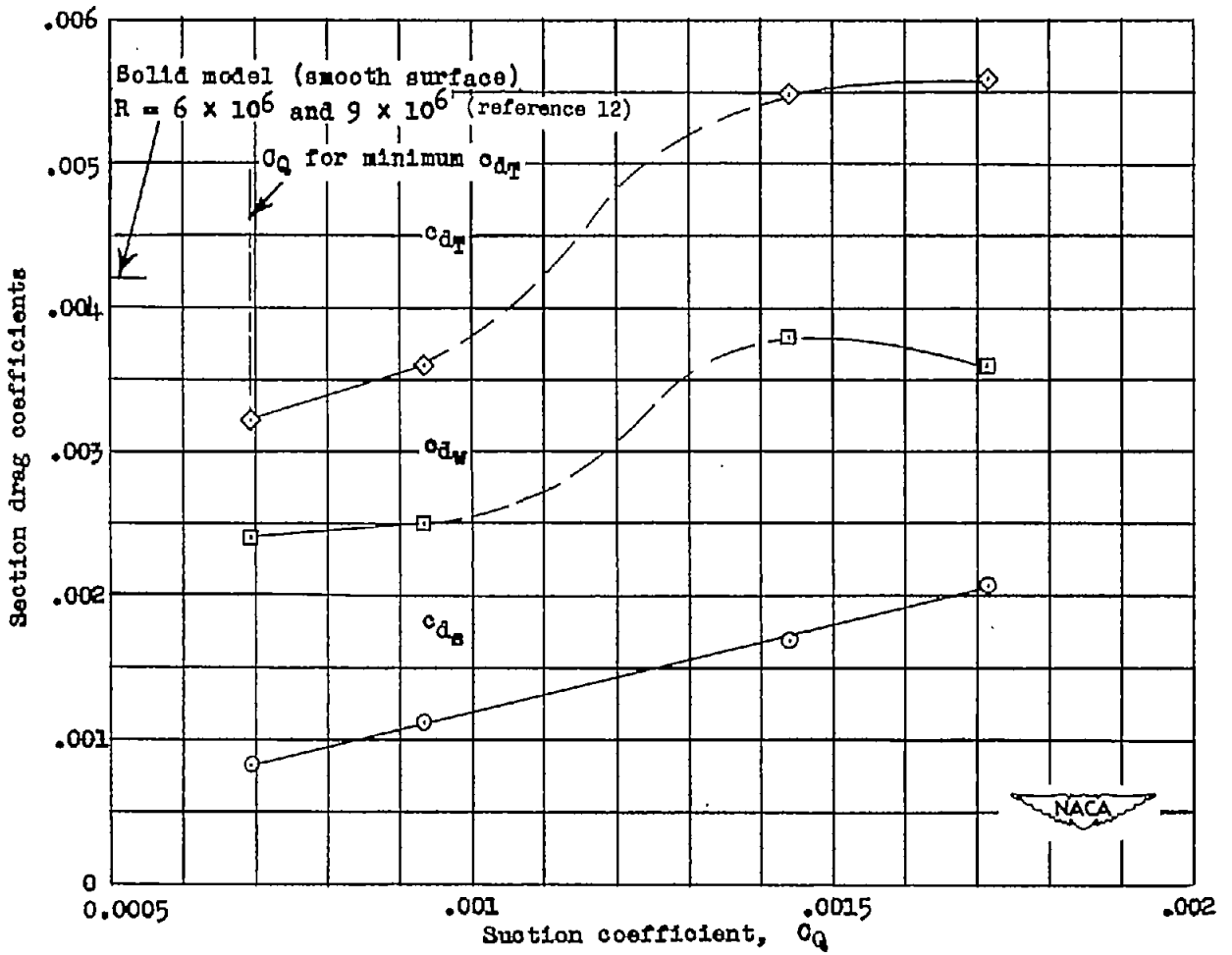


Figure 14.- Suction, wake, and total drag coefficients at suction coefficients from 0.00069 to 0.00171 for the NACA 64A010 slotted airfoil with hand-formed radii; spanwise station 0.5 inch right of model center line. $R = 7.4 \times 10^6$; $\alpha = 0^\circ$.

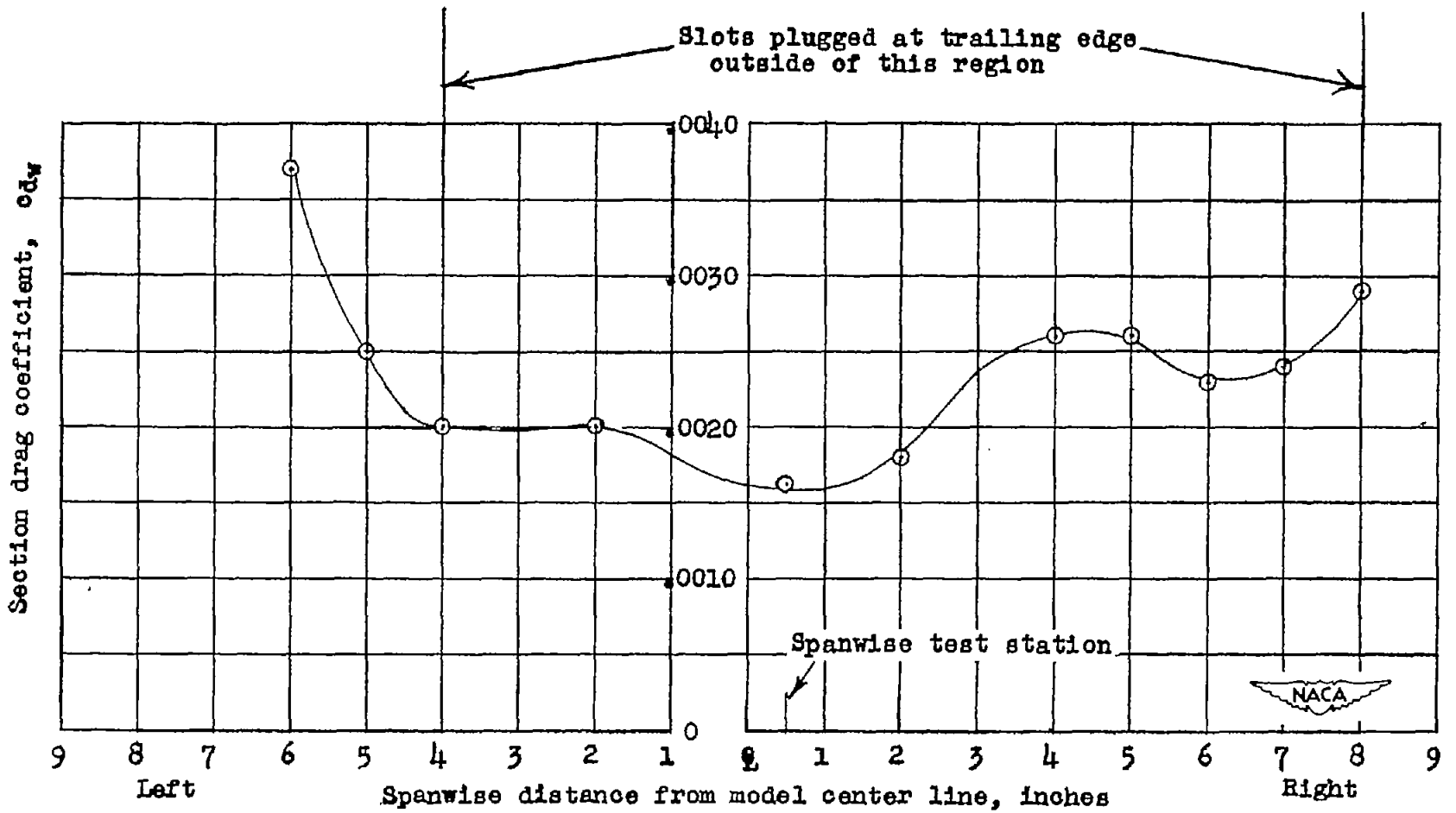


Figure 15.- Spanwise variation of section profile drag coefficient of the NACA 64A010 slotted airfoil with hand-formed slot radii. $R = 6.25 \times 10^6$; $C_Q = 0.0009$; $\alpha = 0^\circ$; same suction control valve settings as used to obtain data in figure 13.

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