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TESTS OF THE NACA 65₃-018 AIRFOIL SECTION
WITH BOUNDARY-LAYER CONTROL BY SUCTION

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

CONFIDENTIAL BULLETIN

TESTS OF THE NACA 65₃-018 AIRFOIL SECTION
WITH BOUNDARY-LAYER CONTROL BY SUCTION

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SUMMARY

Tests of the NACA 65₃-018 airfoil section with boundary-layer control by suction have been made in the Langley two-dimensional low-turbulence and Langley two-dimensional low-turbulence pressure tunnels. Slots were tested at 30 and 75 percent and at 45 and 75 percent of the airfoil chord at Reynolds numbers of 1.9 and 6.0×10^6 . An attempt was made to remove only a moderate amount of air through the slots and to locate the slots so that the low-drag properties of the airfoil could be realized. The results of these tests were compared with results for a plain NACA 65₃-018 airfoil section.

A maximum section lift coefficient of 1.85 at a Reynolds number of 6.0×10^6 was obtained on the NACA 65₃-018 airfoil section with boundary-layer control when the total amount of air removed corresponded to a flow having free-stream velocity through an area equal to approximately 1.2 percent of the wing area. This lift coefficient was found at approximately the same angle of maximum lift as for the plain airfoil and with suction slots at 45 and 75 percent of the airfoil chord. The surface discontinuity, which would be found with a flush-type sliding door placed at 45 percent of the airfoil chord, would not impair the low-drag properties of this airfoil section.

INTRODUCTION

Extensive investigations have been made to develop various types of device to increase the maximum lift of airfoils. The most common high-lift devices are the trailing-edge flap and the leading-edge slat. Both

these devices have disadvantages; the flap produces high pitching moments, whereas a slat definitely limits the region of laminar flow and thus results in high drag even when retracted.

The purpose of the present investigation was to determine the increase in maximum lift coefficient that could be obtained with the arrangement of the NACA 653-018 airfoil section presented herein by using boundary-layer control and removing only a moderate amount of air. Locating the slots so that the low-drag properties of the airfoil could be realized was given primary consideration in the design. By sucking low-energy air off the upper surface of the airfoil, separation of the flow at high lift coefficients may be greatly delayed and the straight portion of the lift curve may be extended to higher angles of attack.

The application of boundary-layer control to increase maximum lift seems advantageous for use with tailless airplanes. The high pitching moments associated with flaps, which would be prohibitive on such a design, and the high drag of leading-edge slats are avoided.

In the present investigation, an NACA 653-018 symmetrical low-drag airfoil section was tested in the Langley two-dimensional low-turbulence and the Langley two-dimensional low-turbulence pressure tunnels (designated LTT and TDT, respectively) at Reynolds numbers of approximately 1.9×10^6 and 6.0×10^6 .

SYMBOLS

c	airfoil chord
c_l	section lift coefficient
α_0	section angle of attack
c_{d_0}	section profile-drag coefficient
b	airfoil span
U_0	free-stream velocity
q_0	free-stream dynamic pressure

- H_o free-stream total pressure
 Q quantity rate of flow through slot
 H_b total pressure inside duct
 $c_{d_{ob}}$ blower drag coefficient; that is, profile-drag coefficient equivalent to power required to discharge at free-stream total pressure air withdrawn from turbulent boundary layer $\left(C_Q \frac{H_o - H_b}{q_o} \right)$
 c_{dT} total section drag coefficient $(c_{d_o} + c_{d_{ob}})$
 C_Q flow coefficient $\left(\frac{Q}{U_o cb} \right)$
 p static pressure on airfoil surface
 u velocity inside boundary layer
 U local velocity outside boundary layer
 S pressure coefficient $\left(\frac{H_o - p}{q_o} \right)$
 δ total thickness of boundary layer
 y perpendicular distance above airfoil surface
 θ momentum thickness of boundary layer $\left[\int_0^\delta \frac{u}{U} \left(1 - \frac{u}{U} \right) dy \right]$
 δ^* displacement boundary-layer thickness $\left[\int_0^\delta \left(1 - \frac{u}{U} \right) dy \right]$
 H shape parameter $\left(\frac{\delta^*}{\theta} \right)$
 R Reynolds number

Subscripts:

- 30 at 30 percent of the airfoil chord
- 45 at 45 percent of the airfoil chord
- 75 at 75 percent of the airfoil chord

MODEL AND TESTS

The airfoil used in the present investigation was a 36-inch-chord wooden model of the NACA 65₃-018 airfoil section, which was painted and prepared for testing by the methods described in reference 1. The slots and ducting arrangement are shown in figure 1. The slots were used in pairs; either the slots at 0.30c and 0.75c or the slots at 0.45c and 0.75c were used together.

Air was sucked off the upper surface through the slots into the ducts in the model and out through the side of the tunnel. Outside the tunnel, the air from each slot was piped through an individual Venturi to the inlet of a blower. The quantity of air flow was determined by measuring total and static pressures in the Venturi throat. Total-pressure tubes were placed inside the wing ducts to determine the loss in total pressure incurred in sucking the air through the slots. In order to measure this loss for the slots at 0.30c and 0.45c, one total-pressure tube was fastened to the downstream wall of the forward duct; for the slot at 0.75c, one total-pressure tube was fastened to the upstream wall of the rear duct.

Approximately twice as much air was sucked from the wing through the rear slot as through the front slot. Preliminary tests were made with tufts to determine the correct proportion of the total flow to be removed through each slot for effective operation.

Pressure-distribution measurements were made by placing a small static-pressure tube at a series of chordwise stations about 3/32 inch above the airfoil surface. At each station, the tube was bent to approximate the contour of the airfoil. Lifts obtained from integration of pressure-distribution diagrams obtained

by this method have been found to be in good agreement with the lifts obtained from force tests. Lift was determined by integrating the pressures along the floor and ceiling of the tunnel test section. External drag was measured by the wake-survey method. Both lift and drag coefficients have been corrected for tunnel-wall interference. Boundary-layer measurements were made by the method described in reference 2.

The values of cd_{ob} were calculated on the assumption that the air removed from the boundary layer was exhausted at free-stream total pressure. When the power required for boundary-layer control is calculated on this basis, there are no additional power effects due to an excess or defect of total pressure at the point where the boundary-layer air is exhausted. The required power was furnished by a machine that was assumed to be 100 percent efficient.

RESULTS AND DISCUSSION

The lift characteristics of the NACA 65₃-018 airfoil section with and without boundary-layer control are presented in figure 2. The characteristics for the plain airfoil at a Reynolds number of 6.0×10^6 were taken from previous tests of a 24-inch-chord model of the NACA 65₃-018 airfoil section in the TDT (unpublished). A maximum section lift coefficient of 1.85 was obtained in the TDT at a Reynolds number of 6.0×10^6 for a flow coefficient of 0.0120. For this flow coefficient, the total amount of air removed from the boundary layer corresponded to a flow with free-stream velocity through an area equal to approximately 1.2 percent of the wing area.

Figure 3 shows that, at an angle of attack near maximum lift and for a given lift coefficient below a flow coefficient of 0.0120, more air was required for the slots at 0.45c and 0.75c than for the slots at 0.30c and 0.75c. This phenomenon may be explained by the fact that the boundary layer was thinner at 0.30c than at 0.45c and, consequently, less air was required to control the boundary layer with the slot at 0.30c than with the slot farther downstream. Figure 3 also

indicates that, at an angle of attack near maximum lift and for a given lift coefficient, a lower flow coefficient was required at $R = 6.0 \times 10^6$ than at $R = 1.9 \times 10^6$. Since the boundary layer was thinner at the higher Reynolds number, relatively less air was required to control the boundary layer at a Reynolds number of 6.0×10^6 than was required at a Reynolds number of 1.9×10^6 . No improvement could be obtained other than a straightening of the lift curve; therefore, greater increments were possible at the lower Reynolds number. At an angle of attack of 12.4° , the favorable effect of Reynolds number is clearly shown and the difference between the curves for the slots at 0.30c and 0.75c and at 0.45c and 0.75c has disappeared.

Little scale effect on maximum lift is evident in figure 2 at the maximum flow rate for the test Reynolds number range. At a Reynolds number of 1.9×10^6 , the angle of maximum lift was $\frac{1}{2}^\circ$ higher for the airfoil with slots than for the plain airfoil. At a Reynolds number of 6.0×10^6 , the angle of maximum lift was approximately 3° lower for the airfoil with slots than for the plain airfoil. In the LTT, at a Reynolds number of 1.9×10^6 , the maximum lift coefficient at the highest flow rate was found to be limited by stalling at the leading edge; the position of the stall was determined from tuft studies. From the similarity of the break at maximum lift for the conditions tested, maximum lift at the highest flow rate for a Reynolds number of 6.0×10^6 seemed also to be limited by stalling at the leading edge. A few exploratory measurements at a Reynolds number of 6.0×10^6 indicated that little further gain in maximum lift could be obtained by increasing the flow rate above 0.0120.

The increases in maximum lift coefficient, which are made possible by boundary-layer control, are due to the increased slope of the lift curve in the range of high lift coefficient - that is, to the extension of the straight portion of the lift curve to higher angles of attack. As long as separation moves forward from the trailing edge without moving forward of the suction slots, boundary-layer control is effective. When stalling at the leading edge limits the maximum lift coefficient, as was the case in the present investigation,

a slot has to be placed extremely close to the leading edge of the airfoil to be effective. Since laminar flow would be maintained with difficulty in the high-speed condition over a slot so placed, no attempt was made in the present investigation to place a slot near the leading edge.

The amount of air removed with boundary-layer control may be presented in terms of the displacement boundary-layer thickness immediately upstream of the slot. A convenient nondimensional form may be given by the expression Q/U_0^*b . When Q/U_0^*b reached a value of 1, the slots were operating near maximum effectiveness. Increasing the flow above this value had no noticeable effect on further delaying separation.

Drag characteristics of the NACA 653-018 airfoil section with and without boundary-layer control are presented in figure 4. The model with the slot at 0.45c sealed with "Scotch" cellulose tape (fig. 4(b)) approximates the plain airfoil, because transition on the NACA 653-018 airfoil section normally occurs at approximately 0.45c. At a Reynolds number of 1.9×10^6 , the drag of the airfoil with the slot at 0.30c sealed (fig. 4(a)) is practically the same as that of the airfoil with the slot at 0.45c sealed; therefore, the airfoil characteristics with the slot at 0.30c sealed are also thought to approximate those of the plain airfoil. The measured values of external-drag coefficient may be obtained by deducting the blower drag coefficient given in figure 5 from the corresponding value of total drag coefficient given in figure 4.

An envelope curve, if drawn outside the polars for different flow rates in figure 4, would indicate that at the higher lift coefficients boundary-layer control results in a net reduction of drag. In figures 4(b) and 4(c), at lift coefficients below approximately 0.4, higher drags are found with than without boundary-layer control because of pressure losses in the internal system. Since no separated flow occurs in this range of lift coefficient, boundary-layer control is not required and some means of sealing the slot - for example, a sliding door - should be provided. Figure 4(c) indicates that, if the flow system is not sealed when no air is being removed, serious drag increases may be expected.

Total drag coefficients depend to a great extent on the way air is ducted into and through the model. No attempt was made in the present investigation, however, to design more efficient ducts and slots because high lifts depend more on the quantity of air taken in than on the slot design. Further tests might be devoted to the development of slots and wing ducts that minimize the power required for boundary-layer control.

A comparison of the values of c_{dop} in figure 5 indicates that much higher drag losses were encountered with slots at 0.30c and 0.75c than at 0.45c and 0.75c. This condition is due primarily to the larger pressure difference against which the slot must operate at 0.30c. Because of these higher drag losses and because of the larger amount of laminar flow that can be obtained with the slot at 0.45c than with the slot at 0.30c, it appears more suitable from drag considerations to keep the slot as far downstream as possible without losing effective lift control.

Values of the ratio of the amount of air flow through the rear slot to that through the front slot are presented in figure 6. Tuft studies were made during the tests for which data are shown in figure 6(a). The tufts indicated that, at the higher angles of attack and higher flow coefficients, a flow ratio of 2 appeared to yield the optimum lift effects. In the rest of the tests, therefore, an attempt was made to maintain a flow ratio of approximately 2 (figs. 6(b) and 6(c)). The curves of figure 6 do not represent a consistent variation of the air-flow ratio but merely present the ratio at several angles of attack for a range of flow coefficient.

Pressure-distribution diagrams at maximum lift and at a Reynolds number of 1.9×10^6 for both slot configurations are presented in figure 7. There appears to be little if any separated flow even at maximum lift. Considerable pressure is recovered in passing over the slots. This recovery is due primarily to the so-called sink effect caused by sucking air from the boundary layer. Integration of these diagrams combined with the integration of diagrams of normal pressures plotted on a base line perpendicular to the chord line yielded a value of -0.058 for the section pitching-moment coefficient. This value of the pitching-moment coefficient indicates that the center of pressure is approximately 3 percent nearer the

trailing edge of the airfoil for a lift coefficient of 1.85 than for the zero-lift condition.

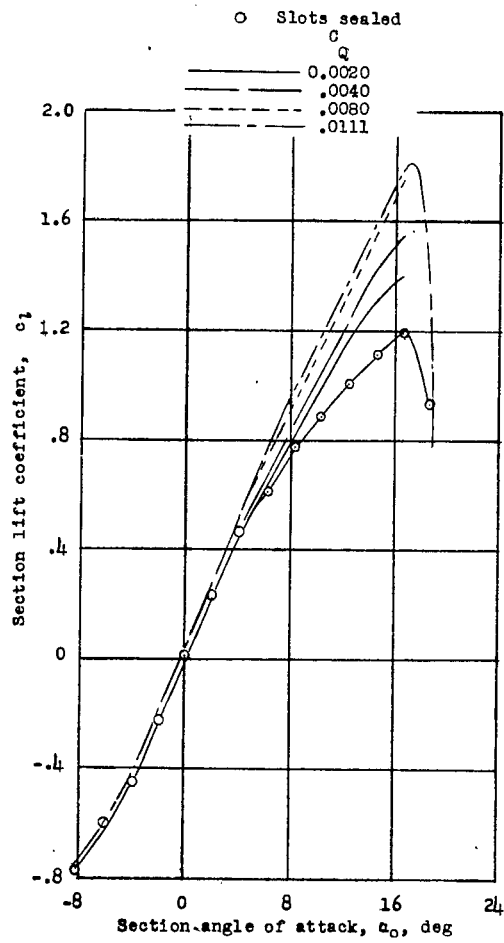
In the region in which lift coefficients are lower than maximum and correspondingly less air flow is required, it is thought that pitching moments approximating those of the plain airfoil may be realized. A pressure distribution on the plain airfoil at a Reynolds number of 6.0×10^6 and at maximum lift is presented in figure 7 for comparison.

The variation of the boundary-layer shape parameter H and the momentum thickness θ/c over the upper surface of the airfoil at maximum lift is shown in figure 8. The shape parameter has an average value of 1.5 and at no point approaches the value of 2.6, at which separation was found to be imminent in the analysis of reference 3. A discontinuity in H is found just downstream of the slot at 0.75c. The boundary-layer profile at this point indicated that some interference effects from the slot were present.

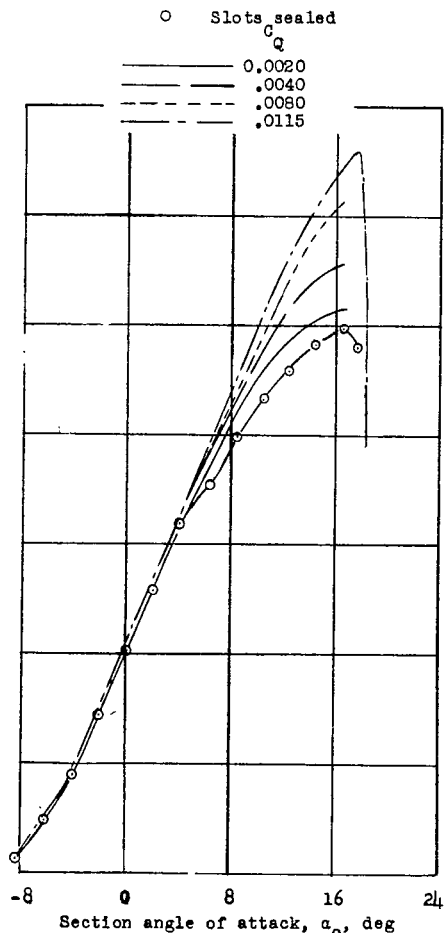
CONCLUSIONS

An NACA 653-018 airfoil section equipped with slots for boundary-layer control was tested in the Langley two-dimensional low-turbulence and Langley two-dimensional low-turbulence pressure tunnels at Reynolds numbers of 1.9 and 6.0×10^6 . Slots were tested at 30 and 75 percent and at 45 and 75 percent of the airfoil chord. Approximately twice as much air was removed through the rear slot as through the forward slot. A comparison of the results of these tests with the results for a plain NACA 653-018 airfoil section indicated the following conclusions:

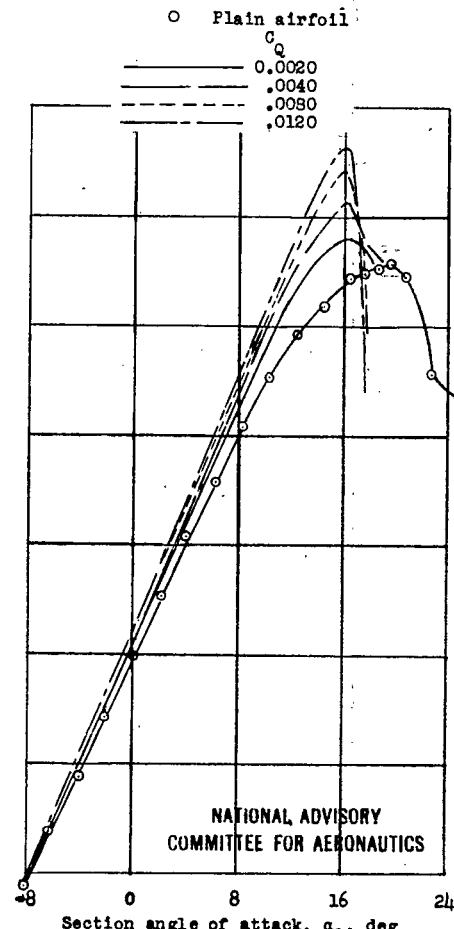
1. A maximum section lift coefficient of 1.85 was obtained at a Reynolds number of 6.0×10^6 with the NACA 653-018 airfoil section by using boundary-layer control. This lift coefficient was obtained with suction slots at 45 and 75 percent of the airfoil chord. The low-drag characteristics of this airfoil section could be realized with this arrangement when the slots were not operating by covering them with flush-type doors. The total amount of air removed at this lift coefficient



(a) Slots at 0.50c and 0.75c in LTT.
 $R, 1.9 \times 10^6$.



(b) Slots at 0.45c and 0.75c in LTT.
 $R, 1.9 \times 10^6$.



(c) Slots at 0.45c and 0.75c in TDT.
 $R, 6.0 \times 10^6$.

Figure 2.- Lift characteristics of NACA 65₃-018 airfoil with and without boundary-layer control.

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	α_0 (deg)	Slot location	Tunnel	R
○	12.4	0.30c and 0.75c	LTT	1.9×10^6
+	12.4	0.45c and 0.75c	LTT	
x	12.4	0.45c and 0.75c	TDT	
□	16.4	0.30c and 0.75c	LTT	1.9
◇	16.4	0.45c and 0.75c	LTT	
△	15.9	0.45c and 0.75c	TDT	6.0

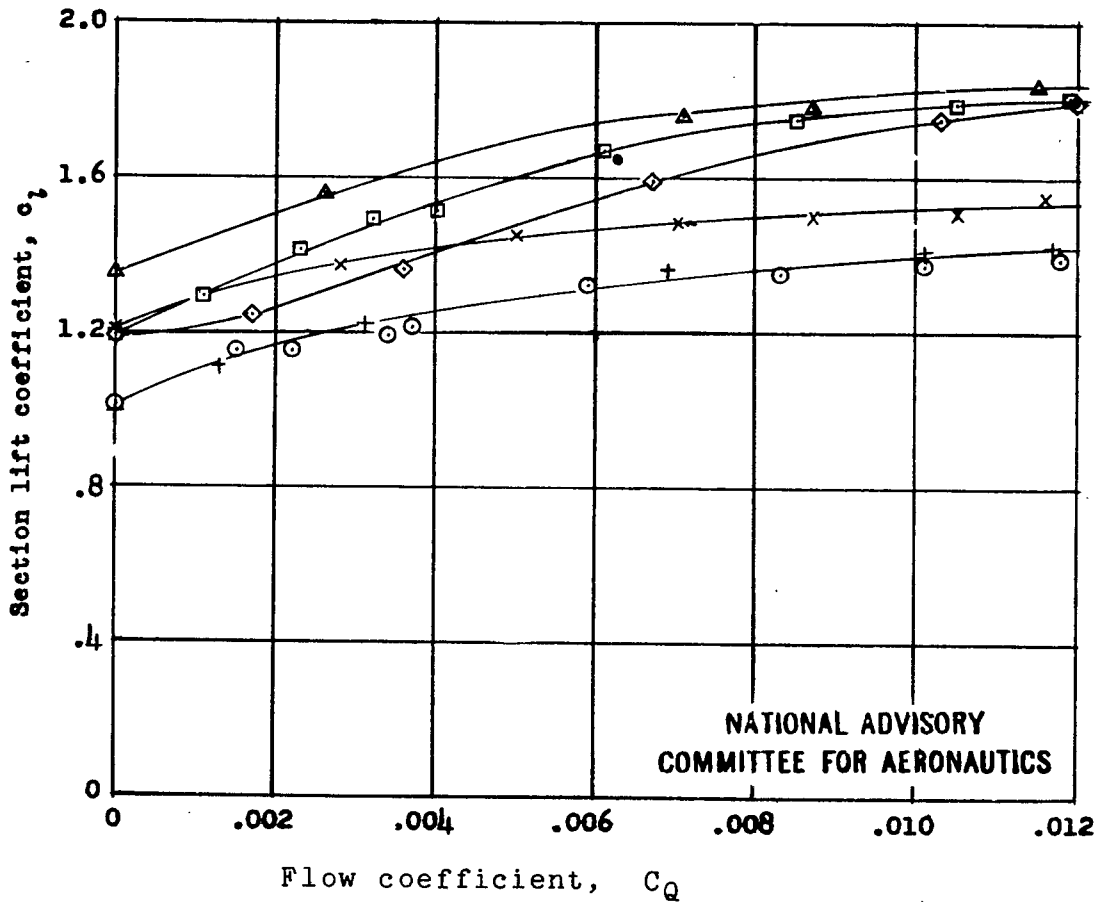
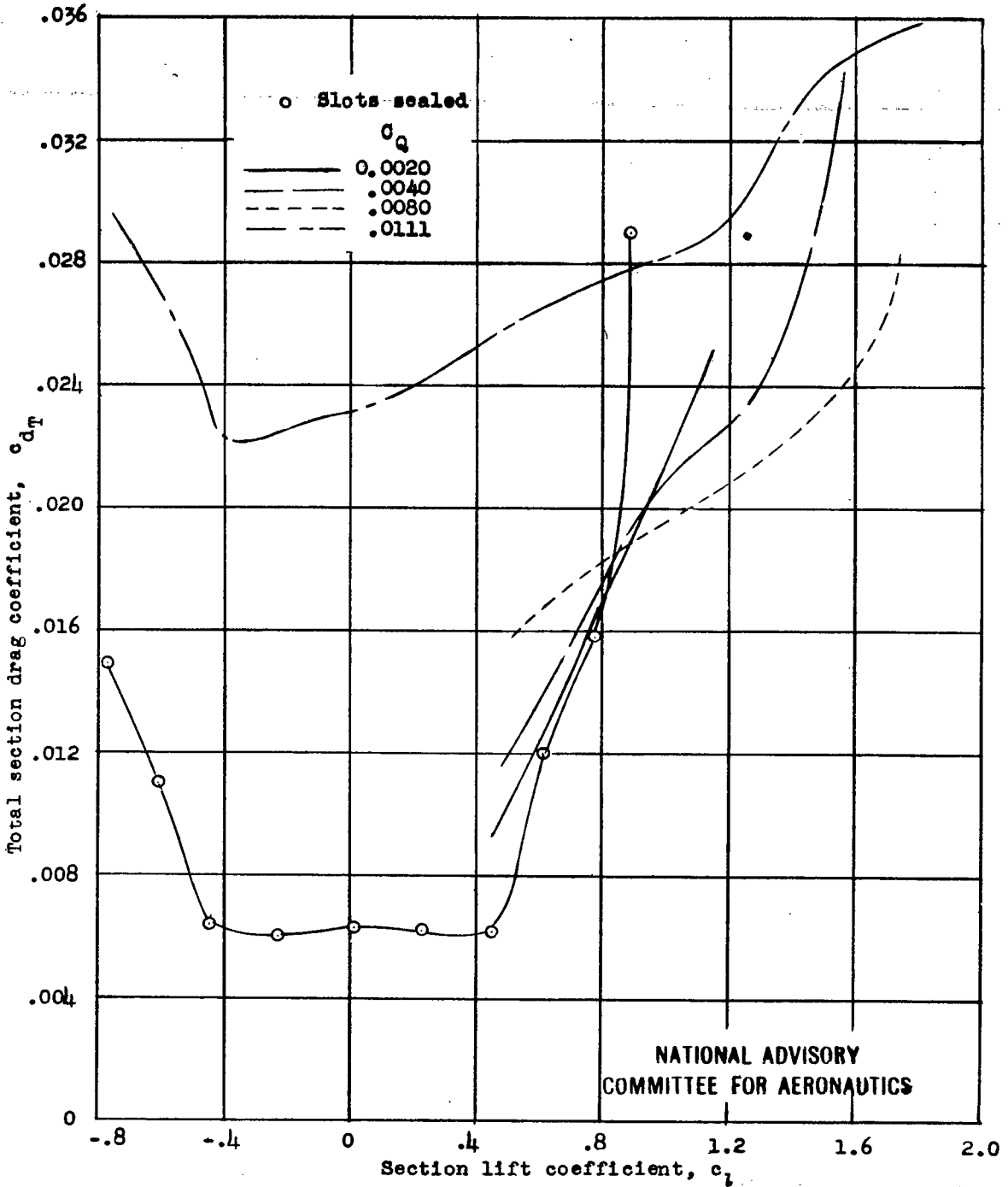
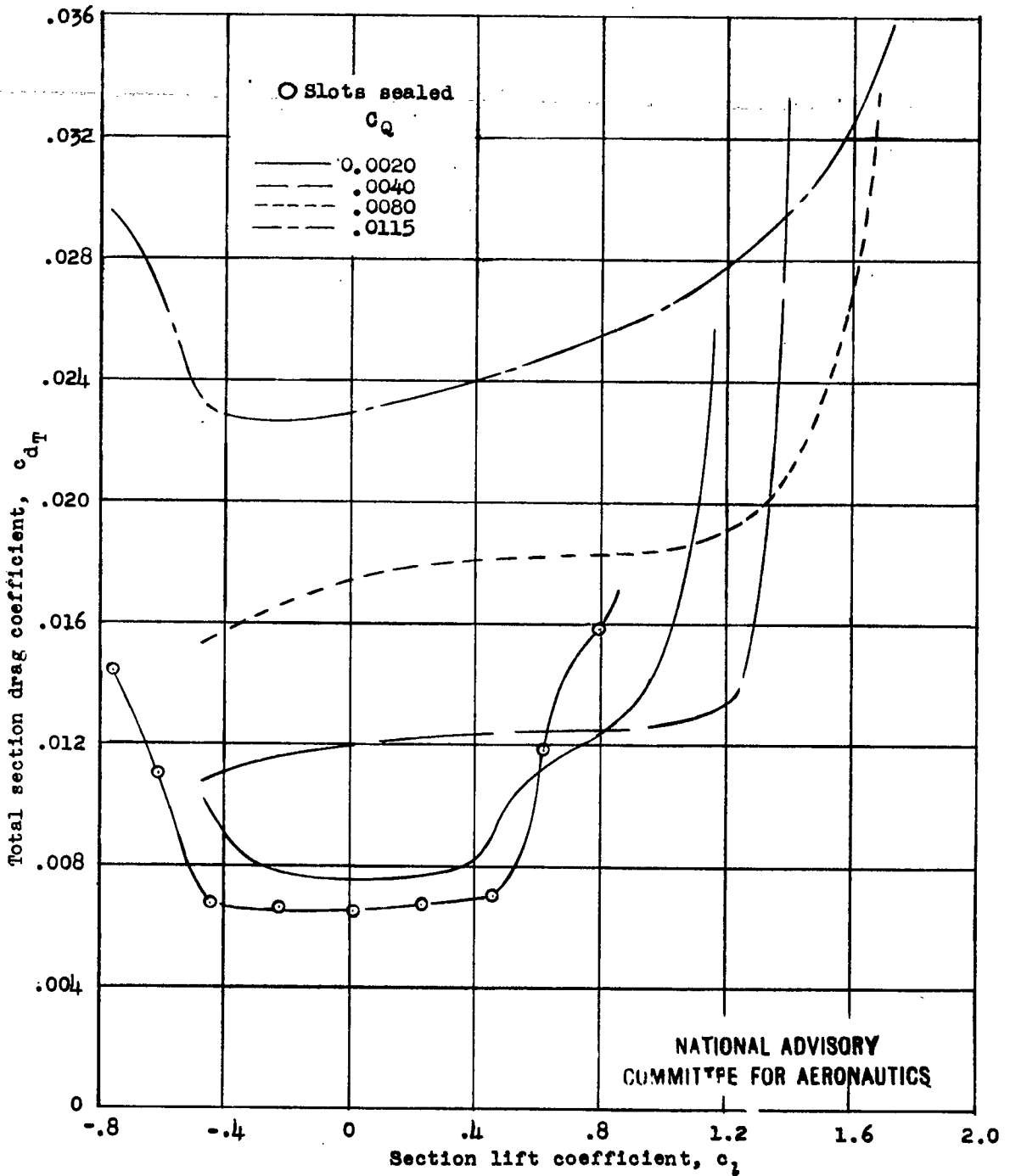


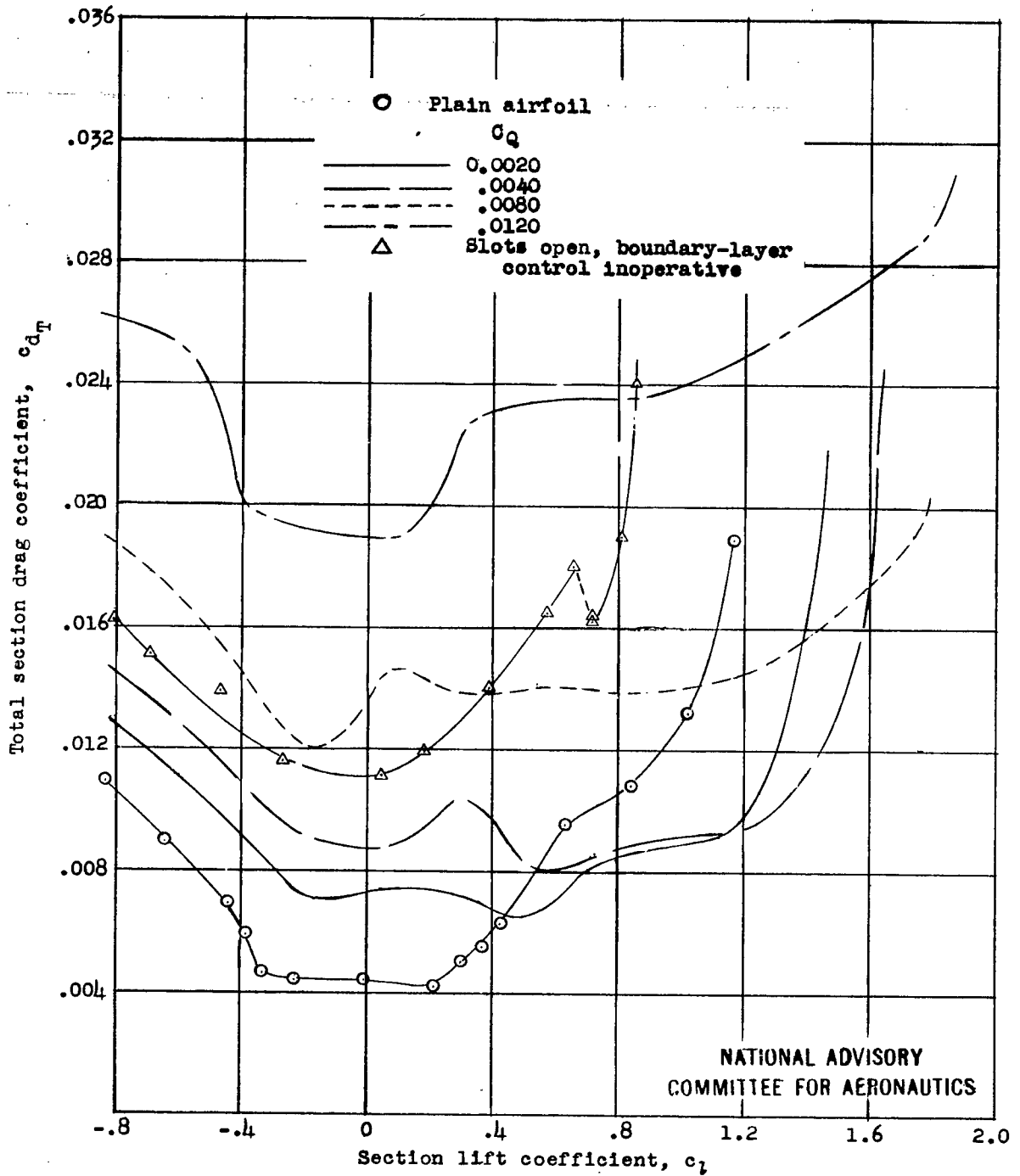
Figure 3.- Variation of section lift coefficient with flow coefficient for the NACA 653-018 airfoil section with boundary-layer control.



(a) Slots at 0.30c and 0.75c in LTT. $R, 1.9 \times 10^6$.
 Figure 4 .- Drag characteristics of NACA 65₃-018 airfoil section with and without boundary-layer control.



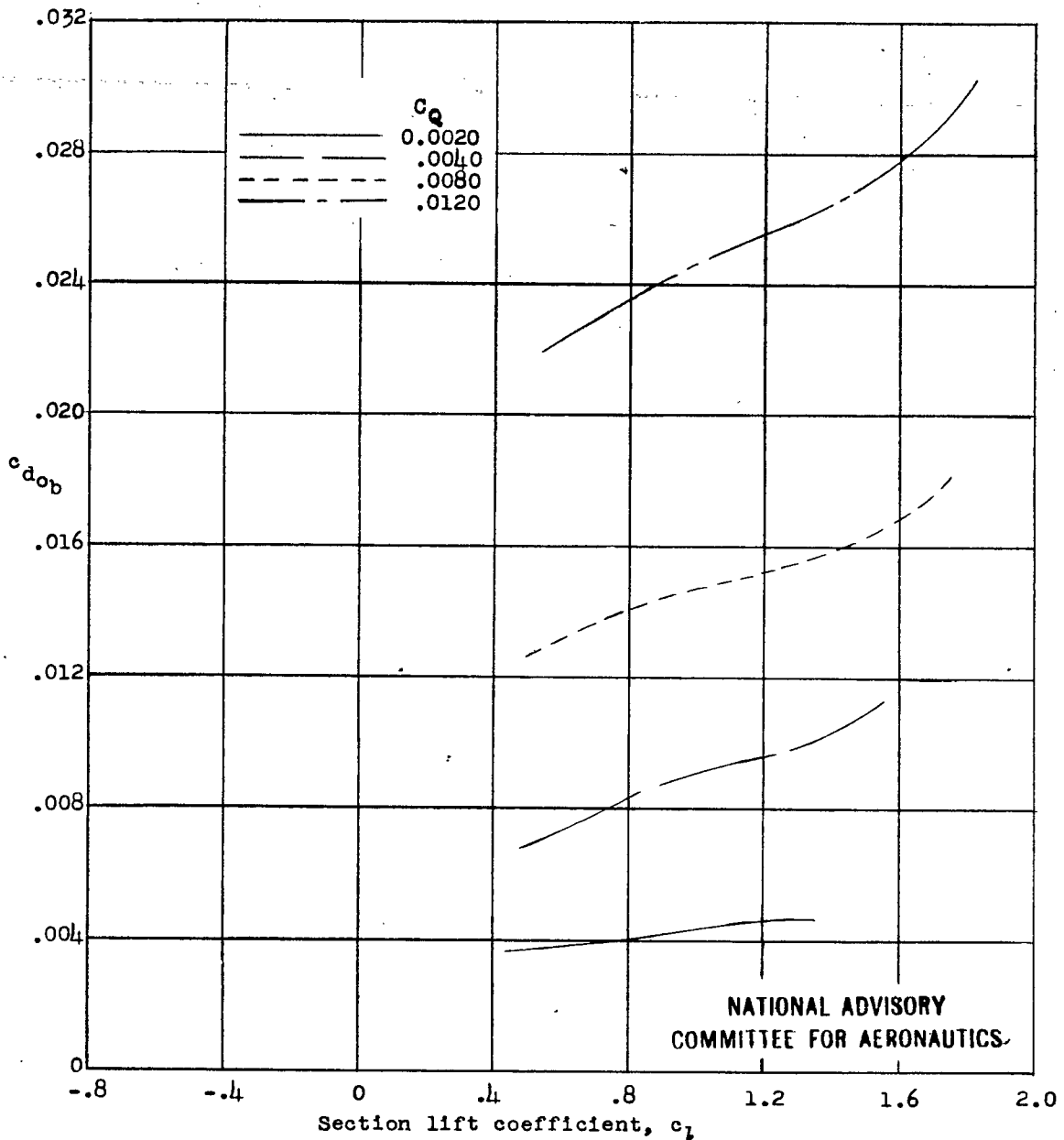
(b) Slots at 0.45c and 0.75c in LTT. $R, 1.9 \times 10^6$.
 Figure 4.- Continued.



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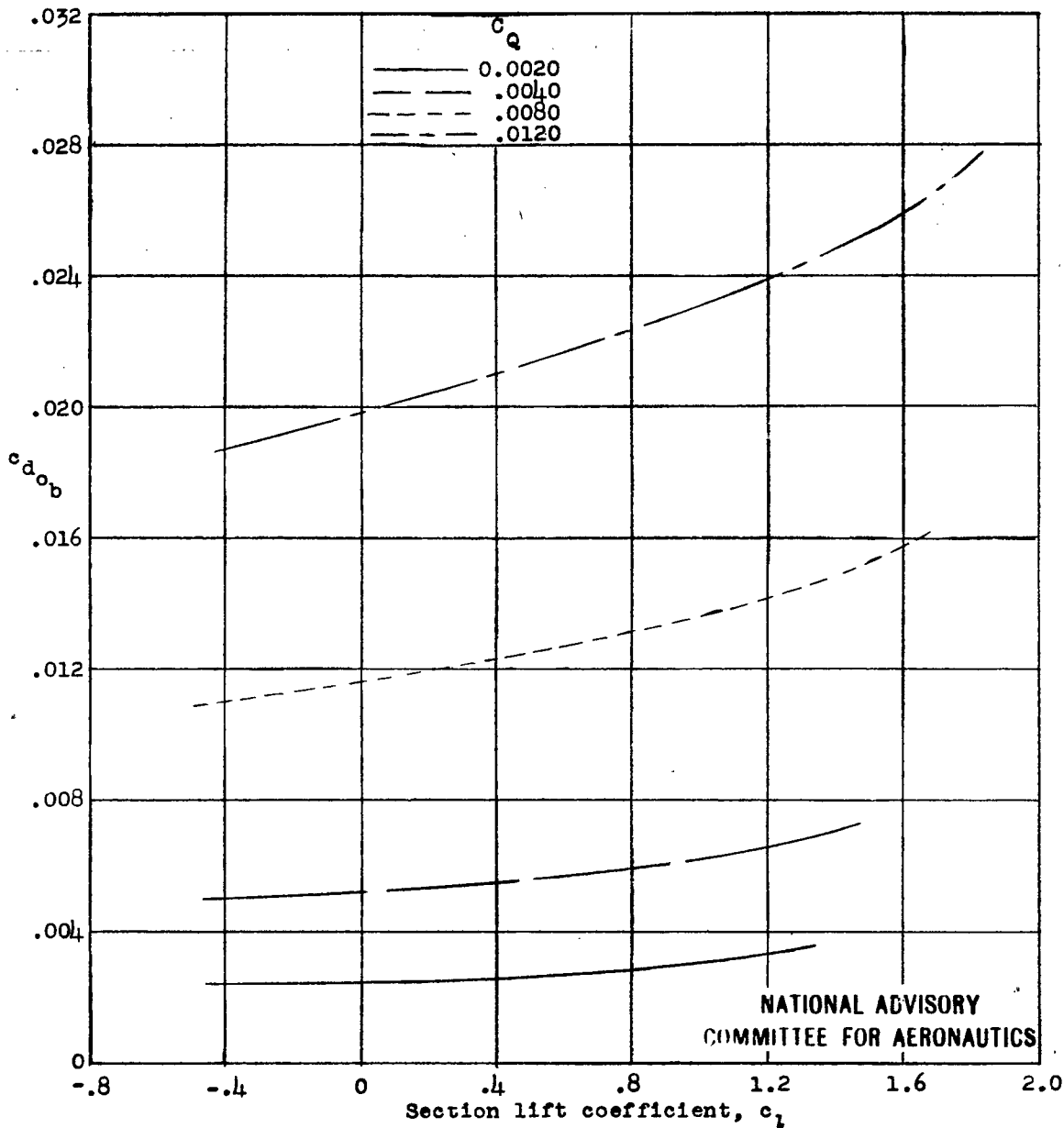
(c) Slots at 0.45c and 0.75c in TDT. $R, 6.0 \times 10^6$.

Figure 4.- Concluded.



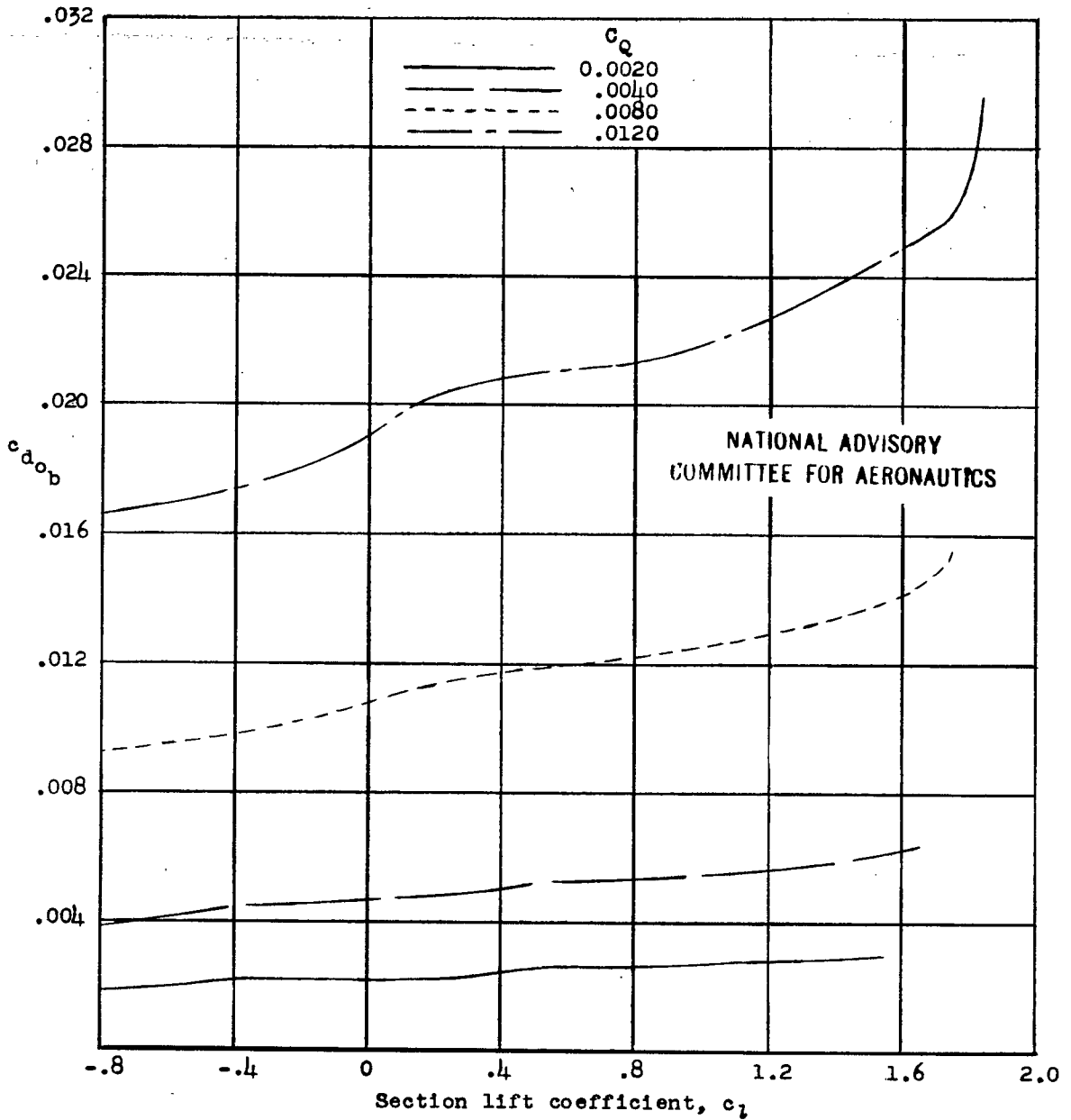
(a) Slots at 0.30c and 0.75c in LTT. $R, 1.9 \times 10^6$.

Figure 5.- Profile-drag coefficient equivalent to power required to discharge at free-stream total pressure air withdrawn from turbulent boundary layer c_{dob} on NACA 65₃-018 airfoil section with boundary-layer control.



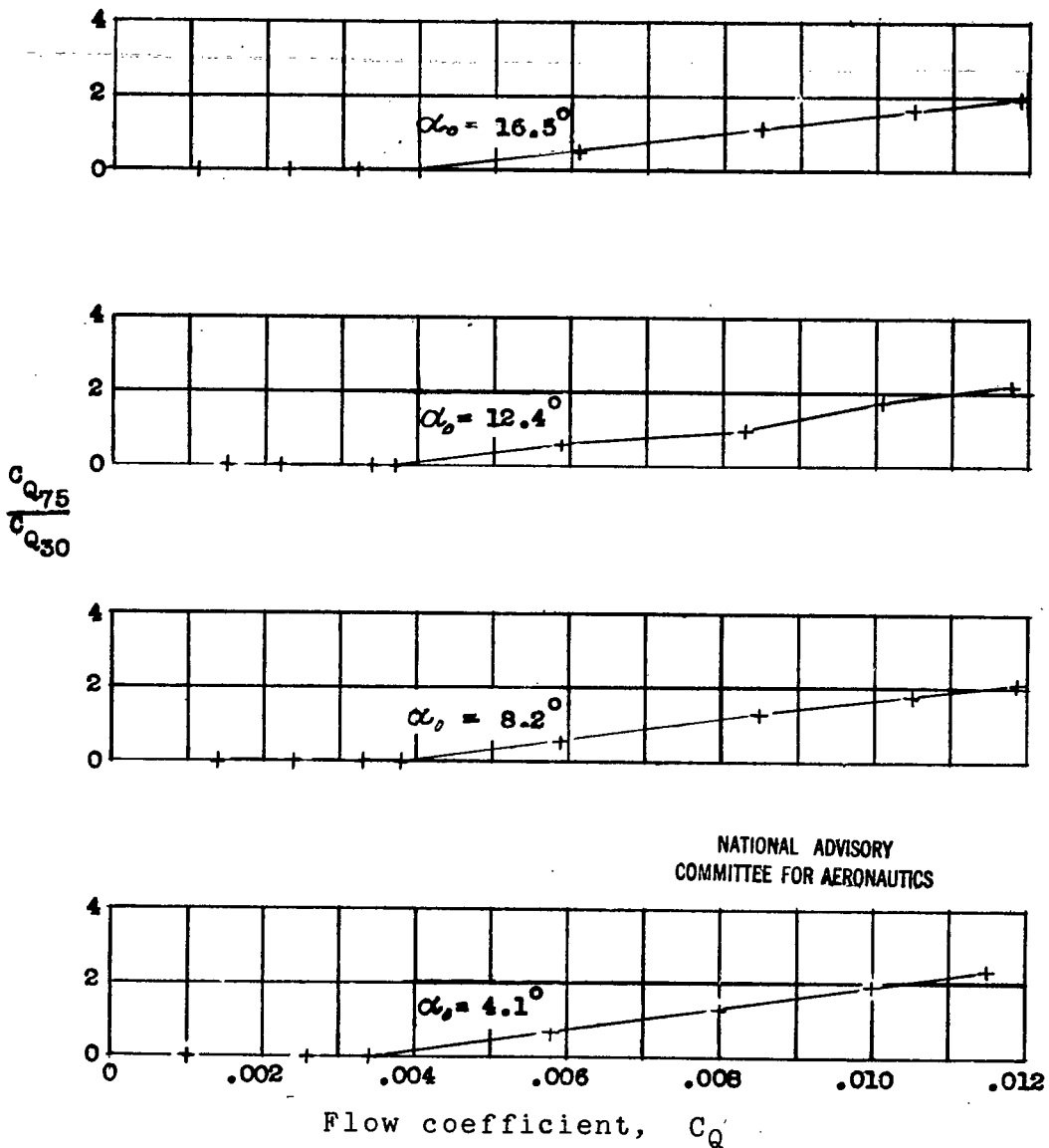
(b) Slots at 0.45c and 0.75c in LTT. $R, 1.9 \times 10^6$.

Figure 5.- Continued.



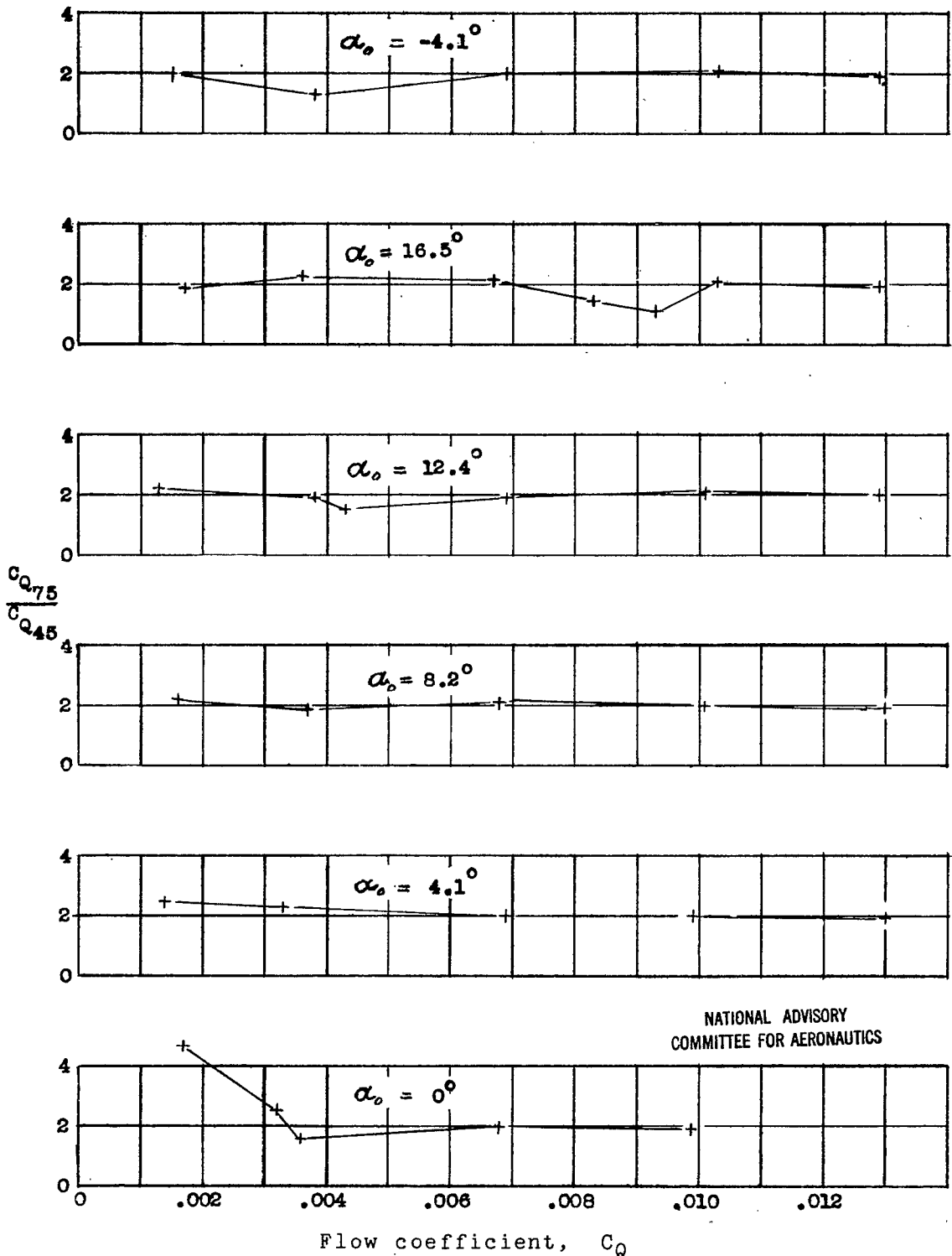
(c) Slots at 0.45c and 0.75c in TDT. $R, 6.0 \times 10^6$.

Figure 5.- Concluded.



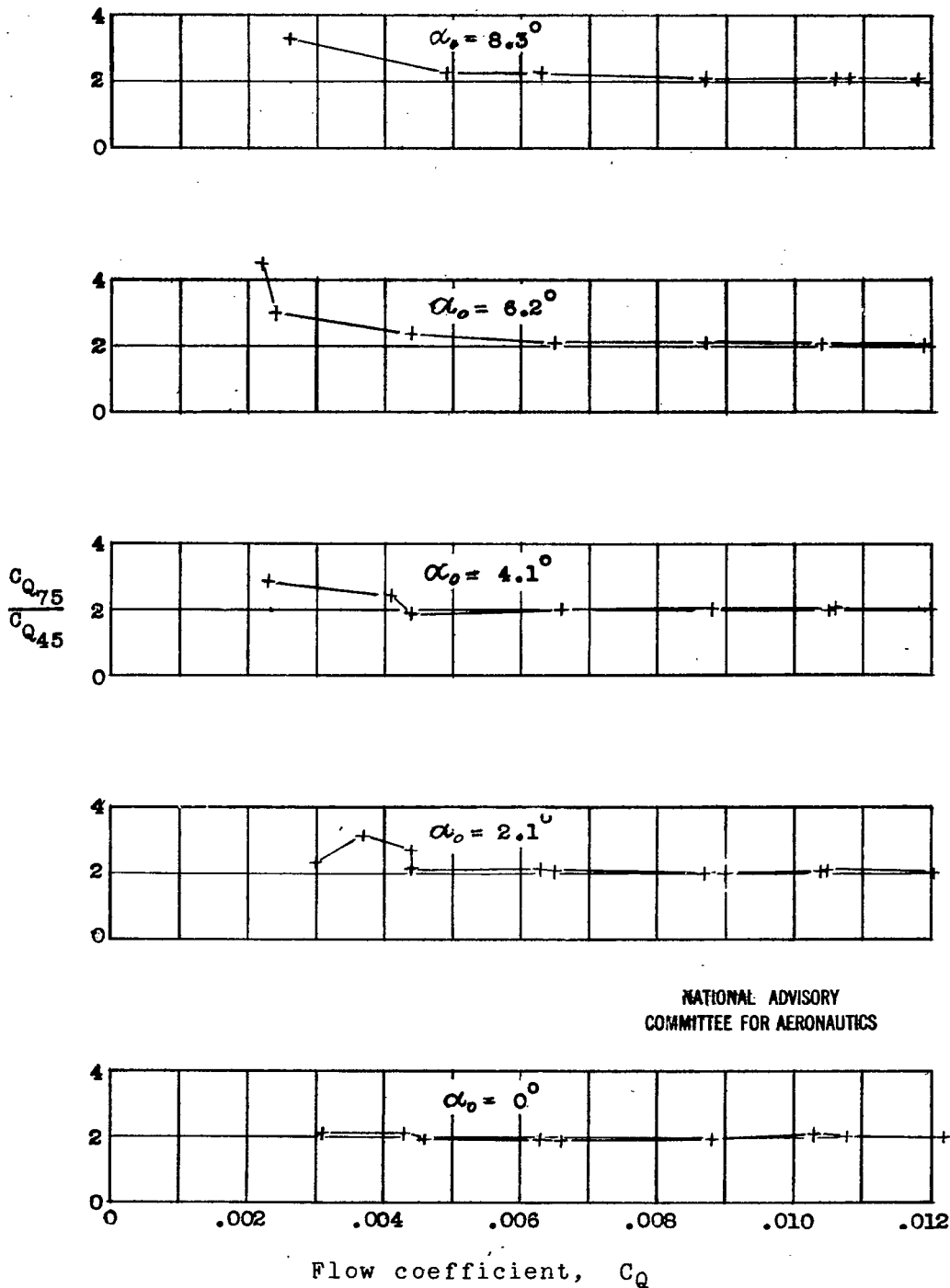
(a) Airfoil with slots at 0.30c and 0.75c in LTT. $R = 1.9 \times 10^6$.

Figure 6.- Ratio of air flow through rear slot to air flow through forward slot at several angles of attack for NACA 653-018 airfoil section with boundary-layer control.



(b) Airfoil with slots at 0.45c and 0.75c in LTT. $R = 1.9 \times 10^6$.

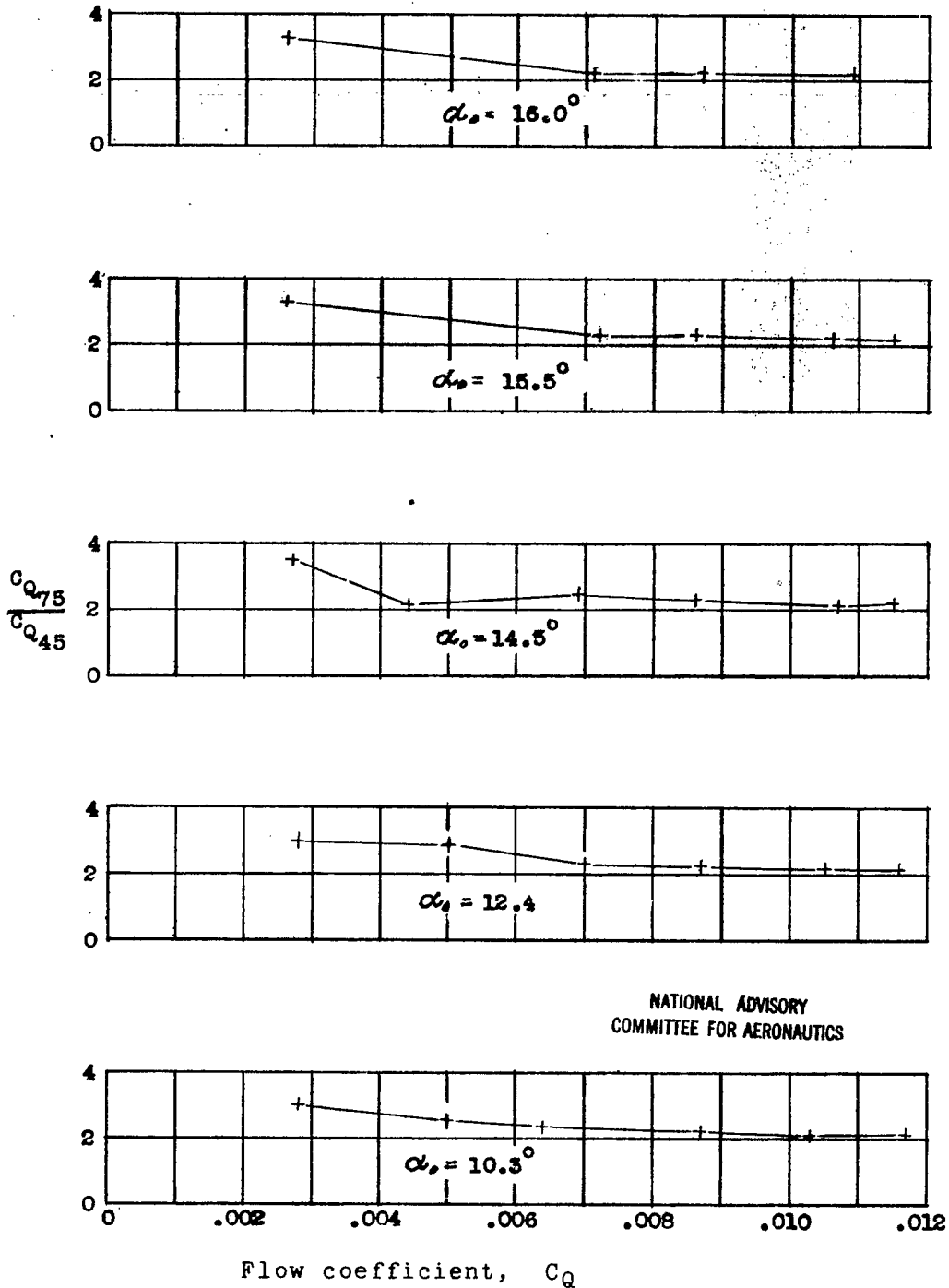
Figure 6.- Continued.



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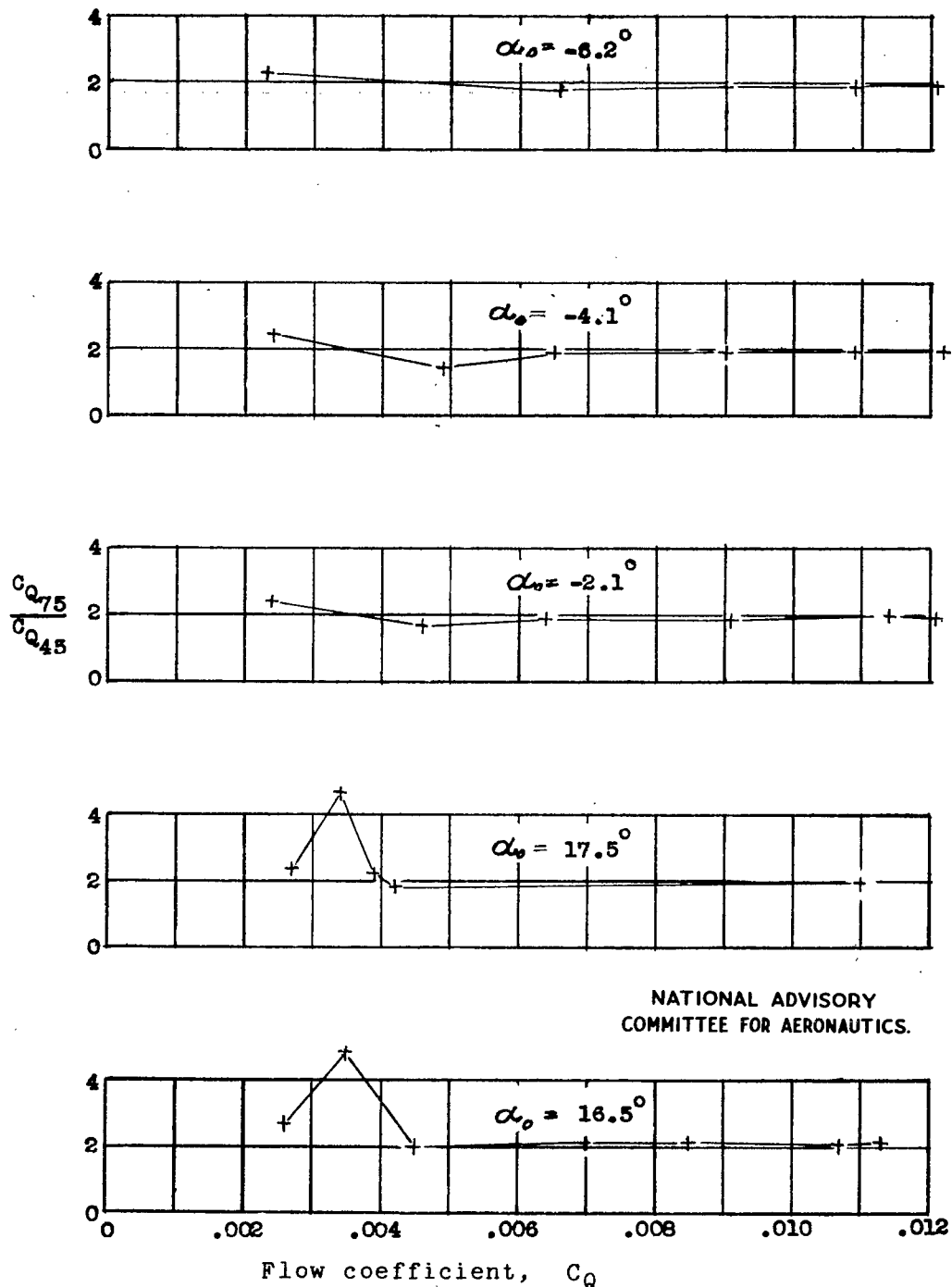
(c) Airfoil with slots at 0.45c and 0.75c in TDT. $R = 6.0 \times 10^6$.

Figure 6.- Continued.



(c) Airfoil with slots at 0.45c and 0.75c in TDT. $R = 6.0 \times 10^6$. Continued.

Figure 6.- Continued.



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(c) Airfoil with slots at 0.45c and 0.75c in TDT. $R = 6.0 \times 10^6$. Concluded.

Figure 6.- Concluded.

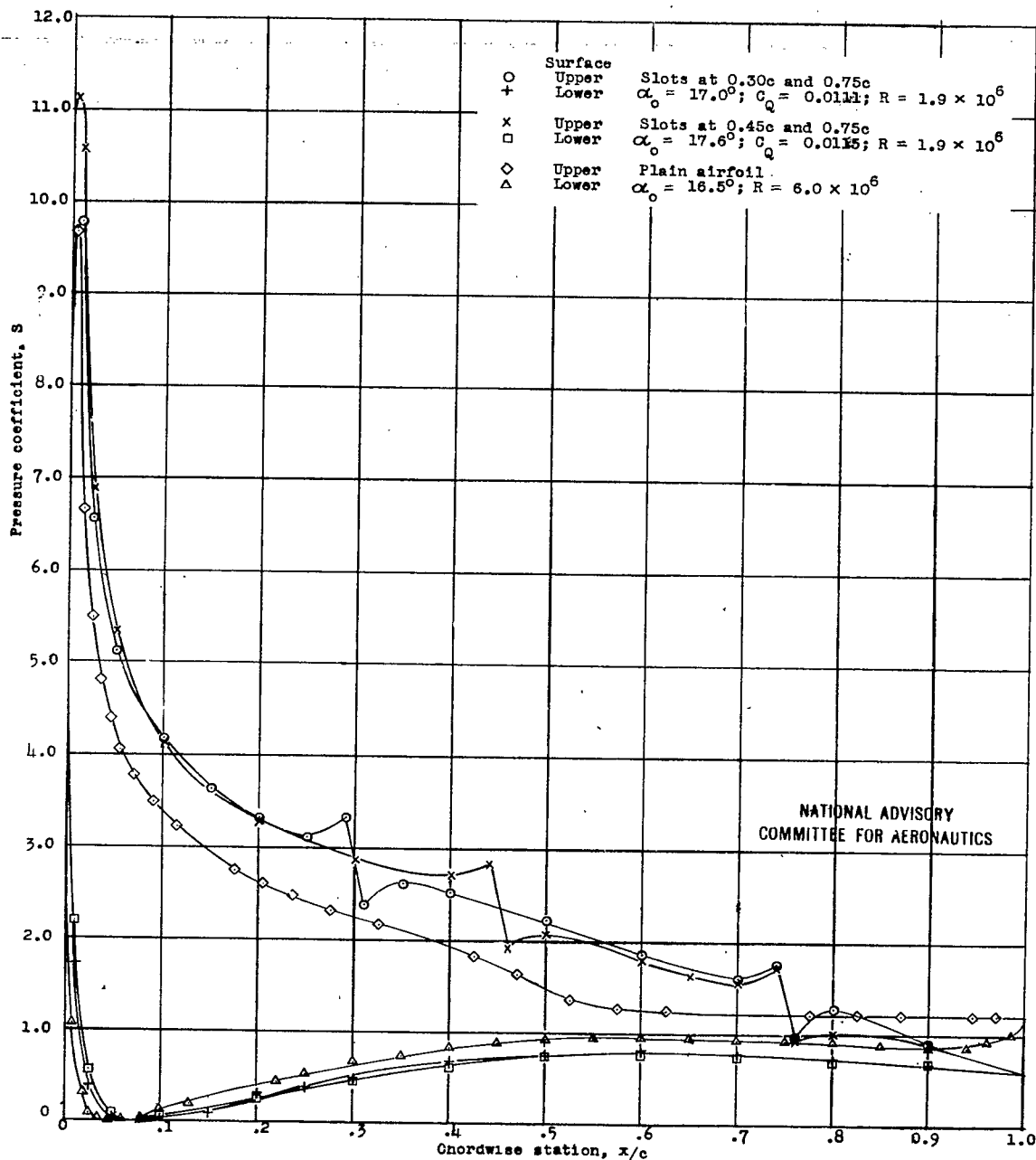


Figure 7.- Pressure distributions on the NACA 65₃-018 airfoil section with and without boundary-layer control.

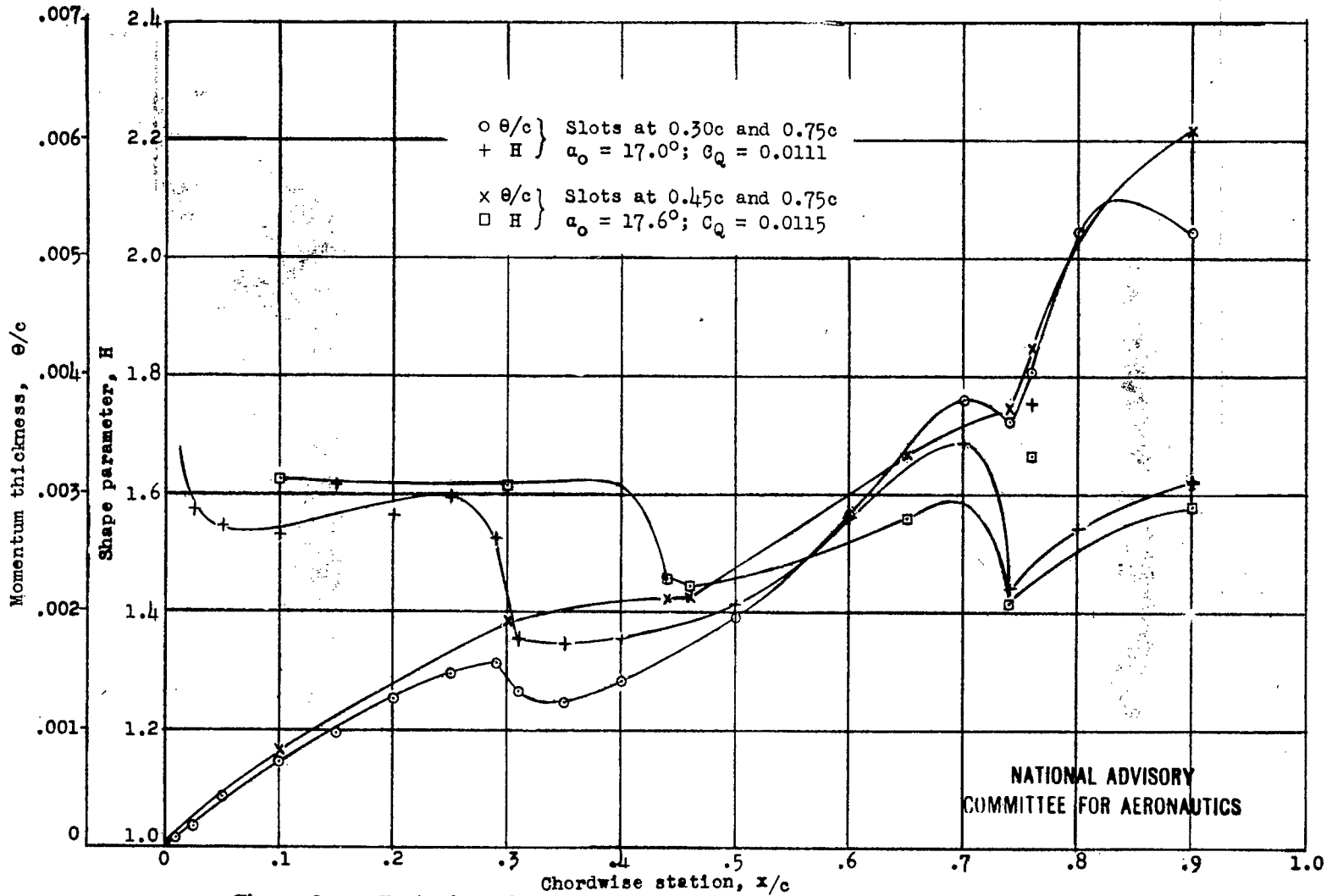


Figure 8.- Variation of boundary-layer shape parameter and momentum thickness on upper surface of NACA 65₃-018 airfoil section with boundary-layer control for two slot configurations. $R, 1.9 \times 10^6$.

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