~~W. L. MITCHELL~~

NACA TN No. 1631

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1631

WIND-TUNNEL INVESTIGATION OF BOUNDARY-LAYER CONTROL BY SUCTION ON NACA 65_5-424 AIRFOIL WITH DOUBLE SLOTTED FLAP

By Stanley F. Racisz and John H. Quinn, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
June 1948

NATIONAL ADVISORY COMMITTEE FOR AERONAUT

TECHNICAL NOTE NO. 1631

WIND-TUNNEL INVESTIGATION OF BOUNDARY-LAYER CONTROL BY SUCTION ON NACA 65_5-424 AIRFOIL WITH DOUBLE SLOTTED FLAP

By Stanley F. Racisz and John H. Quinn, Jr.

SUMMARY

An investigation has been conducted at Reynolds numbers ranging from 1.0×10^6 to 6.0×10^6 in the Langley two-dimensional low-turbulence tunnels to determine the effectiveness of boundary-layer control by suction and of suction-slot location in increasing the maximum lift and decreasing the drag of the NACA 65_5-424 airfoil section equipped with a double slotted flap. Tests were made of the model with a suction slot at 0.45 chord and with a suction slot at 0.65 chord. Measurements were made to determine the section lift, drag, and internal pressure-loss characteristics for flow coefficients ranging from 0 to 0.03 for the airfoil with the flap extended and retracted, with and without leading-edge roughness.

At a Reynolds number of 6.0×10^6, deflecting the flap increased the maximum section lift coefficient of the smooth airfoil from 1.4 to 3.4, and boundary-layer control at 0.65 chord with the flap deflected further increased the value to 4.2. For the model with the flap deflected, the maximum section lift coefficients obtained with the boundary-layer control slot at 0.65 chord were generally higher than those obtained with the slot at 0.45 chord.

Boundary-layer control by means of a single suction slot at 0.65 chord resulted, for an extensive range of section lift coefficient, in a section total-drag coefficient, which included a drag-coefficient allowance for the boundary-layer control power, lower than that of the plain airfoil. The maximum section lift-drag ratio of the airfoil with flap retracted and leading-edge roughness was more than doubled at a Reynolds number of 6.0×10^6 by the use of boundary-layer control and that for the smooth airfoil was increased by approximately 38 percent.

INTRODUCTION

The use of airfoil sections having thicknesses greater than about 21 percent of the airfoil chord has generally been avoided because of the low maximum lift and high drag usually associated with such sections.

In addition, roughening the leading edge of thick airfoils generally results in unreasonably large increases of the drag coefficient even at very moderate lift coefficients. These undesirable characteristics of thick airfoils are caused by premature separation of the turbulent boundary layer. In view of the structural desirability of thick airfoil sections, the need of a satisfactory method of retarding separation of the turbulent boundary layer is apparent.

The results of previous investigations reported in references 1 to 4 indicate that control of the boundary layer by suction may be an effective method of increasing the maximum lift and decreasing the drag of NACA 6-series airfoils having maximum thicknesses ranging from 12 to 21 percent. The purpose of the present investigation is to extend the range of thicknesses covered in previous investigations to include an airfoil of 24-percent thickness. Tests were made in the Langley two-dimensional low-turbulence tunnels of the NACA 65_5-424 airfoil section equipped with a double slotted flap and three arrangements of single boundary-layer control slots. The model was tested with a 0.016-chord slot at 0.45 chord, and with a 0.018-chord and a 0.008-chord slot at 0.65 chord, various amounts of suction being utilized. Both the flap-retracted and flap-deflected configurations were tested with the surfaces aerodynamically smooth and with roughness applied to the airfoil leading edge for Reynolds numbers ranging from 1.0×10^6 to 6.0×10^6.

SYMBOLS AND COEFFICIENTS

c_l	section lift coefficient $\left(\frac{l}{q_o c}\right)$
$c_{l_{max}}$	maximum section lift coefficient
Q	volume rate of air flow through suction slot, cubic feet per second
V_o	free-stream velocity, feet per second
c	airfoil chord, feet
b	span over which boundary-layer control is applied, feet
C_Q	flow coefficient $\left(\frac{Q}{V_o c b}\right)$
H_o	free-stream total pressure, pounds per square foot
H_b	total pressure in wing duct, pounds per square foot

q_o	free-stream dynamic pressure, pounds per square foot
C_p	pressure-loss coefficient $\left(\frac{H_o - H_b}{q_o}\right)$
c_d	section profile-drag coefficient $\left(\frac{d}{q_o c}\right)$
c_{d_b}	blower drag coefficient; that is, profile-drag coefficient associated with power required to discharge at free-stream total pressure the air removed from the boundary layer $\left(\frac{C_Q C_P}{\eta}\right)$
c_{d_T}	section total-drag coefficient $\left(c_d + c_{d_b}\right)$
d	section drag, pounds
l	section lift, pounds
p	local static pressure, pounds per square foot
S	pressure coefficient $\left(\frac{H_o - p}{q_o}\right)$
R	Reynolds number $\left(\frac{\rho_o V_o c}{\mu}\right)$
ρ_o	free-stream mass density, slugs per cubic foot
μ	coefficient of viscosity, pounds per foot-second
η	efficiency of boundary-layer suction system (assumed equal to 1.0 for calculating c_{d_T} in the present paper)
α_o	section angle of attack, degrees
x	distance from airfoil leading edge measured parallel to chord line, feet

MODEL

The model of the NACA 65_5-424 airfoil section with a double slotted flap tested was constructed of metal and had a chord of two feet and a span of three feet. The model completely spanned the test section of the Langley two-dimensional low-turbulence tunnel and of the Langley two-dimensional low-turbulence pressure tunnel. Sketches of the model showing the three suction slots and the flap configuration tested are presented as figure 1. The forward part of the double slotted flap is referred to herein as the vane. Ordinates for the plain airfoil section, vane, and flap are presented in tables 1, 2, and 3, respectively. For each test of the model without boundary-layer control, the suction slots were sealed and faired to conform to the plain airfoil contour. For tests of the model with leading-edge roughness, the surfaces were the same as those for the smooth condition except that carborundum grains had been applied to the leading edge. The carborundum grains had average diameters of 0.011 inch and were sparsely spread to cover from 5 to 10 percent of the surface. The roughness strip extended over a surface length of 0.08c from the leading edge on each surface.

TEST METHODS

Preliminary tests of the model with the suction slot at 0.45c were made in the Langley two-dimensional low-turbulence tunnel at a Reynolds number of 2.2×10^6 and a flow coefficient C_Q of 0.02 to determine the flap configuration for highest maximum lift. These tests consisted of surveys of the flap position with respect to the vane for several flap and vane deflections and surveys of the flap and vane as a unit with respect to the airfoil. The flap configuration that had the highest maximum lift is shown in figure 1 and was the configuration used for all subsequent tests of the model with the flap deflected.

The section lift characteristics of the model with each suction-slot configuration were determined at a Reynolds number of 6.0×10^6 in the Langley two-dimensional low-turbulence pressure tunnel at flow coefficients ranging from 0 to 0.03. In all cases the values given for the condition of $C_Q = 0$ were obtained with the suction slots sealed and faired. In order to obtain an indication of the effects of Reynolds number on the section lift characteristics, the model with the suction slot at 0.45c was also tested at Reynolds numbers of 1.0×10^6 and 2.2×10^6 in the Langley two-dimensional low-turbulence tunnel. In each case, the model was tested with the surfaces aerodynamically smooth and with leading-edge roughness for the configuration with the flap retracted and for the configuration with the flap deflected.

The section profile-drag and total-drag characteristics for the model with each of the three slot configurations were determined with the flap retracted at a Reynolds number of 6.0×10^6.

The section lift and profile-drag characteristics were determined by the methods described in reference 5, which also includes a discussion of the methods used in correcting the test data to free-air conditions. The flow coefficient was determined from measurements of the pressures within the pipe line connecting the duct in the model to a blower inlet.

The pressure-loss coefficients were determined from measurements with a flush surface orifice located in the end of the duct and opposite to the end from which the air was removed. The section total-drag coefficient was determined by adding the section profile-drag coefficient determined from wake-survey measurements to the blower-drag coefficient determined from the internal pressure measurements. Pressure distributions for the upper surface of the airfoil with and without boundary-layer control were determined from measurements with a small static-pressure tube placed approximately $\frac{3}{32}$ inch above the airfoil surface. At each measuring station, the tube was curved to approximate the airfoil contour.

RESULTS AND DISCUSSION

Determination of Slot Configurations

The low maximum lift and high drag of thick airfoil sections are caused primarily by separation of the turbulent boundary layer. The separation of the turbulent boundary layer, which occurs even at low angles of attack, is induced by the adverse pressure gradient over the rear part of the airfoil. A secondary contribution to the high drag is the skin friction, which is increased for thick airfoils because of the relatively higher induced velocities. The effectiveness of a boundary-layer control slot in preventing separation for an extensive range of angle of attack will depend to a large extent upon the change in the chordwise position of separation with section angle of attack and, therefore, a slot that is effective at low angles of attack may be considerably less effective at high angles of attack.

The 0.45c station was chosen for one slot location because previous tests (reference 4) have shown that the maximum lift may be considerably increased by locating the slot at that position and because at low angles of attack the slot itself should not cause transition from laminar to turbulent flow with a resultant increase in profile drag. The 0.65c station was selected for the other slot location because the pressure-distribution diagram presented in figure 2 indicates that at a section lift coefficient of approximately 0.5, which was considered a representative cruising lift coefficient, separation began at approximately 0.65c. The slots at 0.45c and 0.65c, as shown in figure 1, had widths of approximately 0.02c in order to obtain the high flow coefficients required for highest maximum lift. The smaller slot at 0.65c shown in figure 1 was designed for use at low flow coefficients.

Lift

The section lift characteristics of the model with the various slot configurations tested are presented in figures 3 and 4. The main effect of boundary-layer control by an individual suction slot was to maintain a linear variation of section lift coefficient with section angle of attack for a more extensive angle-of-attack range, with a resultant increase in the maximum section lift coefficient. Boundary-layer control generally increased the section angle of attack for maximum lift and also caused the angle of attack for zero lift to become more negative for the model in the smooth and rough conditions. Boundary-layer control generally increased the slope of the lift curve for the model in the rough condition.

The variation of maximum section lift coefficient with flow coefficient at a Reynolds number of 6.0×10^6 is presented in figure 5. These data indicate that the increment of maximum section lift coefficient per increment of flow coefficient became appreciably less as the flow coefficient was increased beyond a value between 0.01 and 0.02. The gain in maximum section lift coefficient with flow coefficient was about twice as much for the flap-retracted configuration as for the flap-deflected configuration. With the flap deflected, higher maximum lift coefficients were obtained with suction applied at 0.65c as compared with those coefficients obtained with suction applied at 0.45c; whereas the opposite was true for the flap-retracted configuration. The maximum section lift coefficient of the airfoil in the smooth condition at a Reynolds number of 6.0×10^6 was 1.4 with the flap retracted; deflecting the flap increased the lift coefficient to 3.4, and boundary-layer control further increased the value to 4.2. Reducing the width of the suction slot at 0.65c had little effect on the value of the maximum section lift coefficient as can be seen from the data obtained at a flow coefficient of 0.01 and presented in figure 5. The high flow coefficients required for high maximum lift, however, were obtainable only with the wider slot because of the excessive power required at high flow coefficients with the narrow slot.

The variation of maximum section lift coefficient with flow coefficient for Reynolds numbers ranging from 1.0×10^6 to 6.0×10^6 for the model with the slot at 0.45c is presented in figure 6. For the model in the smooth condition with the flap deflected, the maximum section lift coefficient generally increased as the Reynolds number was increased from 1.0×10^6 to 2.2×10^6 and decreased as the Reynolds number was increased further to 6.0×10^6, whereas with the flap retracted, the maximum section lift coefficient increased as the Reynolds number was increased from 1.0×10^6 to 6.0×10^6. Varying the Reynolds number generally caused no significant or consistent change in the maximum section lift coefficient. The highest value of the maximum section lift coefficient at a Reynolds number of 2.2×10^6 was 4.2, or 0.4 higher than that obtained for the NACA 65_4-421 airfoil section with a double slotted flap and boundary-layer control by means of a suction slot at 0.45c (reference 4).

Drag and Lift-Drag Ratio

The section profile-drag characteristics of the model with the flap retracted are presented for a Reynolds number of 6.0×10^6 in figure 7. In all cases boundary-layer control reduced the section profile-drag coefficient for an extensive range of section lift coefficient, but the reduction was larger for the configuration with the slot at 0.65c. (Compare fig. 7(a) with fig. 7(b).)

The pressure-loss characteristics for the model with the 0.016c slot at 0.45c, with the 0.018c slot at 0.65c, and with the 0.008c slot at 0.65c are presented in figures 8, 9, and 10, respectively. The power P required for the boundary-layer control may be estimated from the pressure-loss characteristics by the equation $P = \frac{C_Q C_P}{\eta} q_o V_o b_c$ where the efficiency factor η includes both the mechanical and ducting losses.

The section total-drag polars presented in figure 11 indicate that the maximum section lift-drag ratio c_l/c_{d_T} was obtained by using the slot at 0.65c and flow coefficients of 0.002 or 0.003. Uniform suction across the span was obtained at these low flow coefficients only with the 0.008c suction slot. The data presented in figure 11 indicate that, in general, the section total-drag coefficients were lower for the model with the slot at 0.65c than those obtained with the slot at 0.45c. The section total-drag coefficient for the configuration with the 0.008c suction slot at 0.65c and with leading-edge roughness, moreover, was generally lower than that of the model with the slot sealed for an extensive range of lift coefficient.

The data presented in figure 11(c) indicate that at a Reynolds number of 6.0×10^6 the maximum section lift-drag ratio c_l/c_{d_T} with flap retracted was increased from 116 to 160 for the smooth condition and from 30 to 74 for the rough condition by the use of boundary-layer control. It has been shown in reference 7 that, for a plain wing having a fixed ratio of span to root thickness, increasing the aspect ratio beyond a certain limit tends to result in no increase in the maximum lift-drag ratio, particularly for the rough condition, because of the high profile drag resulting from the thick root and inboard sections. The fact that substantial decreases in the drag at cruising lift coefficients and corresponding increases in the section lift-drag ratio were realized in the present investigation by the use of boundary-layer control for a section of 24-percent thickness means that the aspect ratio for maximum lift-drag ratio has been increased. Research on thicker sections is required in order to determine the limit to which it is possible to increase the aspect ratio and still obtain increases in the wing lift-drag ratio. The optimum aspect ratio will be dependent to some extent upon the efficiency of the boundary-layer suction system because of its effect on the section total-drag coefficient.

CONCLUSIONS

An investigation has been conducted in the Langley two-dimensional low-turbulence tunnels to determine the effects of boundary-layer control by suction and of suction-slot location on the section lift and drag characteristics of the NACA 65_5-424 airfoil section with a double slotted flap. The model was tested with a suction slot at 0.45 chord and with a suction slot at 0.65 chord. The results of the investigation indicated the following conclusions:

1. The maximum section lift coefficient of the airfoil in the smooth condition at a Reynolds number of 6.0×10^6 was 1.4 with the flap retracted; deflecting the flap increased the lift coefficient to 3.4, and boundary-layer control at 0.65 chord further increased the value to 4.2. At the same flow coefficient, the increase in the maximum section lift coefficient was about twice as much for the flap-retracted configuration as that for the flap-deflected configuration.

2. The maximum section lift coefficients obtained by the use of boundary-layer control at a Reynolds number of 6.0×10^6 with the flap deflected were generally higher for the configuration with the suction slot at 0.65 chord than those for the configuration with the suction slot at 0.45 chord.

3. Increasing the Reynolds number from 1.0×10^6 to 6.0×10^6 generally caused no significant or consistent change in maximum section lift coefficient.

4. For the configuration with the suction slot at 0.65 chord and leading-edge roughness, the section total-drag coefficient c_{d_T}, which included the drag coefficient associated with the power required to discharge the air removed from the boundary layer, was lower than that of the plain airfoil for an extensive range of lift coefficient.

5. The maximum section lift-drag ratio c_l/c_{d_T} of the airfoil with flap retracted and leading-edge roughness was increased from 30 to 74 at a Reynolds number of 6.0×10^6 and that for the smooth model was increased from 116 to 160 by use of the boundary-layer control slot at 0.65 chord.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., February 6, 1948.

REFERENCES

1. Quinn, John H., Jr.: Tests of the NACA 65_3-018 Airfoil Section with Boundary-Layer Control by Suction. NACA CB No. L4H10, 1944.

2. Quinn, John H., Jr.: Wind-Tunnel Investigation of Boundary-Layer Control by Suction on the NACA 65_3-418, $a = 1.0$ Airfoil Section with a 0.29-Airfoil-Chord Double Slotted Flap. NACA TN No. 1071, 1946.

3. Quinn, John H., Jr.: Tests of the NACA 64_1A212 Airfoil Section with a Slat, a Double Slotted Flap, and Boundary-Layer Control by Suction. NACA TN No. 1293, 1947.

4. Quinn, John H., Jr.: Wind-Tunnel Investigation of the NACA 65_4-421 Airfoil Section with Double Slotted Flap and Boundary-Layer Control by Suction. NACA TN No. 1395, 1947.

5. von Doenhoff, Albert E., and Abbott, Frank T., Jr.: The Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN No. 1283, 1947.

6. Abbott, Ira H., von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA ACR No. L5C05, 1945.

7. Neely, Robert H., Bollech, Thomas V., Westrick, Gertrude C., and Graham, Robert R.: Experimental and Calculated Characteristics of Several NACA 44-Series Wings with Aspect Ratios of 8, 10, and 12 and Taper Ratios of 2.5 and 3.5. NACA TN No. 1270, 1947.

TABLE I

NACA 65_5-424 AIRFOIL SECTION

[Stations and ordinates in percent chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.218	1.771	.782	-1.571
.437	2.156	1.063	-1.876
.898	2.747	1.602	-2.319
2.092	3.873	2.908	-3.129
4.528	5.664	5.472	-4.400
7.002	7.070	7.998	-5.374
9.495	8.249	10.505	-6.181
14.515	10.124	15.485	-7.432
19.561	11.552	20.439	-8.368
24.621	12.635	25.379	-9.055
29.690	13.421	30.310	-9.533
34.766	13.924	35.234	-9.804
39.845	14.141	40.155	-9.857
44.925	14.021	45.075	-9.641
50.000	13.537	50.000	-9.125
55.067	12.715	54.933	-8.335
60.122	11.630	59.878	-7.346
65.165	10.354	64.837	-6.234
70.189	8.933	69.811	-5.045
75.196	7.407	74.804	-3.827
80.186	5.818	79.814	-2.634
85.159	4.227	84.841	-1.535
90.115	2.676	89.885	-.608
95.056	1.229	94.944	.035
100.000	0	100.000	0

L.E. radius: 3.05
Slope of radius through L.E.: 0.168

TABLE 2

VANE FOR NACA 65_5-424 AIRFOIL SECTION

[Stations and ordinates in percent airfoil chord]

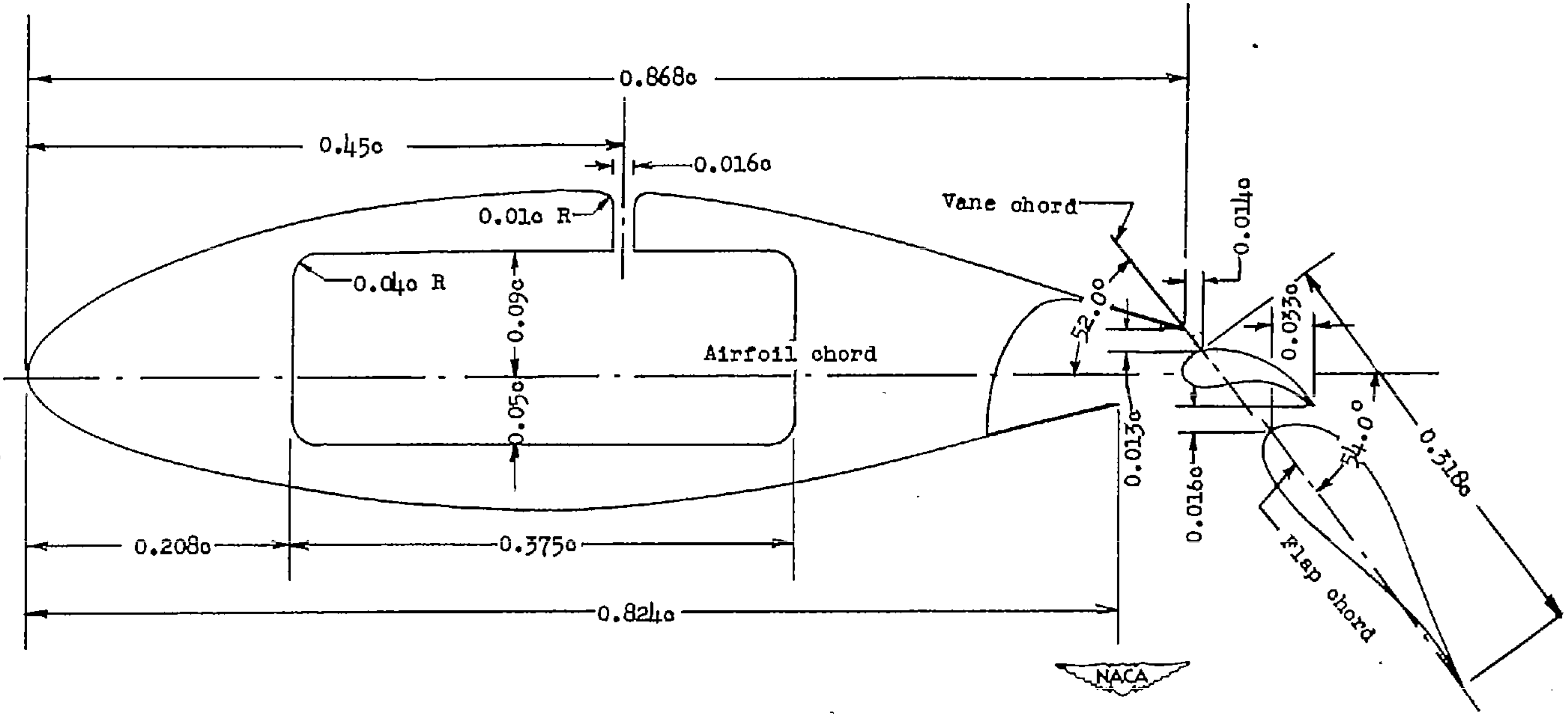
Upper surface		Lower surface	
Vane station	Ordinate	Station	Ordinate
0	-0.958	0	-0.958
.625	.708	.625	-2.208
2.000	2.125	1.334	-2.417
2.792	2.625	2.000	-2.250
3.417	3.000	2.729	-1.542
4.792	3.583	3.417	-.042
6.167	3.958	4.792	1.958
7.584	4.167	6.167	3.208
8.959	4.167	7.584	3.792
		8.959	4.167

TABLE 3

FLAP FOR NACA 65_5-424 AIRFOIL SECTION

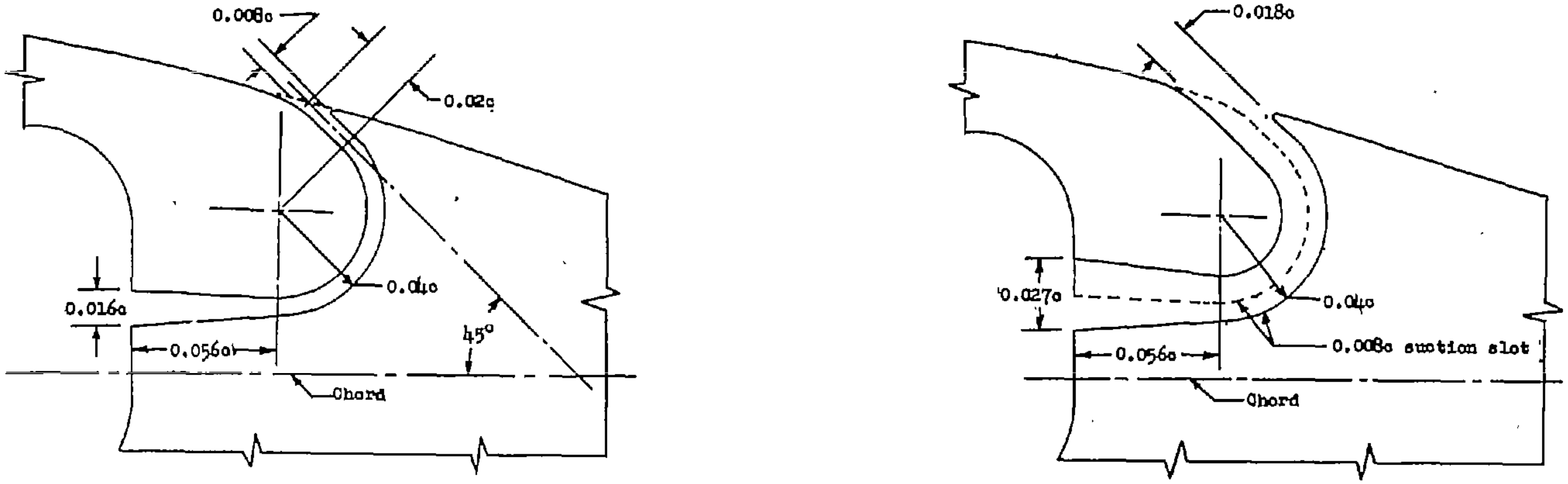
[Stations and ordinates in percent airfoil chord]

Upper surface		Lower surface	
Flap station	Ordinate	Station	Ordinate
0	0	0	0
.334	1.354	.334	-.875
.750	1.917	.750	-1.292
1.792	2.833	1.792	-1.833
2.834	3.458	2.834	-2.188
4.917	4.042	3.875	-2.292
7.000	4.208	5.959	-2.083
9.084	3.958	8.508	-1.535
13.782	2.676	13.552	-.608
17.823	1.229	18.661	.035
23.667	0	23.667	0



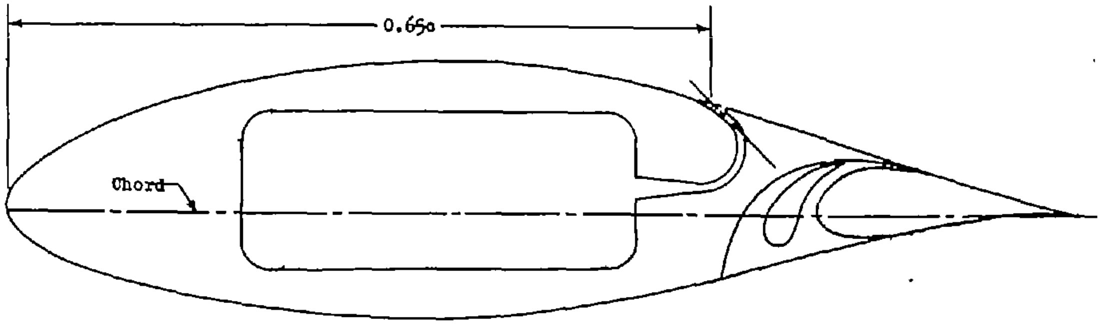
(a) Slot at 0.45c.

Figure 1.- Profile of the NACA 65_5-424 airfoil section with boundary-layer control slots. Vane position given with respect to point corresponding to intersection of vane chord line with upper surface of vane.



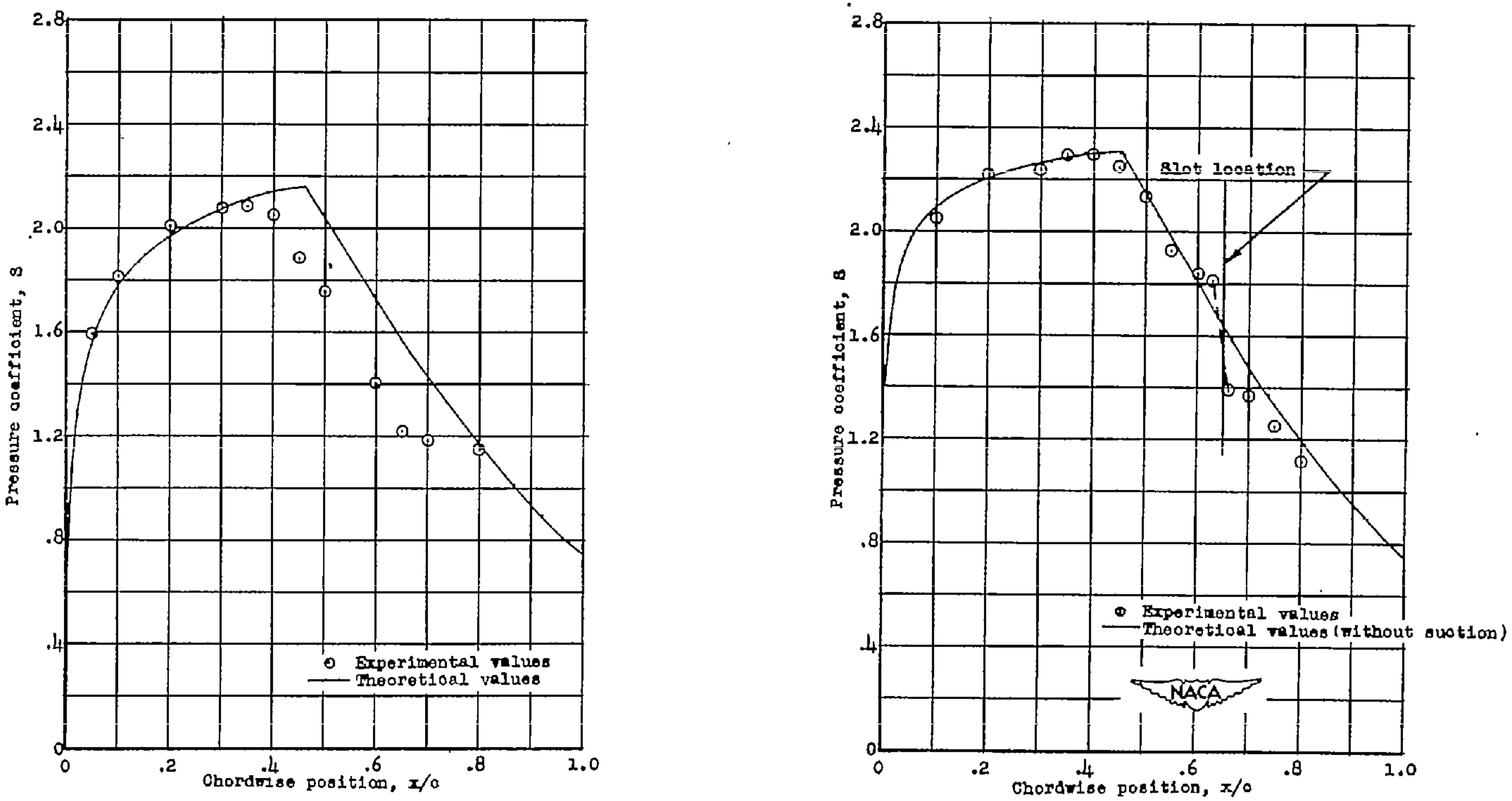
0.008c suction slot

0.018c suction slot



(b) Slots at 0.65c.

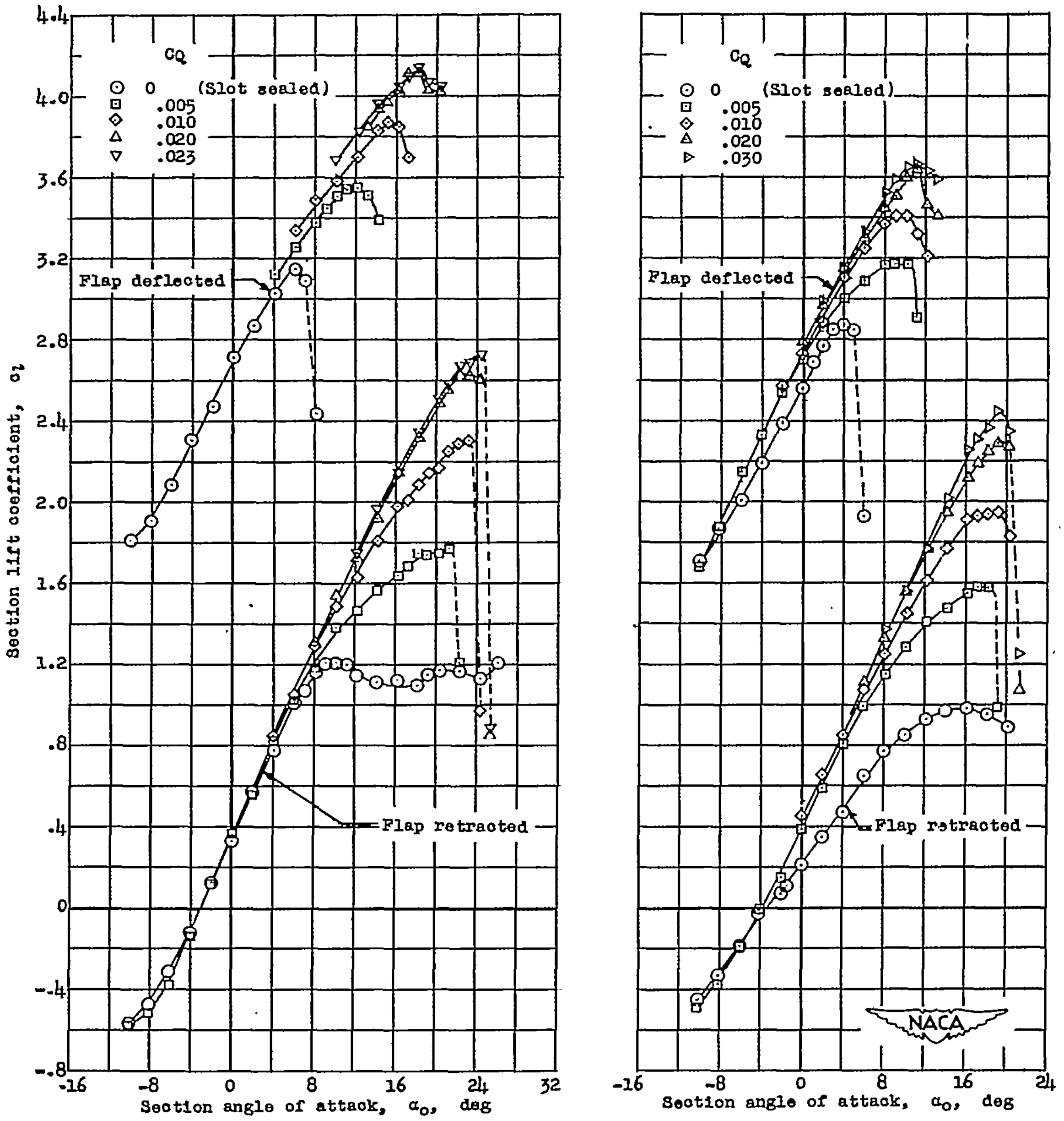
Figure 1.- Concluded.



(a) Plain airfoil; $c_l = 0.49$.

(b) 0.008c boundary-layer control slot; $C_Q = 0.0025$; $c_l = 0.74$.

Figure 2.- Theoretical and experimental pressure distributions for the upper surface of the NACA 65_5-424 airfoil section. Theoretical pressure distributions obtained by methods discussed in reference 6. $\alpha_0 = 4.1°$; $R = 2.2 \times 10^6$.

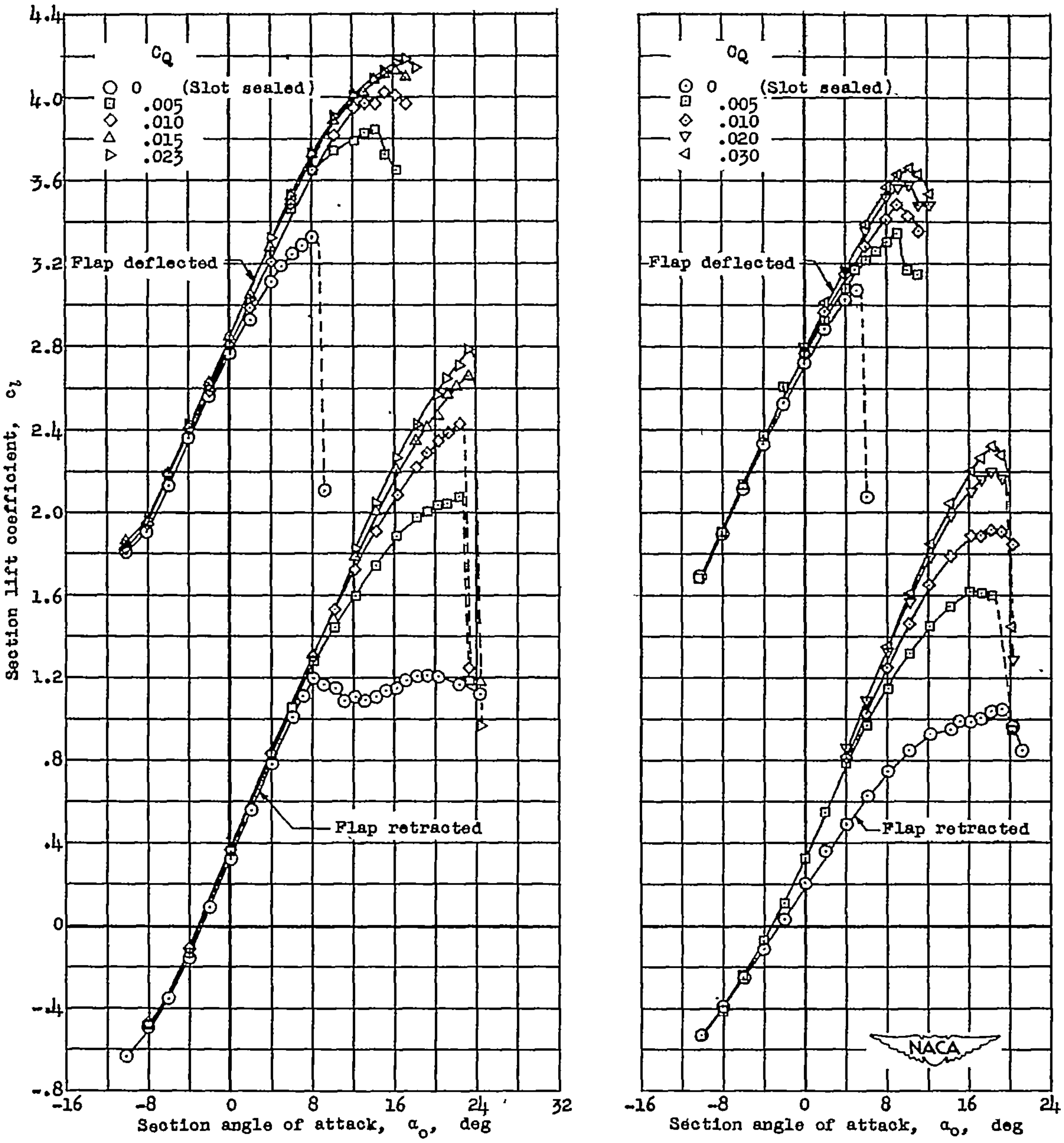


Model in smooth condition

Model in rough condition

(a) $R = 1.0 \times 10^6$.

Figure 3.- Section lift characteristics of the NACA 65_5-424 airfoil section with a 0.016c boundary-layer control slot at 0.45c.

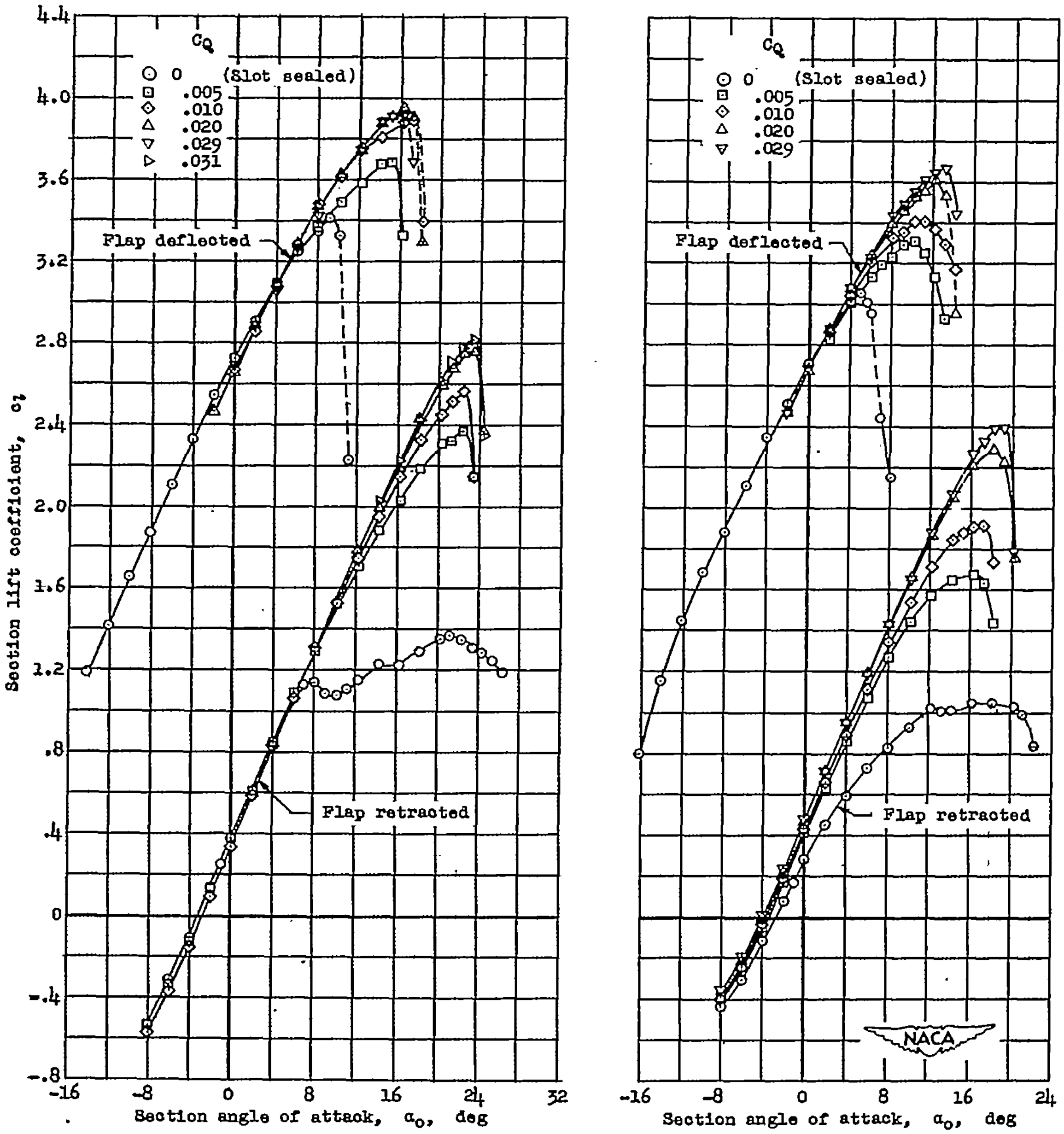


Model in smooth condition

Model in rough condition

(b) $R = 2.2 \times 10^6$.

Figure 3.- Continued.

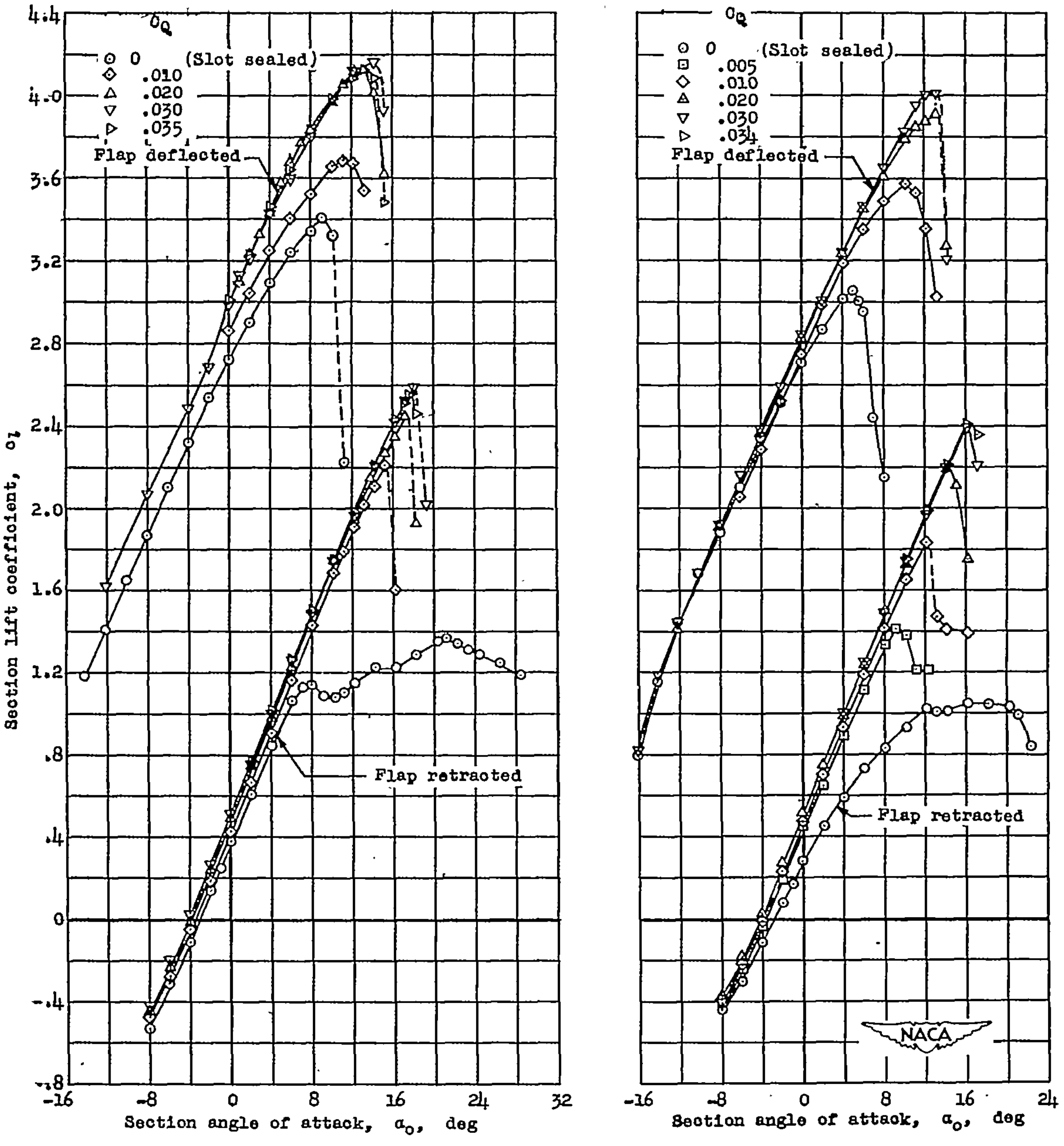


Model in smooth condition

Model in rough condition

(c) $R = 6.0 \times 10^6$.

Figure 3.- Concluded.

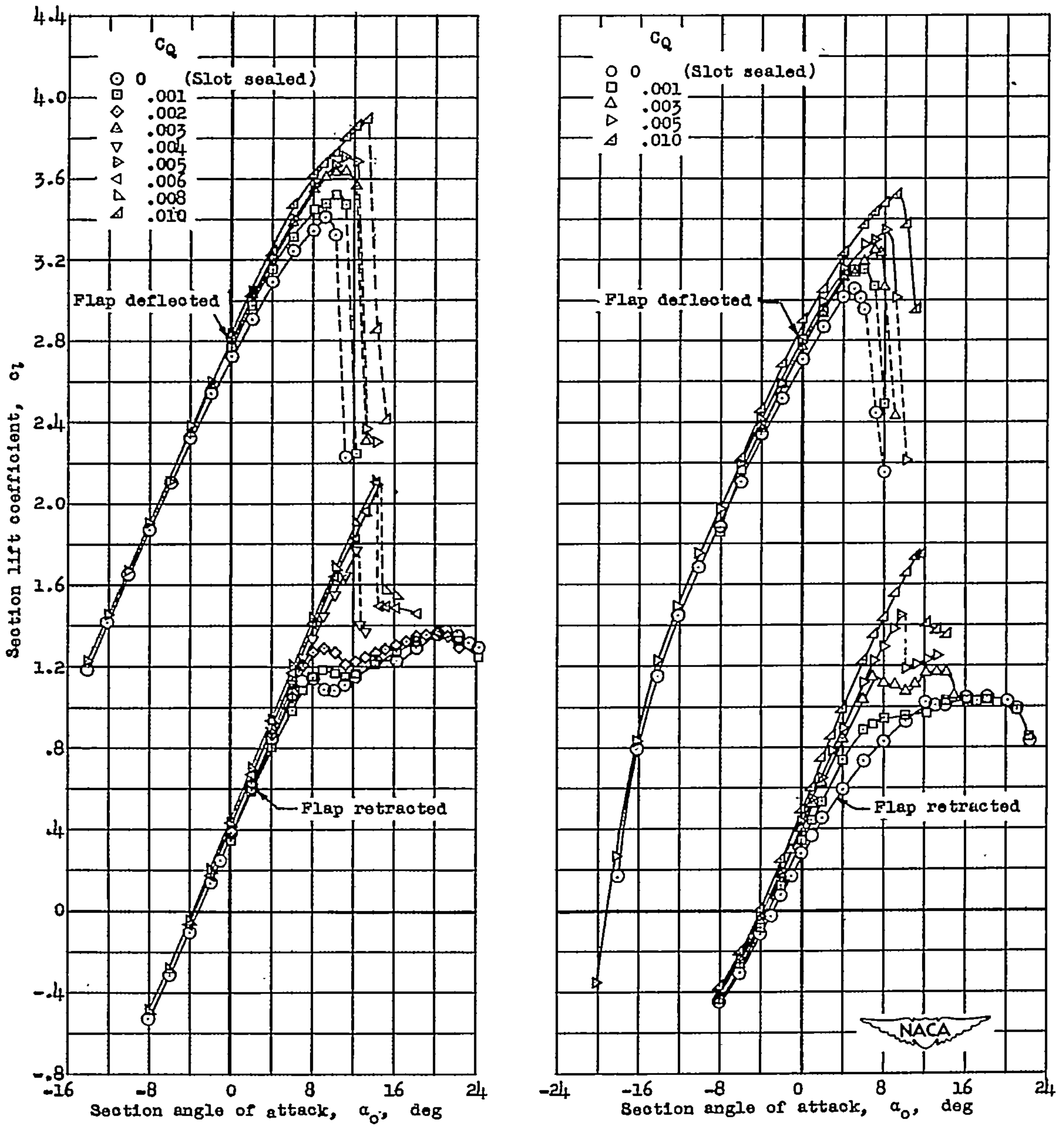


Model in smooth condition

Model in rough condition

(a) 0.018c slot.

Figure 4.- Section lift characteristics of the NACA 65_5-424 airfoil section with a boundary-layer control slot at 0.65c. $R = 6.0 \times 10^6$.

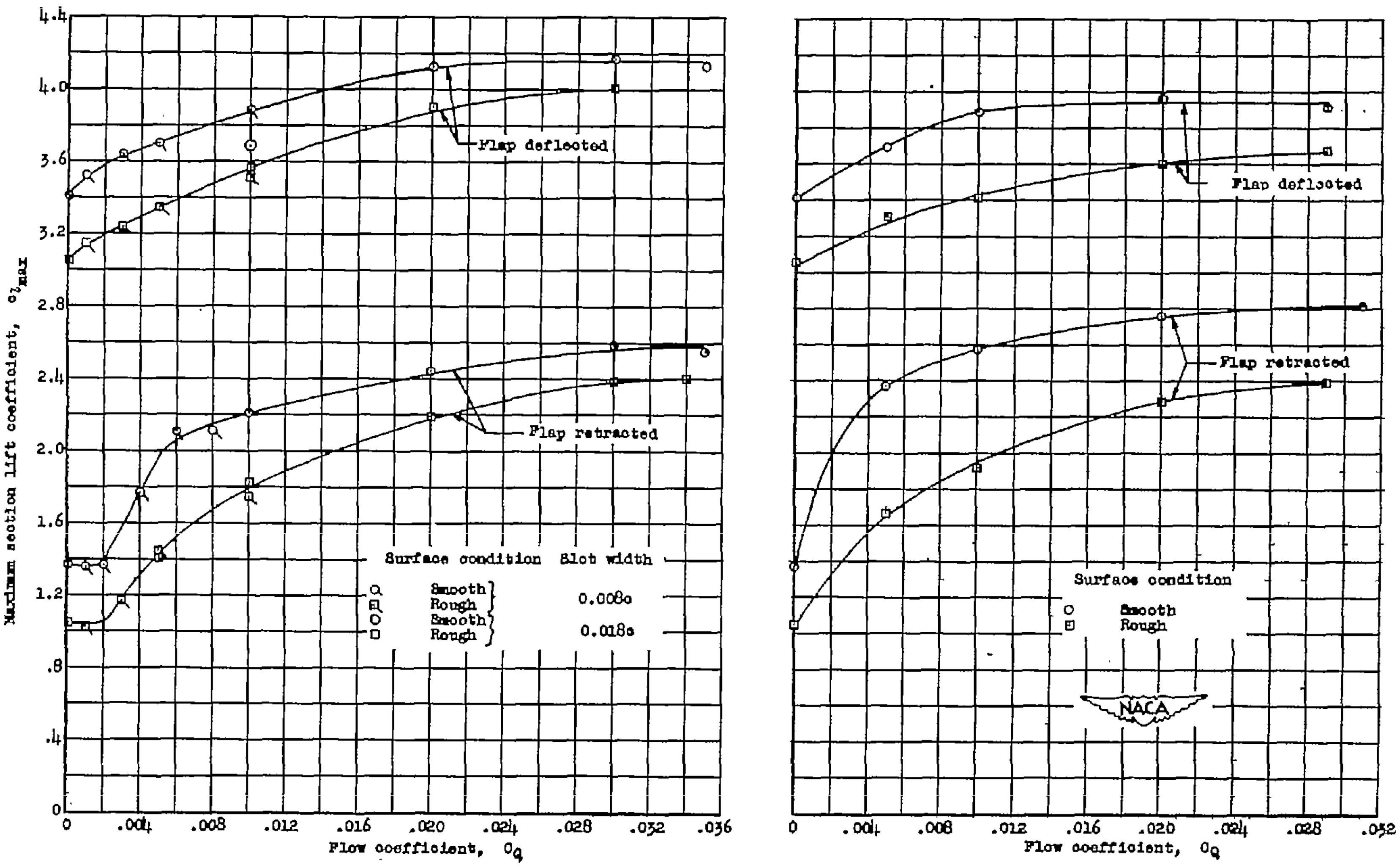


Model in smooth condition

Model in rough condition

(b) 0.008c slot.

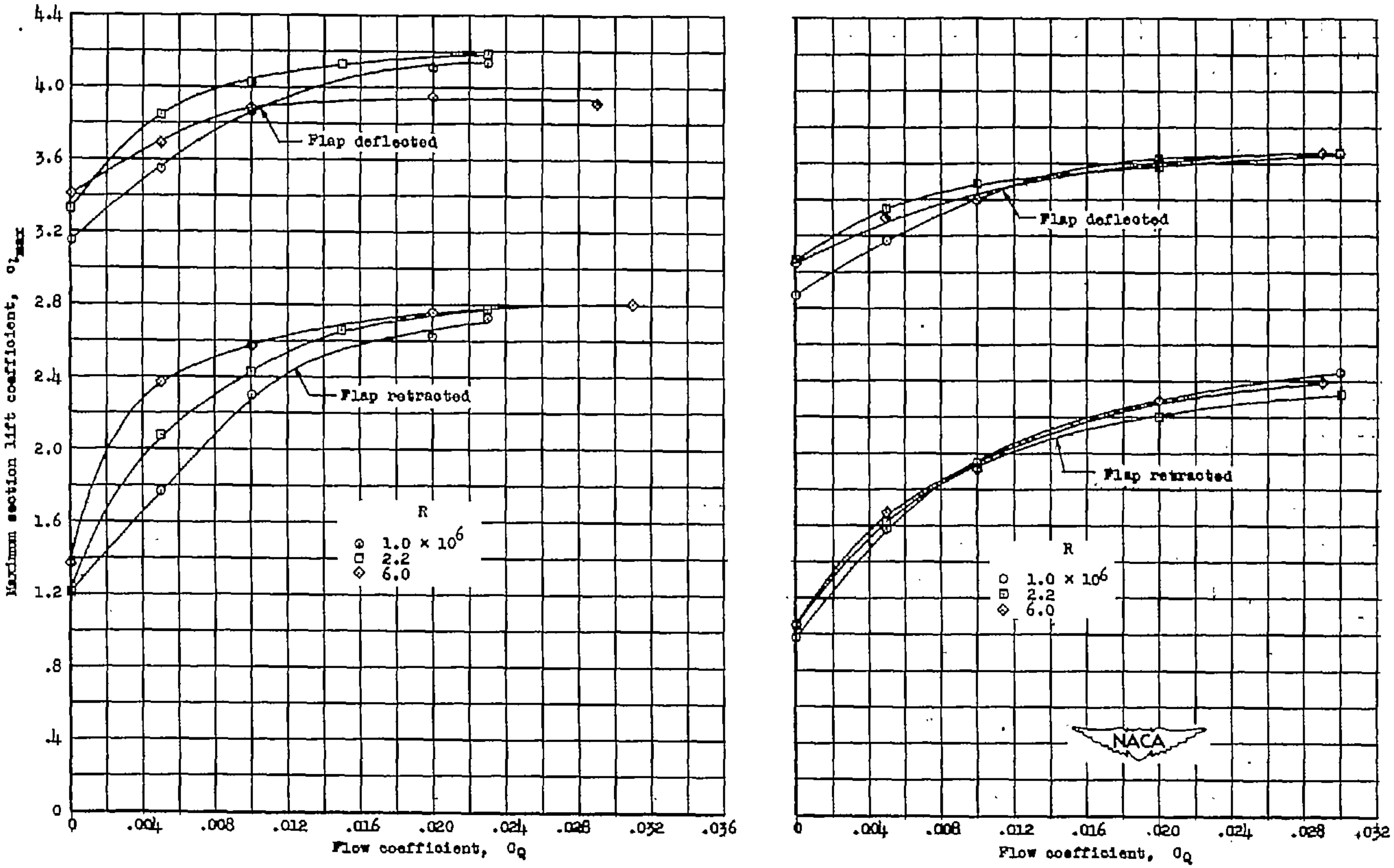
Figure 4.- Concluded.



(a) Suction slot at 0.65c.

(b) 0.016c suction slot at 0.45c.

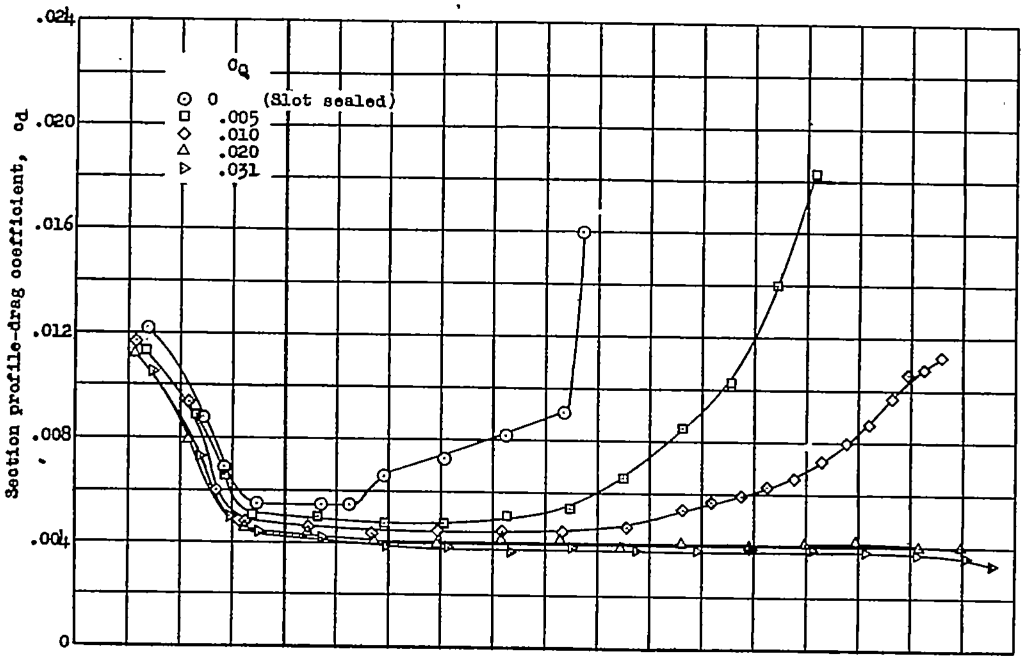
Figure 5.- Variation of maximum section lift coefficient with flow coefficient for the NACA 65_5-424 airfoil section with boundary-layer control by suction. $R = 6.0 \times 10^6$.



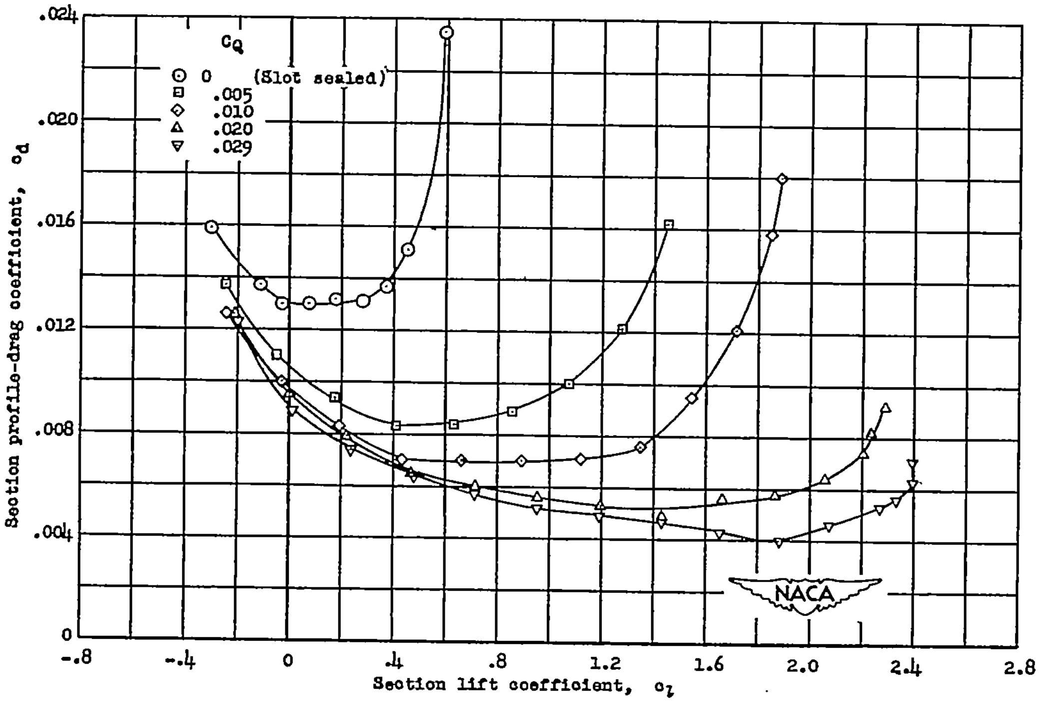
Model in smooth condition

Model in rough condition

Figure 6.- Variation of maximum section lift coefficient with flow coefficient for the NACA 65_5-424 airfoil section with a 0.016c boundary-layer control slot at 0.45c.



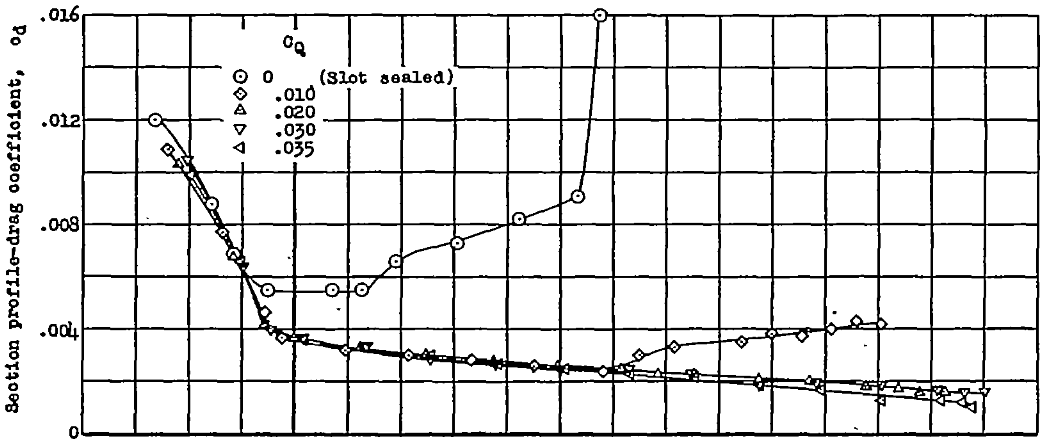
Model in smooth condition



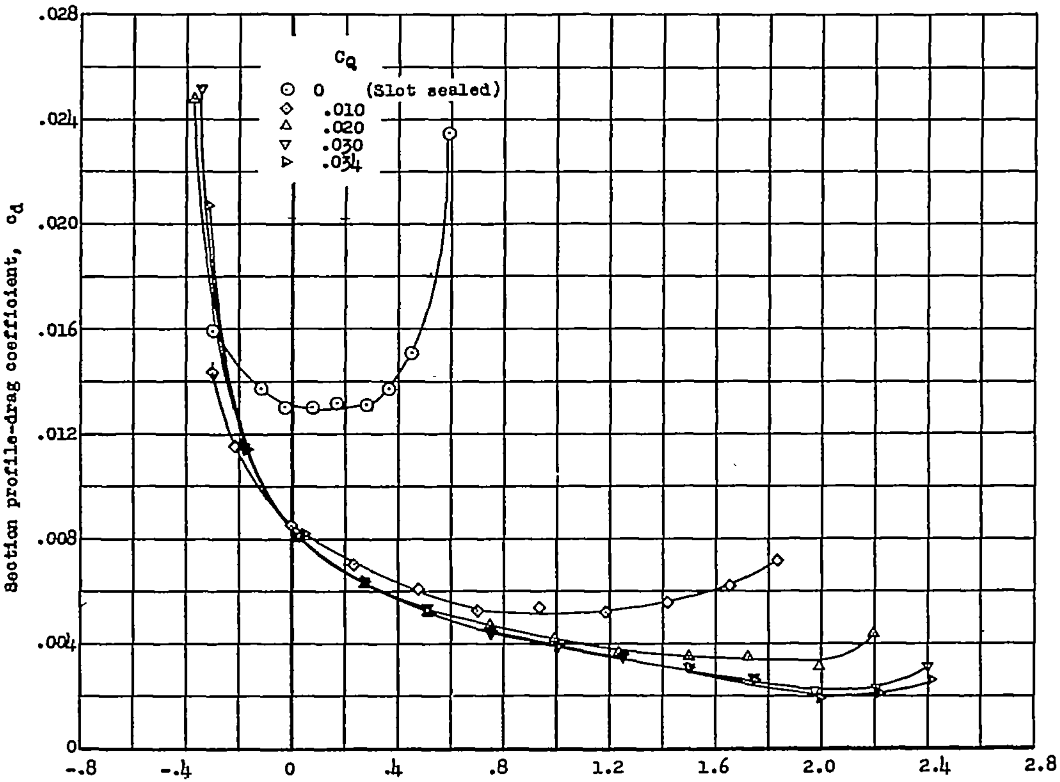
Model in rough condition

(a) 0.016c slot at 0.45c.

Figure 7.- Section profile-drag characteristics of the NACA 65_5-424 airfoil section with boundary-layer control slots. Flap retracted; $R = 6.0 \times 10^6$.



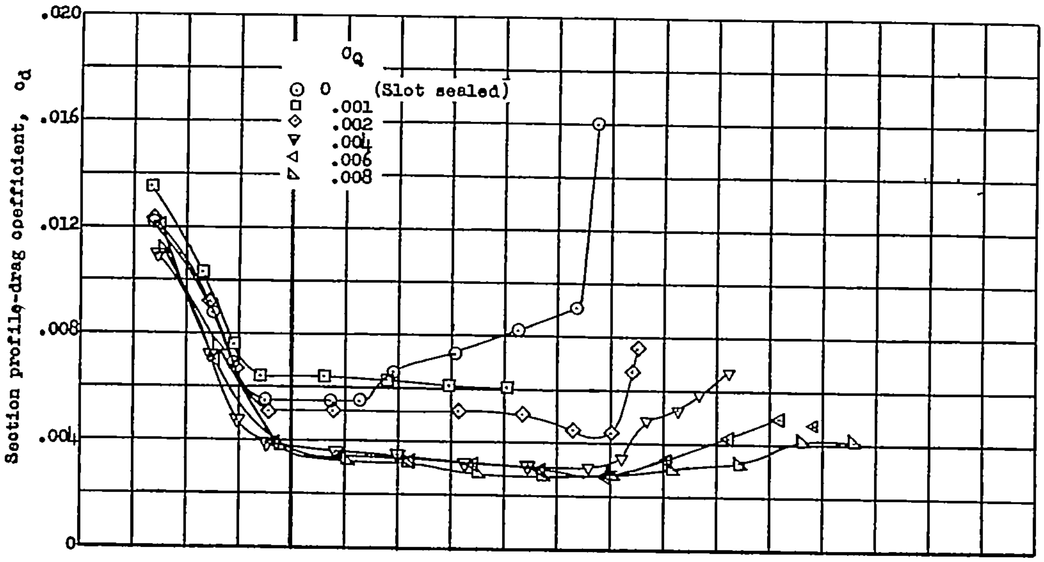
Model in smooth condition



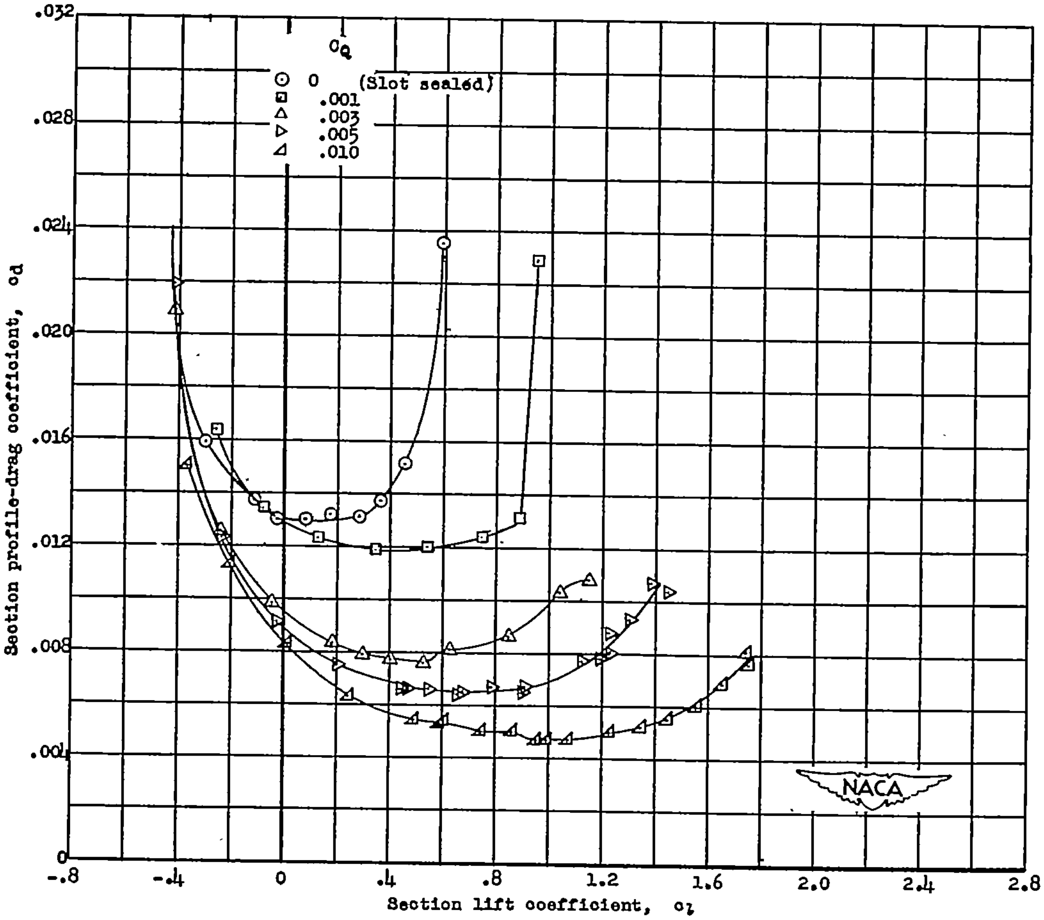
Model in rough condition

(b) 0.018c slot at 0.65c.

Figure 7.- Continued.



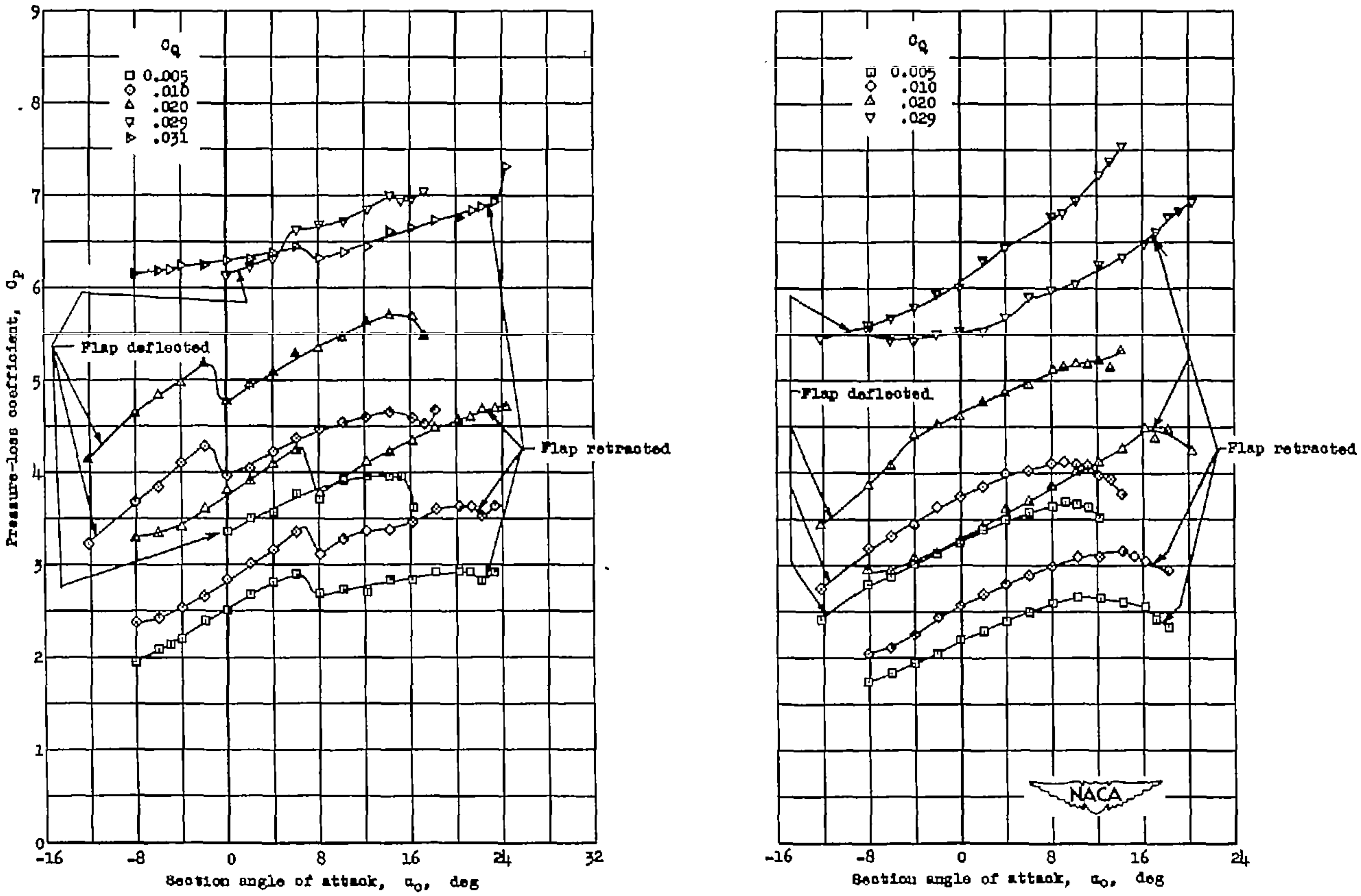
Model in smooth condition



Model in rough condition

(c) 0.008c slot at 0.65c.

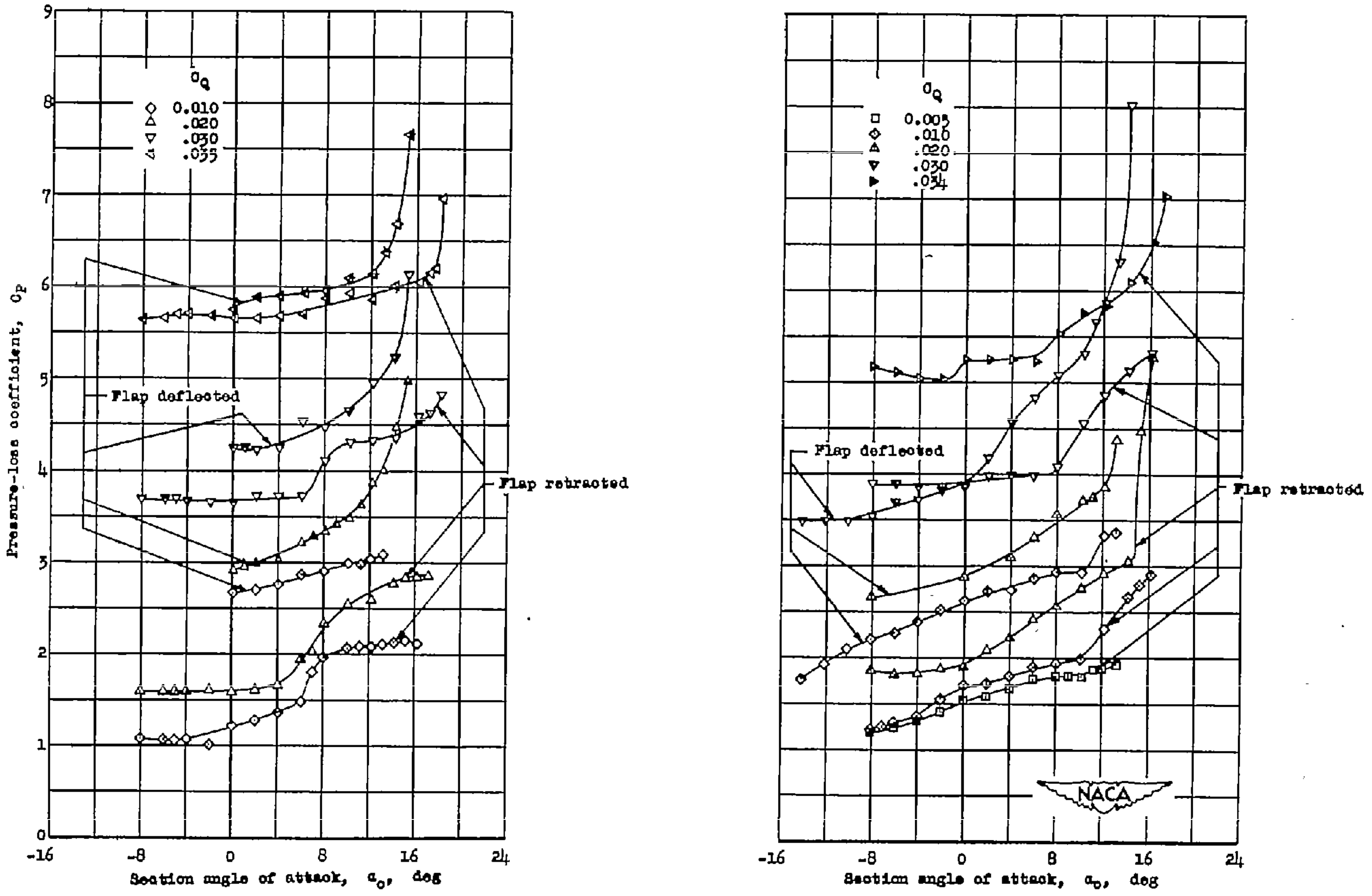
Figure 7.- Concluded.



(a) Model in smooth condition.

(b) Model in rough condition.

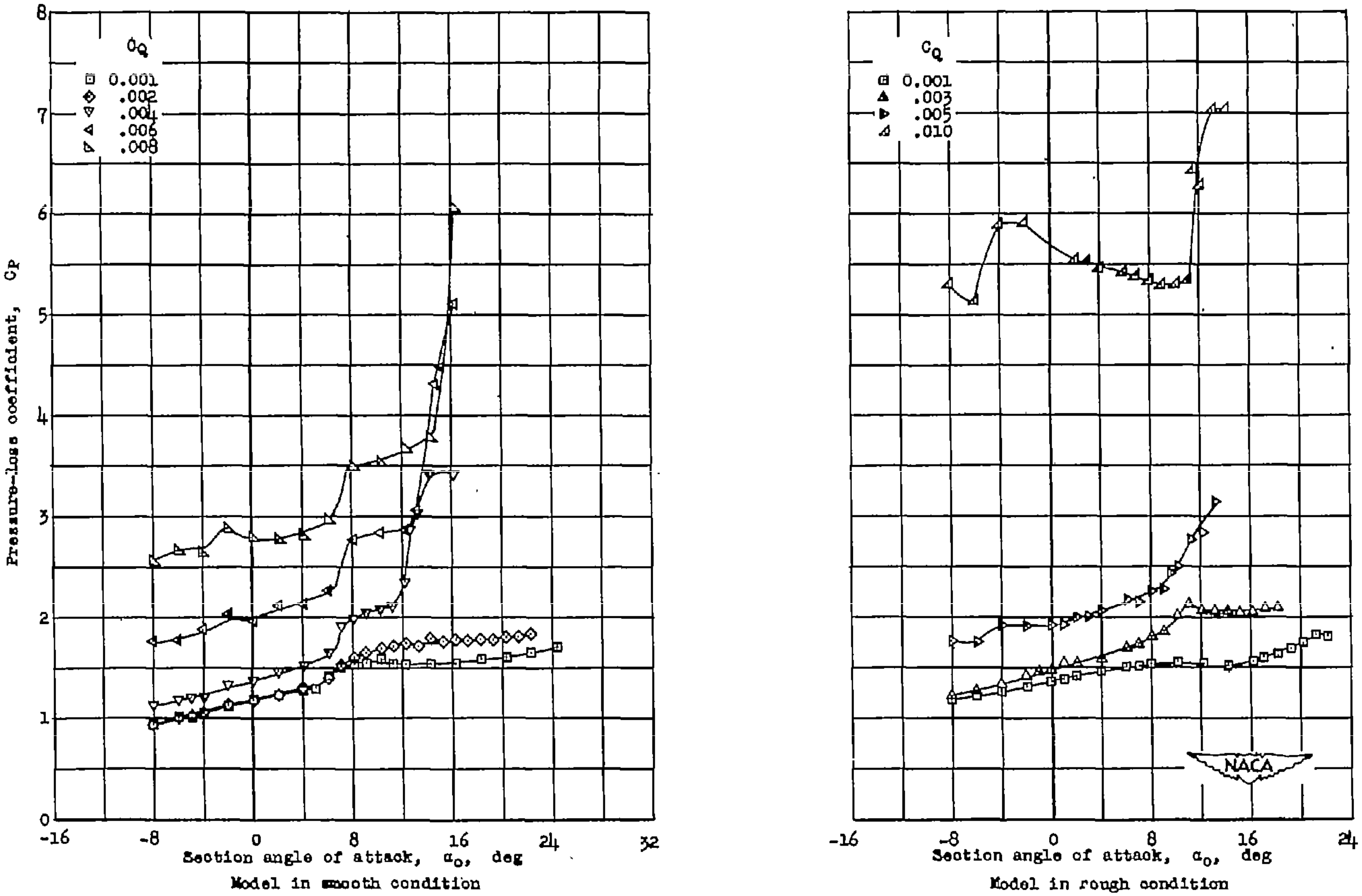
Figure 8.- Variation of pressure-loss coefficient with section angle of attack for the NACA 65_5-424 airfoil section with a 0.016c boundary-layer control slot at 0.45c. R = 6.0 × 10^6.



(a) Model in smooth condition.

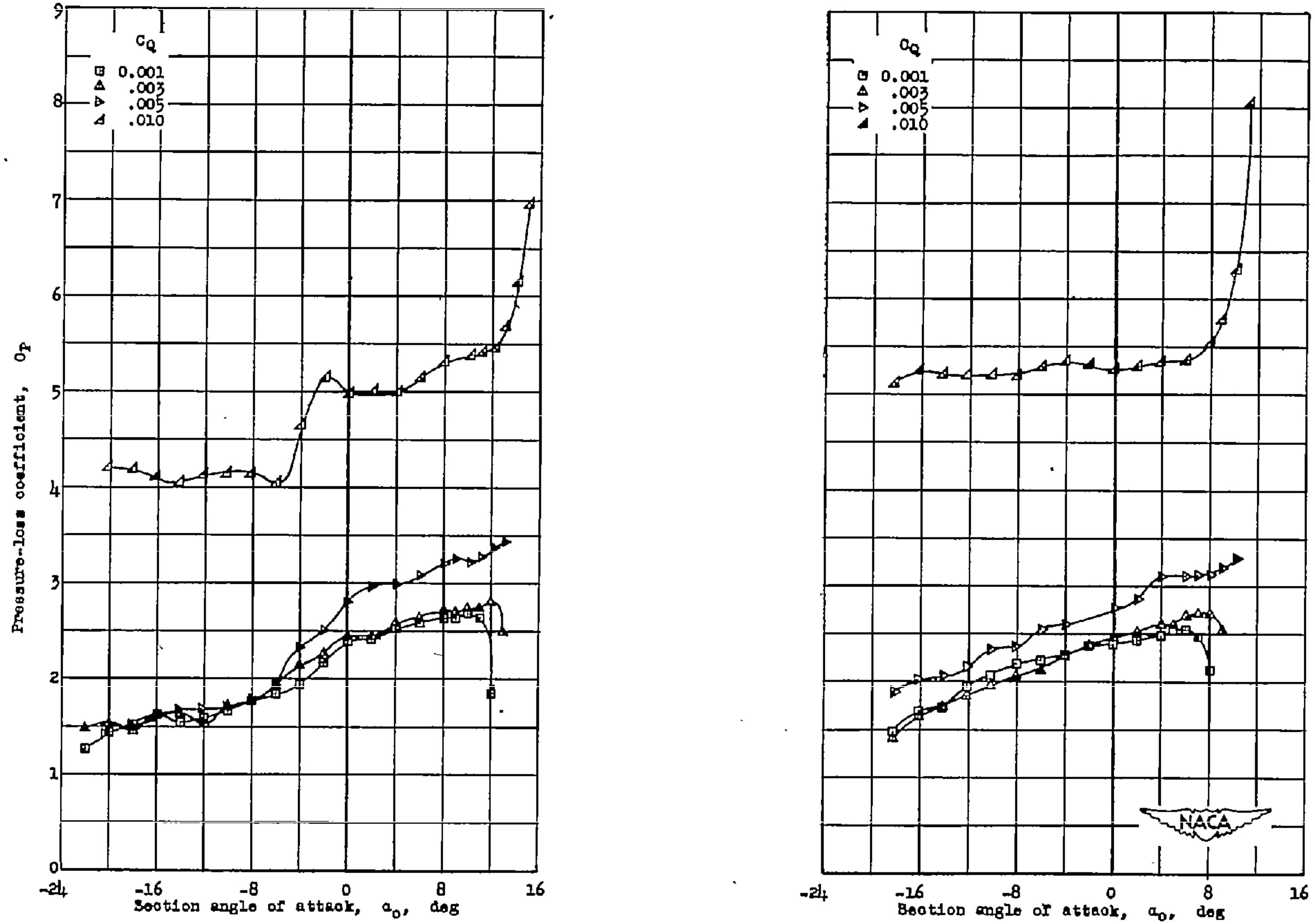
(b) Model in rough condition.

Figure 9.- Variation of pressure-loss coefficient with section angle of attack for the NACA 65_5-424 airfoil section with a 0.018c boundary-layer control slot at 0.65c. $R = 6.0 \times 10^6$.



(a) Flap retracted.

Figure 10.- Variation of pressure-loss coefficient with section angle of attack for the NACA 65_3-424 airfoil section with a 0.008c boundary-layer control slot at 0.65c. $R = 6.0 \times 10^6$.

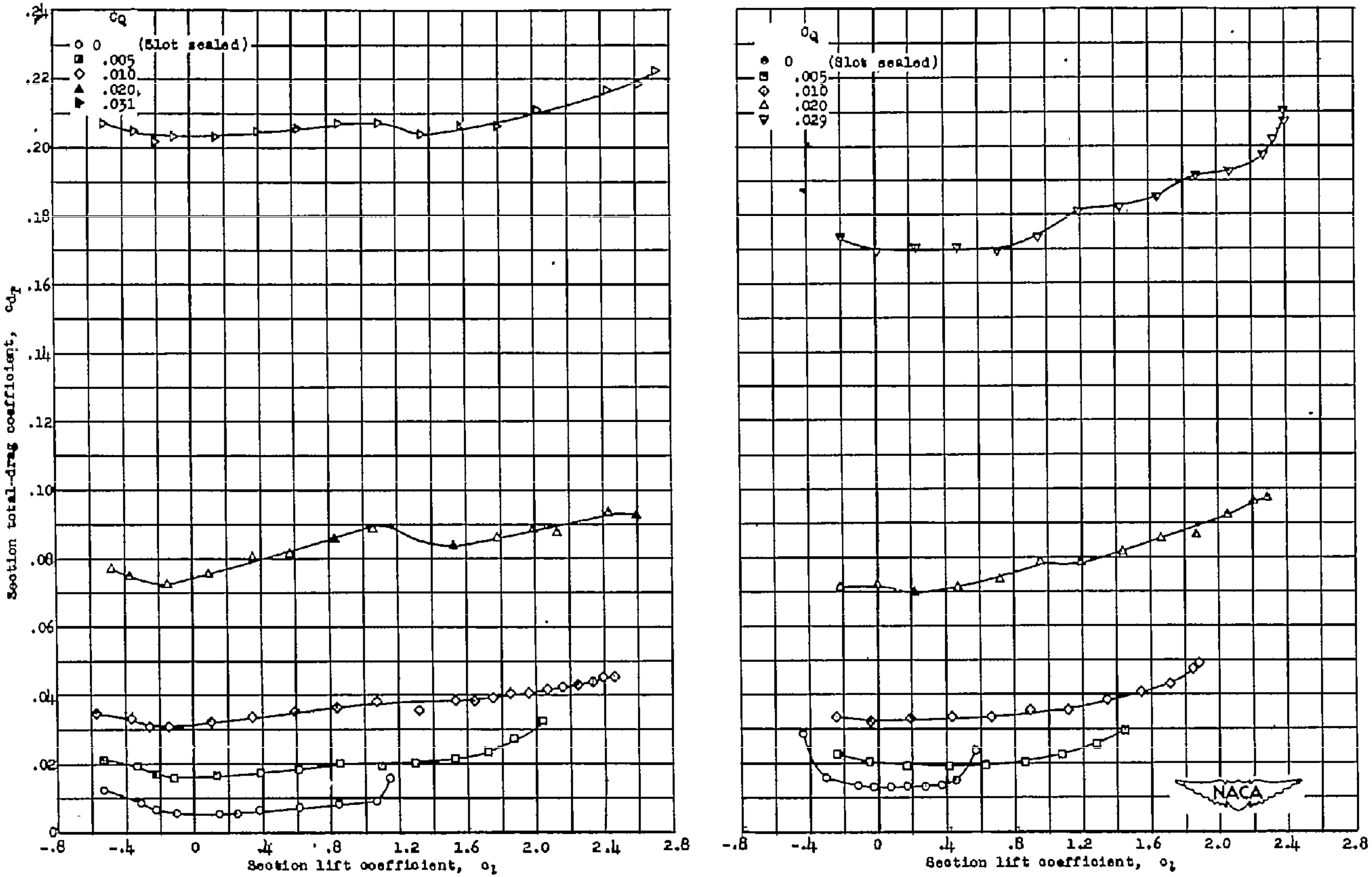


Model in smooth condition

Model in rough condition

(b) Flap deflected.

Figure 10.- Concluded.

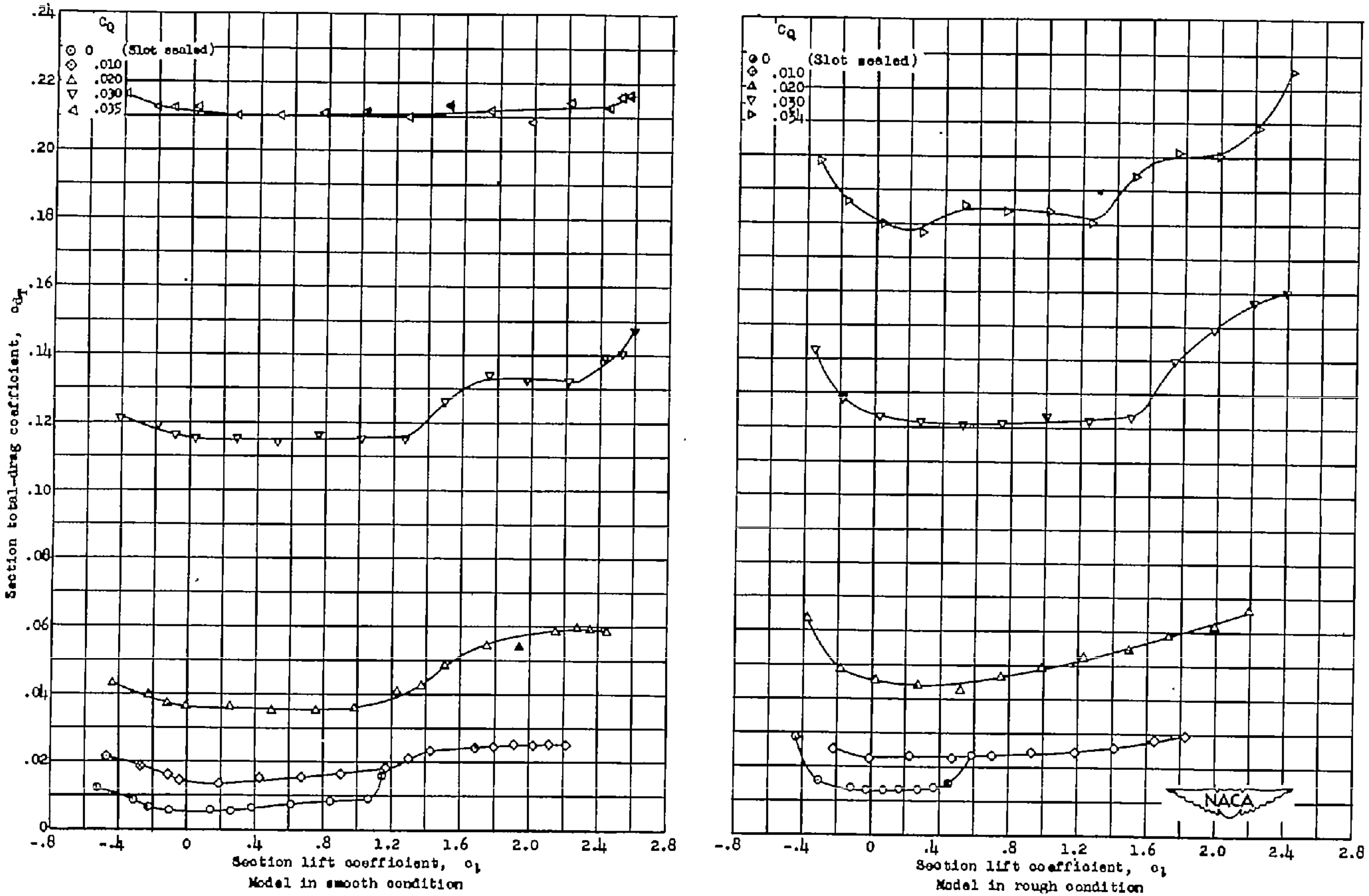


Model in smooth condition

Model in rough condition

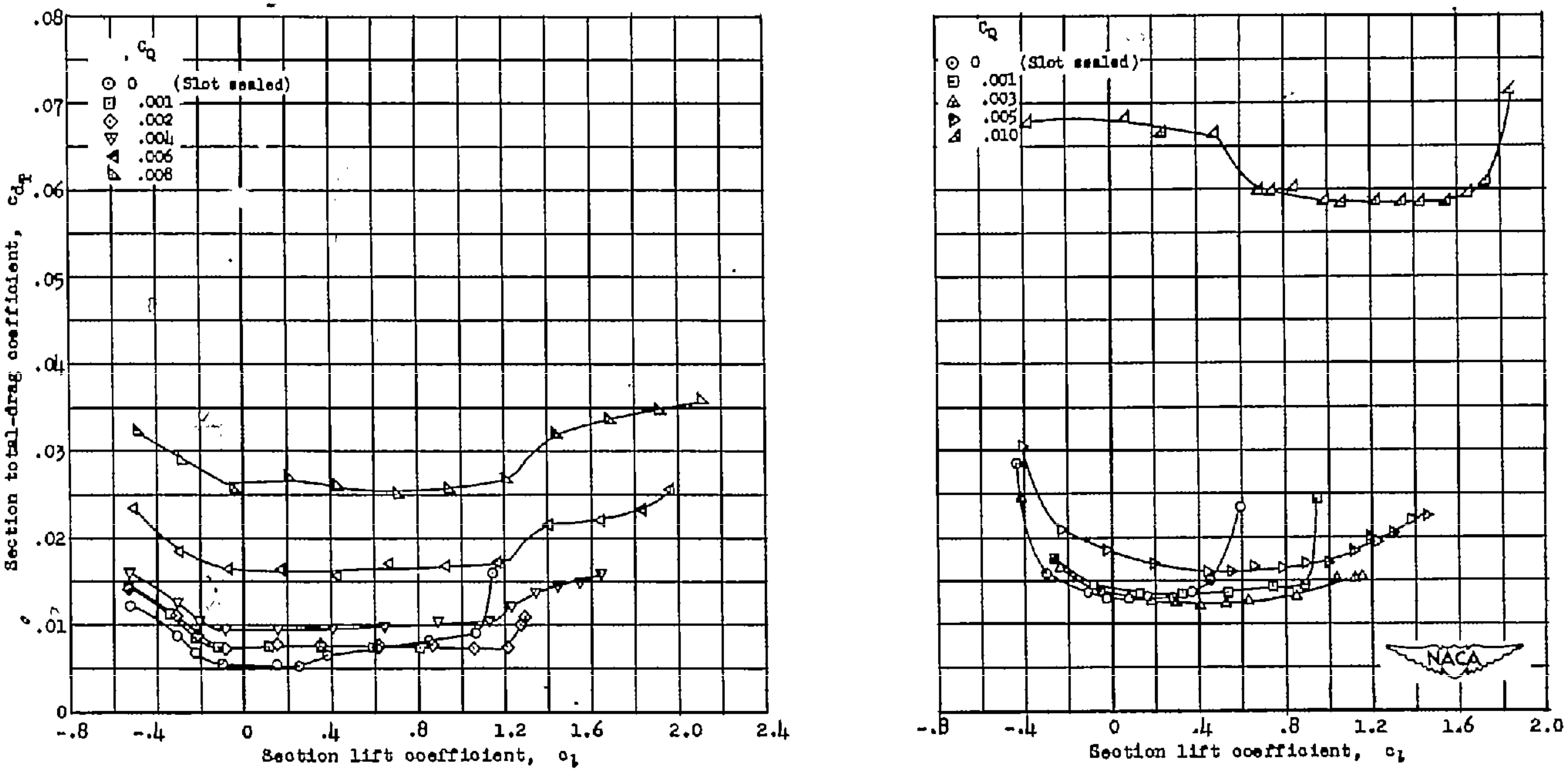
(a) 0.016c slot at 0.45c.

Figure 11.- Section total-drag characteristics of the NACA 65_5-424 airfoil section with boundary-layer control slots. Flap retracted; $R = 6.0 \times 10^6$.



(b) 0.018c slot at 0.65c.

Figure 11.- Continued.



Model in smooth condition

Model in rough condition

(c) 0.008c slot at 0.65c.

Figure 11.- Concluded.