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INVESTIGATION OF BOUNDARY-LAYER CONTROL TO IMPROVE
THE LIFT AND DRAG CHARACTERISTICS OF THE NACA 65₂-415
AIRFOIL SECTION WITH DOUBLE SLOTTED AND PLAIN FLAPS

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SUMMARY

A two-dimensional wind-tunnel investigation has been made of the relative effectiveness of two methods of boundary-layer control in increasing the maximum lift coefficient of an NACA 652-415 airfoil section. Boundary-layer suction was applied at the 45-percent-chord station of the airfoil equipped with a double slotted flap and in the vicinity of the hinge line of the airfoil with a deflected plain flap. The investigation also included the determination of the effectiveness of small deflections of the plain flap in conjunction with suction at the hinge line and of suction at the 45-percent-chord station of the airfoil with the double slotted flap retracted as a means of reducing the drag.

The results of the investigation indicate that for the same expenditure of suction power or for the same flow coefficient the configuration with the double slotted flap gave higher maximum lift coefficients than did the configuration with the plain flap. The data obtained in the investigation supplemented the data from previous investigations of NACA 6-series airfoils of other thickness ratios and showed that the maximum lift coefficient and the increment of lift for a given flow coefficient increased with increasing airfoil thickness ratio.

The application of boundary-layer suction in the vicinity of the hinge line of the NACA 652-415 airfoil section with a 0.30-chord plain flap increased the section lift-drag ratio for lift coefficients above 0.6 for the rough condition and above 0.8 for the smooth condition. The extent to which the maximum lift-drag ratio of airplanes having unswept wings composed entirely of NACA 652-415 airfoil sections can be substantially increased by boundary-layer control was found to depend upon the structural feasibility of building wings having values of the span-to-root-thickness ratio in the range from 40 to 100.

INTRODUCTION

Various methods of boundary-layer control as a means of improving the maximum lift coefficient of airfoil sections have been the subject of much investigation. One arrangement which has been studied extensively by the National Advisory Committee for Aeronautics consists in the use of a single suction slot located at about the midchord position of an airfoil in conjunction with a double slotted flap. Lift and drag data for NACA 6-series airfoils employing this combination of high-lift devices are now generally available for airfoils having thickness ratios of 12, 18, 21, and 24 percent of the chord (references 1 to 4). The data of these references show that the use of a single suction slot in combination with a double slotted flap is a very effective means of increasing the maximum lift coefficient and, in some cases, results in increases of the section lift-drag ratio which may lead to improved airplane lift-drag ratios. Data for the airfoil having a thickness ratio of 15 percent of the chord are needed, however, to complete the thickness series.

Another method of boundary-layer control which has proved quite effective in improving the maximum lift coefficient consists in the use of suction slots in the vicinity of the hinge line of a deflected plain flap. (See, for example, references 5 and 6.) The relative effectiveness of suction in increasing the maximum lift coefficient when applied near the hinge line of a deflected plain flap or when applied near the midchord position of an airfoil in conjunction with a double slotted flap has been open to some question, however, because of the lack of data for these two devices when applied to the same airfoil section.

An experimental investigation has therefore been made of the NACA 652-415 airfoil section to determine the lift, drag, and suction pressure-loss characteristics of the airfoil section when equipped with a midchord suction slot and a double slotted flap and when equipped with suction slots in the vicinity of the hinge line of a plain flap. The model with both types of flaps was tested at Reynolds numbers of 1.0×10^6 and 2.2×10^6 , and the model with a double slotted flap was also tested at a Reynolds number of 6.0×10^6 . The investigation was made for both the smooth and rough leading-edge conditions. The data thus obtained, which are presented herein, are sufficient in scope to permit an evaluation of the effectiveness of the two types of boundary-layer control as a means of improving the section lift-drag ratio of the NACA 652-415 airfoil section as well as their effectiveness in improving the maximum lift coefficient. A short analysis of the effect of improvements in the section lift-drag ratio of the NACA 652-415 airfoil section on the lift-drag ratio of airplanes employing this airfoil section is included. Some measurements of the spanwise distribution of flow into a suction slot with different types of internal ducts are also presented.

SYMBOLS AND COEFFICIENTS

c_l	section lift coefficient $\left(\frac{l}{q_0 c}\right)$
$c_{l_{\max}}$	maximum section lift coefficient
Q	volume rate of air flow through suction slot, cubic feet per second
V_0	free-stream velocity, feet per second
c	airfoil chord, feet
t	thickness, feet
b	span over which boundary-layer control is applied, feet
c_r	chord at wing root, feet
c_t	chord at wing tip, feet
t_r	wing root thickness, feet
C_Q	section flow coefficient $\left(\frac{Q}{V_0 c b}\right)$
H_0	free-stream total pressure, pounds per square foot
H_b	total pressure in wing duct, pounds per square foot
q_0	free-stream dynamic pressure, pounds per square foot
C_p	section pressure-loss coefficient $\left(\frac{H_0 - H_b}{q_0}\right)$
c_d	section profile-drag coefficient determined from measurements in wake $\left(\frac{d}{q_0 c}\right)$
c_{db}	section blower drag coefficient $(C_Q C_p)$ (See reference 7.)

c_{dT}	section total-drag coefficient $\left(c_d + \frac{\eta_p}{\eta_b} c_{db} \right)$ (See reference 7.)
d	drag per unit span, pounds per foot
l	lift per unit span, pounds per foot
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, pound seconds per square foot
α_o	section angle of attack, degrees
δ_f	flap deflection, degrees
η_b	combined duct and blower efficiency
η_p	efficiency of main propulsive unit

(See reference 7.)

APPARATUS AND TESTS

Wind tunnel.- Tests of the model at Reynolds numbers of 1.0×10^6 and 2.2×10^6 were made in the Langley two-dimensional low-turbulence tunnel, whereas those at a Reynolds number of 6.0×10^6 were made in the Langley two-dimensional low-turbulence pressure tunnel. The test sections of the two tunnels are similar and are 3 feet wide and 7.5 feet high. The model, when mounted, completely spanned the 3-foot dimension so that two-dimensional flow was obtained. The gaps between the ends of the model and the tunnel walls were sealed to prevent air leakage. Lift measurements were made by taking the difference between the integrated pressure reaction upon the floor and ceiling of the tunnel, and drag measurements were obtained from surveys of the momentum defect in the wake. A more complete description of the tunnels and the methods of obtaining and correcting the data to free-air conditions are contained in reference 8.

Models.- The 2-foot-chord model of the NACA 652-415 airfoil section tested in the present investigation was constructed of aluminum alloy. Ordinates for the plain airfoil are given in table 1. The rear portion of the model was constructed in such a manner that the double slotted

flap and plain flap could be interchanged. A sketch and photograph of the model with the double slotted flap are shown in figures 1 and 2, respectively. As can be seen, the 0.021c suction slot was located at the 0.45c station. Ordinates of the vane and flap are given in tables 2 and 3.

A sketch and photograph of the model with the two boundary-layer control slots located in the vicinity of the hinge line of the plain flap are shown in figures 3 and 4, respectively. The configuration is generally similar to that employed by Regenscheit in his investigations (reference 5). The partition between the two slots was formed by two segments separated by a spacer as shown in figure 4. The width of each slot could be varied independently by changing the position of the segment forming the slot and inserting a spacer of the proper width. Variations in the relative flow into each slot were obtained by varying the relative widths of the slots. The two slots were designed so that only the rear slot was open for small flap deflections and both slots were open when the flap deflection was 30° or more.

The duct within the model was connected to the inlet of a variable-speed blower by means of a pipe line containing pressure tubes for measuring the flow. Loss of total pressure through the slots was obtained from the difference between free-stream total pressure and the pressure within the duct as measured by a flush orifice in the end of the duct opposite to that from which the air was removed. For the rates of flow involved, the velocities in the duct of the model were sufficiently low so that the pressure measured by the flush orifice could be assumed to be substantially total pressure.

The three ducts investigated (fig. 5) consisted of a rectangular duct, a tapered duct, and a tapered duct divided into compartments. The compartmented tapered duct was employed in all the lift and drag tests made in the present investigation.

Tests.— All the tests described were made with the model in both the aerodynamically smooth condition and with standard roughness applied to the leading edge. The roughness employed consisted of 0.011-inch carborundum grains spread over a surface length of 0.08c back from the leading edge on the upper and lower surfaces of the model. The grains were spread to cover from 5 to 10 percent of the included area.

Preliminary tests were first made of the model with the double slotted flap and single suction slot at 0.45c to determine the position and deflection of the flap and vane for the highest maximum lift coefficient. These tests were made at a Reynolds number of 2.2×10^6 and with a flow coefficient of 0.02. This particular flow coefficient was chosen because in other tests of similar configurations (references 1 and 4) flows in excess of 0.02 were found to result in very little

increase in the maximum lift. The configuration shown in figure 1(b) with the 55° flap deflection was found by a systematic investigation of horizontal and vertical positions of the flap and vane with respect to the wing to be the optimum position for maximum lift coefficient. Lift measurements were then made of this optimum configuration for Reynolds numbers of 1.0×10^6 , 2.2×10^6 , and 6.0×10^6 , and flow coefficients of 0, 0.005, 0.015, 0.020, 0.025, 0.026, and 0.030. The suction slot was sealed and faired for the tests with zero flow. With the flap in the retracted position, drag measurements were made for the same range of Reynolds number and flow coefficient. Pressure-loss measurements were obtained in all cases.

For the airfoil with the plain flap, tests were made to determine the flap deflection and slot configuration corresponding to the highest maximum lift at a Reynolds number of 2.2×10^6 and a flow coefficient of 0.015 and 0.020. Two of the more promising configurations found in these preliminary tests, the best being the 55° flap deflection which is shown in figure 3, were then tested at Reynolds numbers of 1.0×10^6 and 2.2×10^6 for a series of flow coefficients which varied from 0 to 0.040. Lift and pressure-loss data were obtained in these tests. Because of the difficulty of maintaining a satisfactory seal in the front slot, the tests for the zero-flow condition were made with the rear slot sealed and faired and sufficient suction applied to the front slot to prevent outflow. With a flap deflection of 50° , the model was also tested with the rear slot sealed in order to determine whether as high a maximum lift could be obtained with a given flow coefficient by the use of one slot as with two slots. The configuration employed in this test is shown in figure 3(c).

The investigation of the effect of small deflections of the plain flap in conjunction with boundary-layer control on the drag was made with the use of only the rear suction slot on the plain flap. The position, with respect to the upper surface of the flap, and size of the suction slot are shown in figure 3 for the model with the flap fully retracted. In order to evaluate properly the effect of boundary-layer control on the drag, measurements were first made of the drag and lift for a range of flap deflections from 0° to 20° with the suction slot sealed. The tests were then repeated for a series of suction flow coefficients from 0.0006 to 0.003. Pressure-loss measurements were made in all cases where suction was used in order that the power required for boundary-layer control could be evaluated if desired.

A few qualitative measurements were made of the effect of duct design on the spanwise distribution of inflow into the suction slot. These measurements consisted of the determination of the ratio of the flow velocity into the slot at various points along the span to the

inflow velocity at the midspan position. The tests were made with zero tunnel speed and for several flow rates. A simple pitot tube mounted in the slot was employed for making the measurements.

RESULTS

The basic data obtained in the investigation are presented in figures 6 to 15. Unless otherwise specified, data are presented in all cases for both the smooth and rough surface condition.

The drag data obtained for the airfoil with the two types of boundary-layer control are presented as section profile-drag and section total-drag coefficients in all cases. The section profile-drag coefficient as determined from measurements of the momentum defect in the wake gives an indication of the effectiveness of the boundary-layer control in reducing the external drag; it does not, however, provide an adequate means of judging the over-all effectiveness of the boundary-layer control because the boundary-layer-control suction power is not accounted for. For this reason, the sum of the wake drag and the drag equivalent of the suction power $C_p C_Q$ is also given in all cases. This method of accounting for the suction power is shown in reference 7 to be valid if the efficiency of the boundary-layer suction system is the same as the efficiency of the main propulsive system of the airplane.

The section profile-drag coefficients and the section total-drag coefficients for the airfoil in the smooth and rough conditions are presented as functions of the section lift coefficient in figures 11 and 12, respectively, for the airfoil with the suction slot at 0.45c and the double slotted flap retracted. The pressure-loss data, necessary for calculating the total-drag coefficient, were obtained from figure 7. Drag data in a similar form are presented in figures 13 and 14 for the airfoil with plain flap. In addition to the drag data, corresponding lift and pressure-loss data are given in figures 13 and 14 for the airfoil with small deflections of the plain flap and suction through a boundary-layer control slot.

The results obtained from the qualitative measurements of the effect of duct design upon the spanwise distribution of inflow velocity in a slot are presented in figure 15.

DISCUSSION

In order to facilitate an evaluation of the rather large quantity of data presented in figures 6 to 15, portions of the data are plotted

in figures 16 to 19 against several significant parameters. In figures 18 and 19 some of the data points were obtained from faired experimental data. The data contained in the plots were selected to show the following relations:

(a) The relative effectiveness of boundary-layer control in improving the maximum lift coefficient when applied at the 0.45c station of an airfoil with a double slotted flap, and when applied to a plain flap on the same airfoil

(b) The comparison of the NACA 652-415 airfoil with a double slotted flap and boundary-layer control at the 0.45c station with other similar airfoils having the same high-lift devices but different thickness ratios

(c) The effectiveness of boundary-layer control applied through a single slot at the 0.45c position and of boundary-layer control applied to a slightly deflected plain flap as a means of decreasing the drag in such a way as to permit the realization of higher airplane lift-drag ratios

A few remarks pertaining to the proper design of ducts for a uniform spanwise distribution of inflow into a slot are also included.

Lift

Comparison of two high-lift arrangements.- An indication of the relative effectiveness of boundary-layer suction applied to a plain flap and to an airfoil equipped with a double slotted flap can be obtained from figure 16. In this figure, the maximum lift coefficient has been plotted against the flow coefficient for both configurations, smooth and rough, for Reynolds numbers of 1.0×10^6 and 2.2×10^6 and flap deflections of 55° . The use of the flow coefficient as a basis for comparison is of interest because it gives an indication of the relative size of the ducting and blower which would be required for a particular application. This criterion is not always satisfactory, however, because the flow fields in the vicinity of the slots and in the slots themselves are by no means similar for the two airfoils considered; hence, comparative values of the flow coefficient alone give no indication of the comparative amount of power required for a given flow rate. For this reason, the maximum lift data of figure 16 have also been plotted against the drag-coefficient equivalent of the boundary-layer control suction power (fig. 17).

An examination of the data presented in figures 16 and 17 shows that when the flow coefficient is used as a basis of comparison (fig. 16) the airfoil with the double slotted flap has a higher maximum lift than the airfoil with the plain flap throughout the range of flows investigated.

The relative advantage in maximum lift shown by the airfoil with the double slotted flap decreases appreciably with increasing flow coefficient. The data of figure 17, however, show that when the drag-coefficient equivalent of the suction power is used as a basis of comparison the maximum lift is for all cases very much greater for the airfoil with a double slotted flap than with a plain flap. Thus, for given values of either flow coefficient or equivalent blower drag coefficient, the airfoil with the double slotted flap is seen to have the higher maximum lift throughout the range of flow coefficient and Reynolds number investigated for both the smooth and rough surface conditions. It is also seen from figures 16 and 17 that the decrement in maximum lift due to leading-edge roughness increases at the higher Reynolds number. It is interesting to note that the results discussed by Regenscheit for NACA 230-series airfoils equipped with suction flaps (reference 5) are in essential agreement with those presented herein with regard both to the maximum lift values obtained and the associated quantity-flow requirement.

In connection with the application of boundary-layer control to the airfoil with the plain flap, suction must be applied at both slots in order to obtain the results shown in figure 16. The data of figure 12 show that, if the rear slot on the flap is sealed but the flow removal through the front slot is increased to a value corresponding to the total flow removed through both slots before sealing, a rather large decrease in maximum lift is obtained. This result suggests that airfoils with suction flaps may be rather sensitive to the location of the slots. This conclusion is in agreement with the findings of reference 6. Although the comparative maximum lift capabilities of the two boundary-layer control configurations are of primary concern, a comparison of some of the other lift characteristics of the two configurations may be of interest.

From an examination of the data of figure 6, the application of boundary-layer control at the 0.45c station of the airfoil with the double slotted flap is seen to have little effect on the linear portion of the lift curve. The boundary-layer control increases the maximum lift by straightening the lift curve at the higher angles of attack and by increasing somewhat the angle of attack for maximum lift. On the other hand, the data for the airfoil with boundary-layer control applied to a plain flap (fig. 8) show that the boundary-layer removal causes a large increase in lift for all angles of attack throughout the range of angles of attack investigated. The reduction or elimination of the extensive regions of separated flow which exist on the upper surface of a plain flap, even at low angles of attack, explains the very large effect of boundary-layer control on the lift of the airfoil with the plain flap. A similar effect of boundary-layer suction on the lift was not observed for the airfoil with the double slotted flap because the

air flowing through the passages of the double slotted flap between the rear of the airfoil and the leading edge of the flap serves to reduce greatly the amount of separation which normally occurs on the upper surface of a plain flap.

Comparison of airfoils with double slotted flap and boundary-layer control.- Figures 18 and 19 show a comparison of the maximum lift coefficient of the NACA 652-415 airfoil section with varying amounts of boundary-layer control and a double slotted flap with other NACA 65-series airfoils. Also included are data for the NACA 641A212 airfoil equipped with boundary-layer control and a double slotted flap. The slightly different shape and camber of the 12-percent-thick airfoil would not be expected to alter markedly the comparisons presented. The maximum lift coefficient is plotted against flow coefficient in figure 18 and against thickness ratio in figure 19.

The data in figures 18 and 19 indicate that the results for the NACA 652-415 airfoil section show consistent trends with those data obtained for the other airfoils of different thicknesses having the same high-lift devices. These trends indicate that, by the use of boundary-layer control and double slotted flaps, maximum lift coefficients between 3.0 and 4.0 can be obtained for NACA 6-series airfoils in the smooth condition with a relatively small suction flow coefficient. In the rough surface condition, maximum lift coefficients varying from 2.7 to 3.6 can be obtained. In all cases, increasing the airfoil thickness ratio increases the magnitude of the maximum lift coefficient for a given flow coefficient for flow coefficients in excess of 0.003. In general, the increment in maximum lift coefficient to be derived from a given flow coefficient increases with the airfoil thickness ratio. The addition of leading-edge roughness reduces the magnitude of this effect as does increasing the Reynolds number (figs. 18 and 19). In many cases, particularly for the thicker airfoils in the smooth surface condition, the use of relatively small flow rates of the order of 0.01 accounts for the greater part of the increment in maximum lift to be gained by the use of boundary-layer control. When the results for the plain airfoils and the airfoils with double slotted flaps are compared, the boundary-layer control, in the case of the thicker sections at least, seems to be more effective in increasing the maximum lift of the plain airfoils. This result means, of course, that the double slotted flap becomes less effective as the flow coefficient is increased. The effectiveness of the double slotted flap in increasing the maximum lift is more nearly independent of the quantity flow removed for the thinner sections which were 12 to 15 percent thick.

Drag

Airfoil with suction slot at 0.45c.- The data in figures 11 and 12 indicate that the use of the single suction slot on the 15-percent-thick

airfoil causes relatively large decreases in the drag associated with the momentum defect in the wake. When the drag-coefficient equivalent of the suction power is included, however, the boundary-layer control is seen not to reduce the total drag except possibly in some cases at very high lift coefficients where the drag is also high. Consequently, boundary-layer suction through a midchord slot does not appear to be an effective means of increasing the lift-drag ratio of 15-percent-thick airfoil sections. Tests of an NACA 65₅-424 airfoil equipped with a single suction slot located near the midchord (reference 4), however, have shown that boundary-layer control is effective in reducing the total-drag coefficient of the thicker airfoil sections by extending the relatively flat portion of the total-drag polar to high-lift coefficients; thus the maximum value of the section lift-drag ratio is greatly increased.

Airfoil with plain flap.- In order to interpret better the drag data of figures 13 and 14, the values of the section lift-drag ratio have been plotted as a function of lift coefficient in figure 20 for flap deflections of 0°, 5°, 10°, and 15° with and without boundary-layer control. The curves in figure 20(a) for the smooth surface condition and figure 20(b) with leading-edge roughness are for the optimum flow coefficient for minimum total drag. The drag values used are the total-section-drag coefficients which include the drag due to the momentum defect in the wake and the drag-coefficient equivalent of the suction power.

The curves of section lift-drag ratio against lift coefficients for the smooth surface condition (fig. 20(a)) show that increasing the flap deflections from 0° to 10° with or without boundary-layer control resulted in some increase in section lift-drag ratio for lift coefficients of 0.8 or less, but the principal increase in section lift-drag ratio occurred for lift coefficients greater than 0.8. Further deflection of the flap to 15° results in a decrease in section lift-drag ratio throughout the lift range investigated and the use of boundary-layer control results in an additional decrease of the section lift-drag ratio. It will be shown later that an increase in the section lift-drag ratio for lift coefficients in excess of 0.8 is of very little importance for wings of medium aspect ratio composed of airfoil sections of 15 percent chord in thickness.

The curves of figure 20(b) show that, for the rough surface condition, deflecting the flap without the use of boundary-layer control decreases the value of the lift-drag ratio in all cases. The use of boundary-layer control, however, results in a slight improvement in the lift-drag ratio of the airfoil without a flap and the combination of boundary-layer control and flap deflection increases the lift-drag ratio still more. An appreciable increase in section lift-drag ratio due to boundary-layer control is first observed at a section lift coefficient of 0.6, increases with increasing lift coefficient, and reaches a

maximum at a section lift coefficient of about 1.05. The maximum gain in lift-drag ratio due to the flap and boundary-layer control is about 42.5 percent for the rough surface condition as compared with 10.5 percent for the smooth surface condition. The effectiveness of the boundary-layer control and flap in increasing the lift-drag ratio of the 18-percent-thick section with rough surfaces (reference 6) was comparatively much greater than that observed in the present investigation.

Unfortunately, increases in the airfoil-section lift-drag ratio at relatively high lift coefficients do not necessarily mean improved airplane lift-drag ratios. In order to indicate the possible value of the increase in section lift-drag ratio obtained with flap and boundary-layer control on the NACA 65₂-415 airfoil section, calculations were made of the maximum lift-drag ratio for a series of assumed airplanes having wings composed entirely of NACA 65₂-415 airfoil sections. In determining the airplane lift-drag ratio it can be shown that if the sum of the parasite drag C_{Dp} and profile drag C_{Do} is essentially independent of the lift coefficient, the maximum airplane lift-drag ratio will occur at the lift coefficient for which the induced drag equals the sum of the parasite and wing profile drags, that is,

$$C_{L(L/D)_{\max}} = \sqrt{\pi A e (C_{Dp} + C_{Do})} \quad (1)$$

In this relation the lift coefficient for maximum airplane lift-drag ratio $C_{L(L/D)_{\max}}$ increases as the square root of the aspect ratio A .

Structural considerations, however, limit the aspect ratio of a wing having a given airfoil section and, consequently, the lift coefficient for maximum lift-drag ratio. It is therefore possible that the lift coefficient for maximum lift-drag ratio may be lower than that for which improvements in the section lift-drag ratio may be obtained by the use of boundary-layer control. Under such circumstances, no increase in the airplane maximum lift-drag ratio would be obtained, even though the section lift-drag ratio in the high-lift range would be increased. Inasmuch as the data of figure 20 showed the profile-drag coefficient to be essentially independent of the lift coefficient, equation (1) was employed in calculating the lift-drag ratio of the assumed airplanes. The parameter e in equation (1) is a factor which for untwisted wings corrects for the departure of the wing plan form from the elliptical shape. The value of e usually varies from about 0.96 to 1.0 and in the present case was assumed to be 1.0. The total parasite-drag coefficient, which is the sum of the drags of the fuselage, tail surfaces, nacelles, and so forth, was assumed to be 0.015 (based on wing area) and independent of the lift coefficient. The total wing profile-drag

coefficients determined from figure 20 were 0.0060 and 0.0133 for the smooth and rough conditions, respectively. The maximum value of the aspect ratio for a given airfoil section and taper ratio depends upon the value of some parameter which specifies the wing structural strength. A parameter frequently used for this purpose is the ratio of the span to root thickness.

The lift coefficient for maximum lift-drag ratio was calculated for the assumed airplanes with wings composed entirely of NACA 65₂-415 airfoil sections for taper ratios of 1.0, 3.0, and 5.0 and for various values of the structural parameter, and the results are shown in figure 21. The data of figure 20 indicate that the use of boundary-layer control and flap result in an appreciable improvement in the section lift-drag ratio for lift coefficients of 0.8 or higher for the smooth condition and 0.6 or higher for the leading-edge rough condition. The data for the smooth condition, figure 21(a), show that for a maximum airplane lift-drag ratio to occur at a lift coefficient of 0.8, the aspect ratio must be 10 or more and the ratio of span to root thickness must be between 40 and 65 to 1.0 depending upon the taper ratio; whereas for the rough condition (fig. 21(b)), the airplane maximum lift-drag ratio occurs at a lift coefficient of 0.6 or less for aspect ratios of less than 5 and span-to-root-thickness ratios of less than 30 regardless of taper ratio. To utilize the maximum section lift-drag ratio for either the smooth or rough condition, however, it would be necessary to have an aspect ratio of approximately 15 and a ratio of span to root thickness between 60 and 100 to 1.0 depending on the taper ratio. Whether the gains in section lift-drag ratio shown in figure 20 can be utilized on an airplane would seem, therefore, to depend entirely on the structural feasibility of building wings with sufficiently large span-to-root-thickness ratios. A value of the span to root thickness of the order of 35 or 40 to 1.0 seems to be representative of present-day design practices for unswept wings. Consequently, little or no improvement in airplane lift-drag ratio can be expected by the use of boundary-layer control when applied to smooth wings composed entirely of NACA 65₂-415 airfoil sections. For the leading-edge rough condition, even though some improvement in the airplane lift-drag ratio would be obtained, the utilization of the maximum section lift-drag ratio in improving the airplane lift-drag ratio seems doubtful. This conclusion is in agreement with that of reference 7.

This conclusion, however, does not apply for airplanes having wings composed of airfoils of greater thicknesses than 15 percent of the chord. The maximum permissible aspect ratio increases, of course, with increasing airfoil thickness ratio as does the section profile-drag coefficient. Both of these effects cause increases in the lift coefficient for maximum lift-drag ratio which indicates that boundary-layer control may be used to advantage on wings with thick airfoil sections. The use of wings of

very high aspect ratios with correspondingly thick airfoil sections may, with the use of boundary-layer control, provide a means of obtaining values of the airplane lift-drag ratio larger than those of present-day airplanes. This possibility is discussed briefly in reference 4 in connection with the drag results obtained for a 24-percent-thick airfoil equipped with a single suction slot located near the midchord position.

Spanwise Flow Distribution

The results obtained from the qualitative measurements of the effect of duct design on the spanwise distribution of velocity into a suction slot are shown in figure 15. These results indicate that a uniform distribution of inflow velocity can be obtained with a rectangular duct if the ratio of the duct area to the slot area is large (fig. 15(a)). Unfortunately, data are not available which show the effect of decreasing the ratio of duct area to slot area for a rectangular duct. The comparison of figures 15(a) and 15(b), however, shows that even though the duct is tapered to improve the distribution of inflow velocity, the reduced duct to slot area results in a velocity through one end of the slot which is approximately five times that through the other end. The distribution of inflow velocity into the tapered duct was greatly improved by dividing the duct into compartments as can be seen by the data in figure 15(c). From these preliminary results, it might be concluded that large values of the ratio of duct to slot area are of very great importance in obtaining a uniform distribution of inflow velocity but that proper compartmentation may permit some reductions in the value of this ratio.

CONCLUSIONS

From a two-dimensional wind-tunnel investigation of an NACA 652-415 airfoil section equipped with a single suction slot located at 0.45 chord and a double slotted flap, and of the same airfoil equipped with suction slots in the vicinity of the hinge line of a deflected plain flap, the following conclusions can be made:

1. For the same expenditure of suction power or flow coefficient, the configuration with a double slotted flap and a 0.45-chord suction slot had higher maximum lift coefficients than did the configuration with suction slots on a deflected plain flap.

2. The data obtained in the present investigation with those from other investigations indicated that the maximum lift coefficients of NACA 6-series airfoils equipped with a single suction slot and a double

slotted flap increased as the airfoil thickness ratio increased from 12 to 24 percent and that the increment in maximum lift coefficient associated with a given flow removal also increased with increasing thickness ratio. Maximum lift coefficients between 3.0 and 4.0 were obtained with NACA 6-series airfoils in the smooth condition depending on the thickness and quantity flow removed. The corresponding range of maximum lift coefficients obtainable with NACA 6-series airfoils in the rough surface condition extended from 2.7 to 3.6.

3. The application of boundary-layer control in the vicinity of the hinge line of the NACA 652-415 airfoil section with an 0.30-chord plain flap increased the section lift-drag ratio for lift coefficients above 0.6 for the rough condition and above 0.8 for the smooth condition. The maximum section lift-drag ratio occurred at a lift coefficient of 1.05 and was increased 10.5 percent for the smooth condition and 42.5 percent for the rough condition by the use of boundary-layer control.

4. The extent to which the maximum lift-drag ratio of airplanes having unswept wings composed entirely of NACA 652-415 airfoil sections can be substantially increased by boundary-layer control was found to depend upon the structural feasibility of building wings having values of the span-to-root-thickness ratio in the range from 40 to 100. For an airplane having a wing composed entirely of NACA 652-415 airfoil sections and a span-to-root-thickness ratio of 35 to 1.0, the effect of boundary-layer control on the airplane maximum lift-drag ratio will be negligible for the smooth condition, and although the airplane maximum lift-drag ratio would be increased somewhat for the rough condition it is unlikely that the maximum section lift-drag ratio could be utilized.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., May 16, 1950

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2. Quinn, John H., Jr.: Wind-Tunnel Investigation of Boundary-Layer Control by Suction on the NACA 65₃-418, $\alpha = 1.0$ Airfoil Section with a 0.29-Airfoil-Chord Double Slotted Flap. NACA TN 1071, 1946.
3. Quinn, John H., Jr.: Wind-Tunnel Investigation of the NACA 65₄-421 Airfoil Section with a Double Slotted Flap and Boundary-Layer Control by Suction. NACA TN 1395, 1947.
4. Racisz, Stanley F., and Quinn, John H., Jr.: Wind-Tunnel Investigation of Boundary-Layer Control by Suction on NACA 65₅-424 Airfoil with Double Slotted Flap. NACA TN 1631, 1948.
5. Regenscheit, B.: Absaugeklappenflügel 23012. Teilbericht einer systematischen Dickenreihe. Forschungsbericht Nr. 1543, Deutsche Luftfahrtforschung (Göttingen), 1942.
6. Regenscheit, B., and Schrenk, H.: Tests on Boundary Layer Suction of Flapped Aerofoils of Various Camber and Camber Position. Reps. and Translations No. 484, British M.O.S.(A) Völkenrode, June 1947.
7. Von Doenhoff, Albert E., and Horton, Elmer A.: Wind-Tunnel Investigation of NACA 65₃-418 Airfoil Section with Boundary-Layer Control through a Single Suction Slot Applied to a Plain Flap. NACA RM L9A20, 1949.
8. Von Doenhoff, Albert E., and Abbott, Frank T., Jr.: The Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN 1283, 1947.

TABLE 1

ORDINATES FOR THE NACA 65₂-415 AIRFOIL SECTION

[Stations and ordinates in
percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.313	1.208	.687	-1.008
.542	1.480	.958	-1.200
1.016	1.900	1.484	-1.472
2.231	2.680	2.769	-1.936
4.697	3.863	5.303	-2.599
7.184	4.794	7.816	-3.098
9.682	5.578	10.318	-3.510
14.697	6.842	15.303	-4.150
19.726	7.809	20.274	-4.625
24.764	8.550	25.236	-4.970
29.807	9.093	30.193	-5.205
34.854	9.455	35.146	-5.335
39.903	9.639	40.097	-5.355
44.953	9.617	45.047	-5.237
50.000	9.374	50.000	-4.962
55.043	8.910	54.957	-4.530
60.079	8.260	59.921	-3.976
65.106	7.462	64.894	-3.342
70.124	6.542	69.876	-2.654
75.131	5.532	74.869	-1.952
80.126	4.447	79.874	-1.263
85.109	3.320	84.891	-.628
90.080	2.175	89.920	-.107
95.040	1.058	94.960	.206
100.000	0	100.000	0
L. E. radius: 1.505			
Slope of radius through L. E.: 0.168			

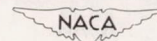


TABLE 2

VANE FOR NACA 65₂-415 AIRFOIL SECTION

[Stations and ordinates in
percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	1.042	0	1.042
.208	1.667	.208	.458
.417	1.938	.417	.271
.833	2.292	.833	.083
1.250	2.521	1.250	0
1.667	2.667	1.667	.083
2.083	2.771	2.500	.425
2.500	2.833	3.333	.792
2.917	2.875	4.167	1.021
3.333	2.854	5.000	1.125
4.167	2.729	5.833	1.125
5.000	2.458	6.667	1.021
5.833	2.125	7.500	.792
6.667	1.708	8.333	.417
7.500	1.188	9.083	-.083
8.333	.625		
9.167	0		

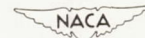
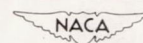


TABLE 3

FLAP FOR NACA 65₂-415 AIRFOIL SECTION

[Stations and ordinates in
percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	-0.421	0	-0.421
.167	.142	.167	-.892
.583	.800	.583	-1.358
1.292	1.442	1.292	-1.529
2.708	2.279	3.375	-1.263
4.000	2.779	8.392	-.629
5.417	3.108	13.421	-.108
6.792	3.188	18.458	.204
8.917	3.058	23.500	-.021
11.000	2.688		
13.579	2.175		
18.542	1.058		
23.500	.021		



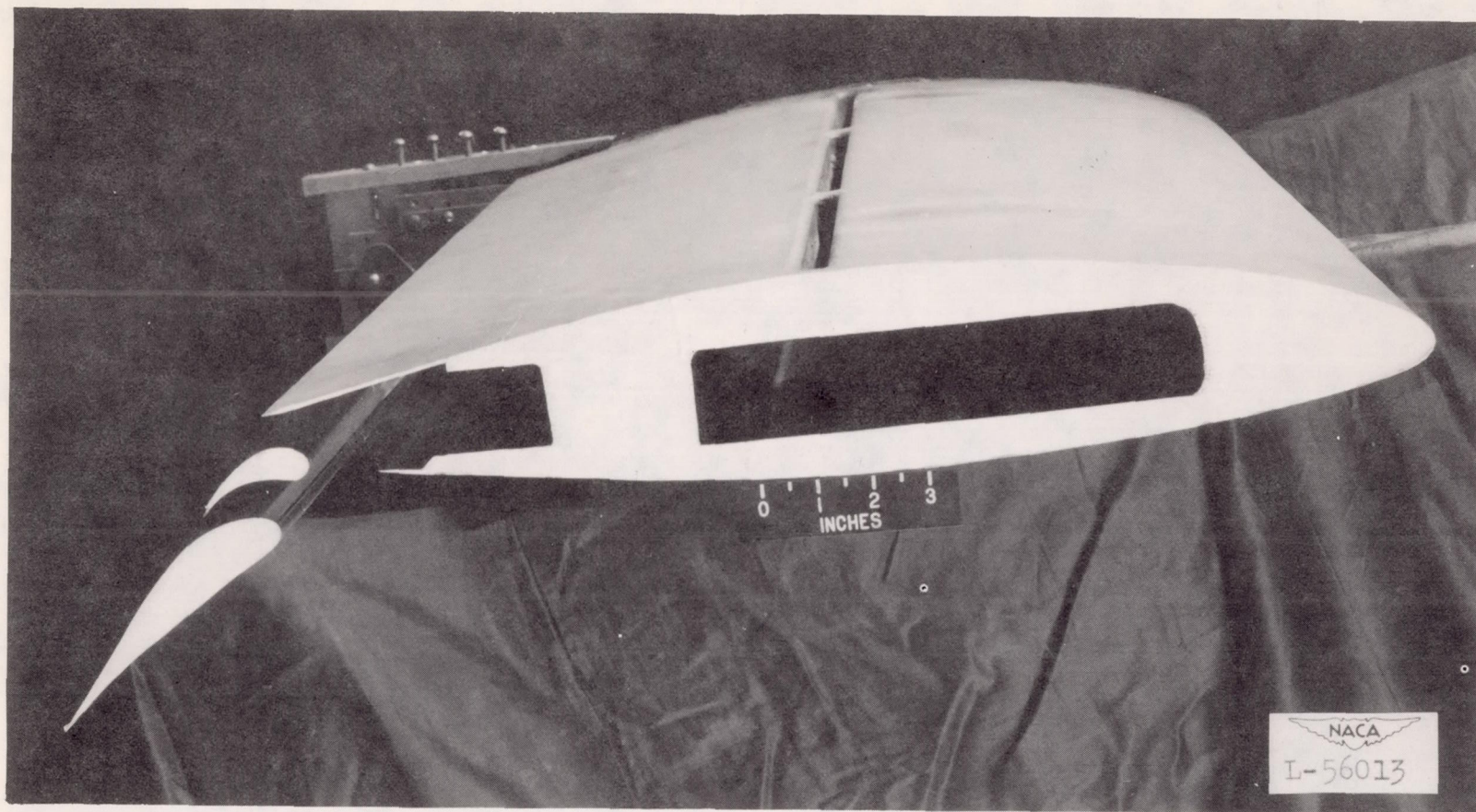
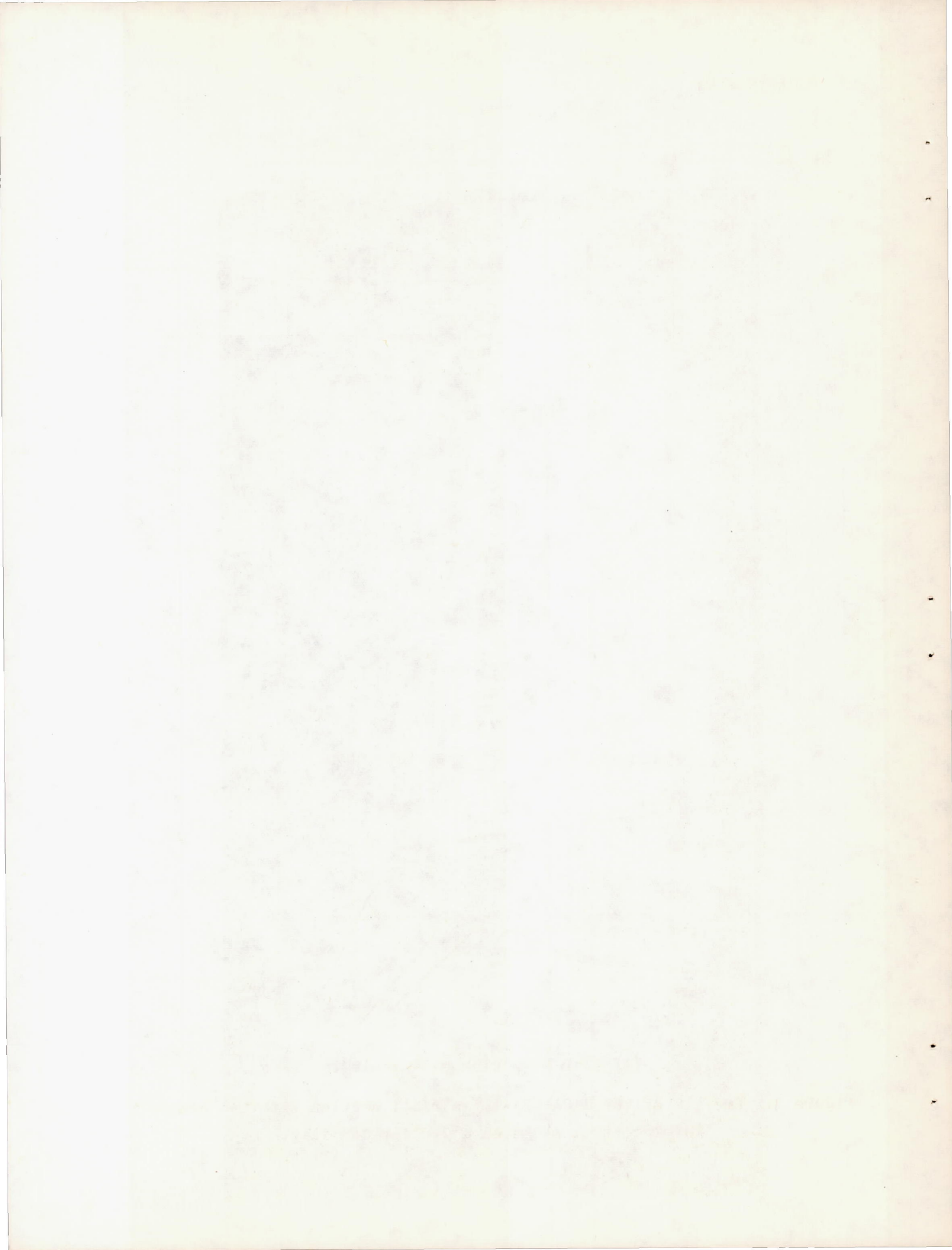
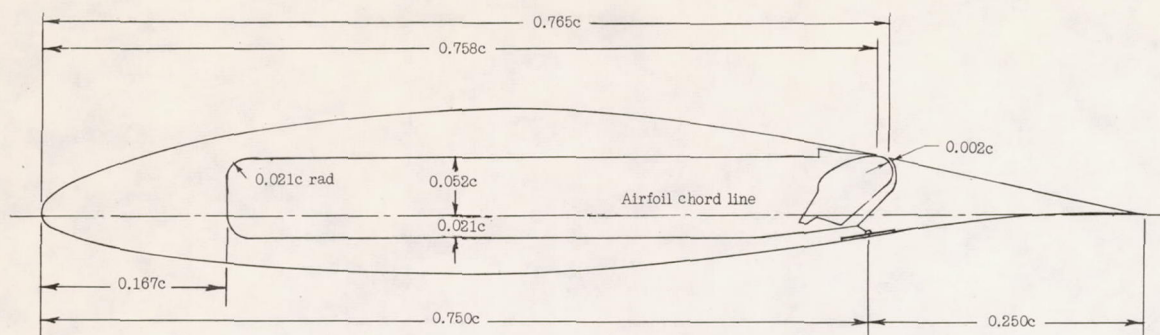
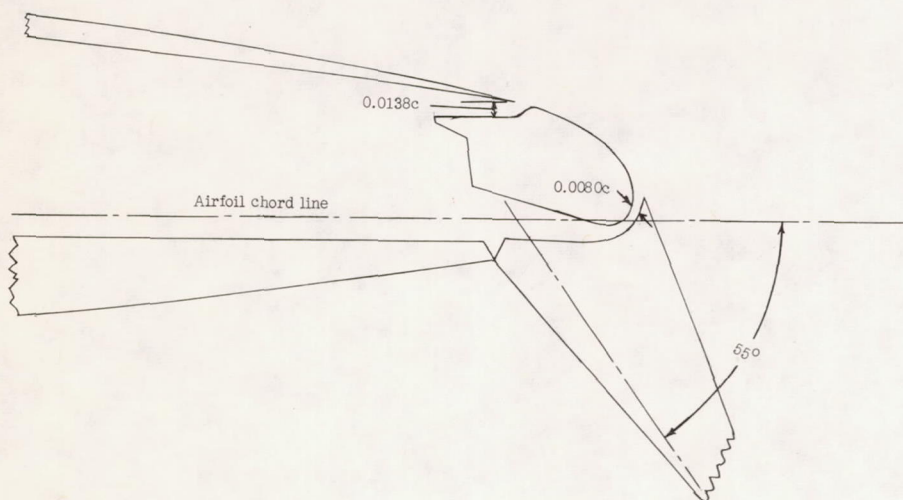


Figure 2.- End view of the model of the NACA 65₂-415 airfoil section with a double slotted flap and a boundary-layer control slot on the upper surface at 0.45c.

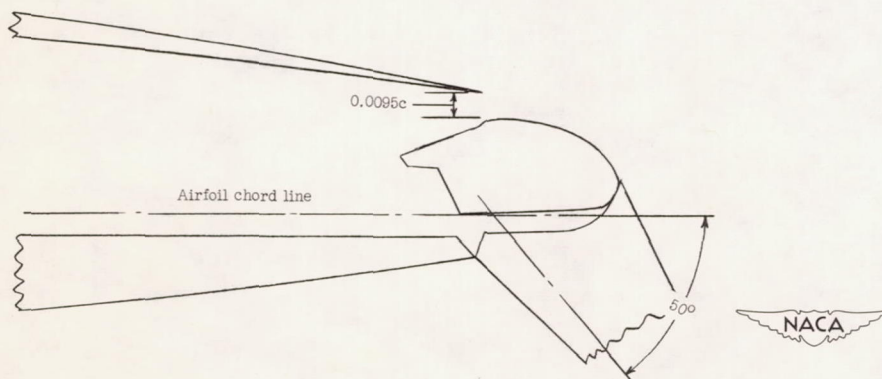




(a) Airfoil with flap retracted.

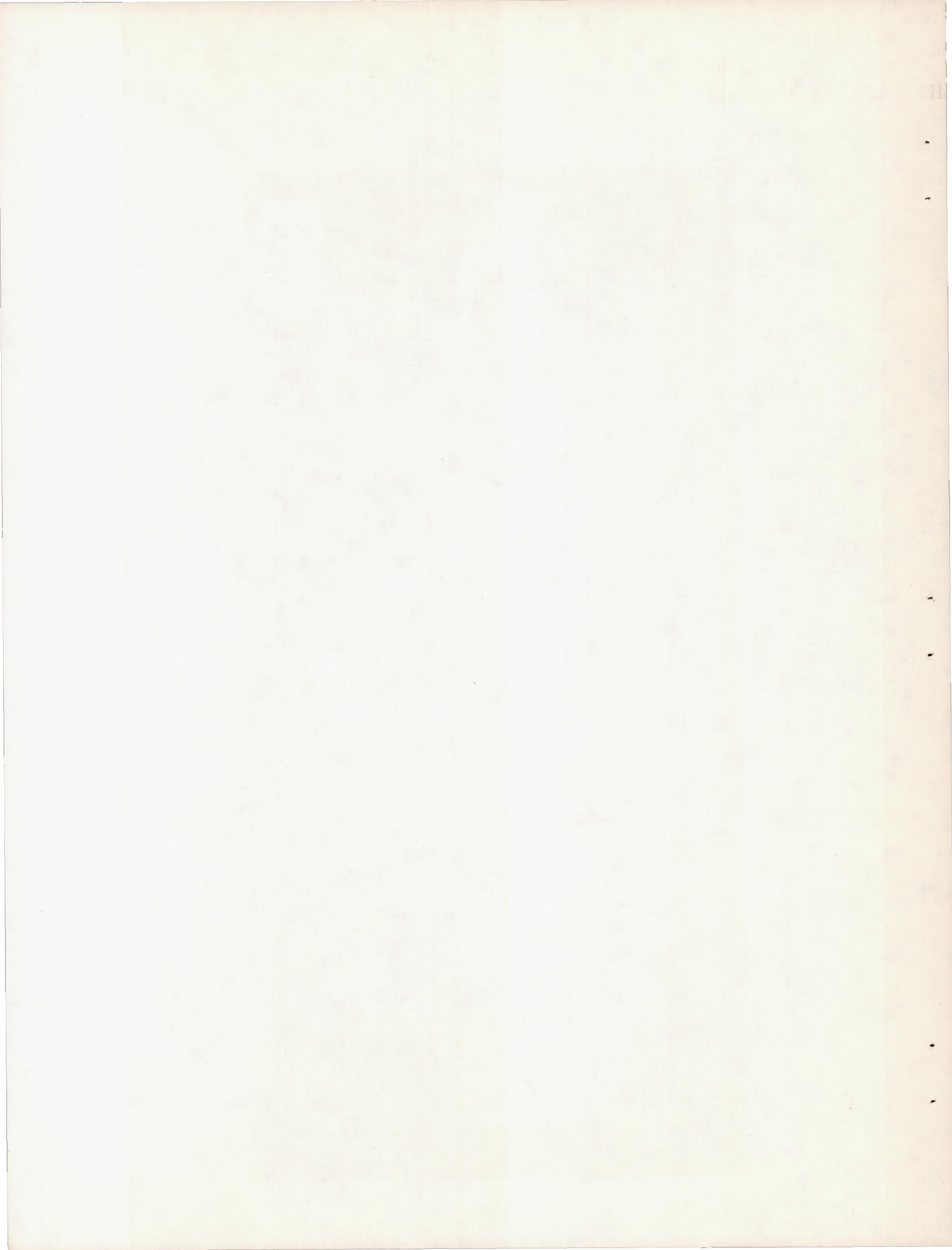


(b) Flap with both slots open.



(c) Flap with rear slot sealed.

Figure 3.- Profile of the NACA 652-415 airfoil section with two boundary-layer control slots on a 0.25c plain flap.



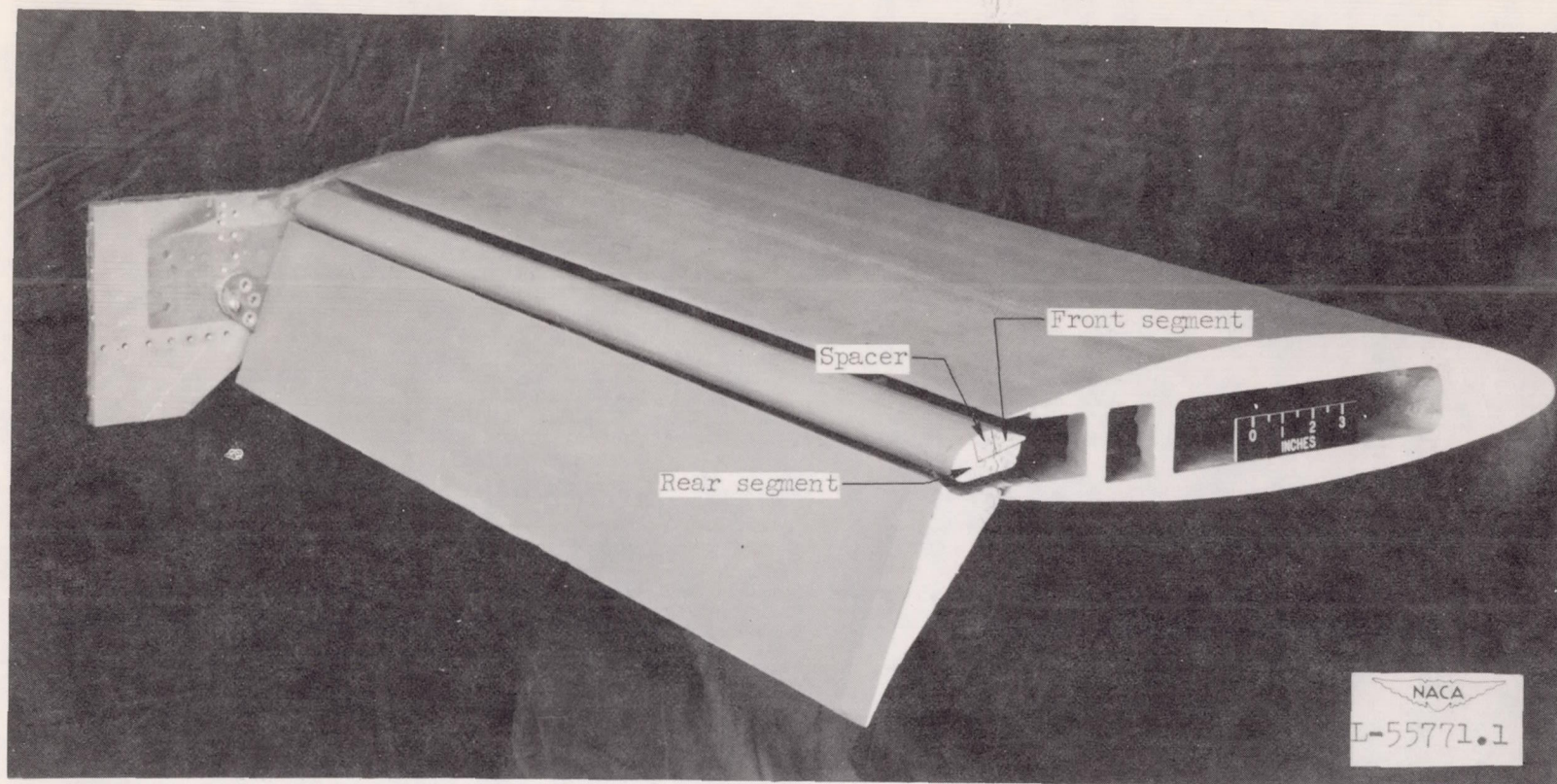
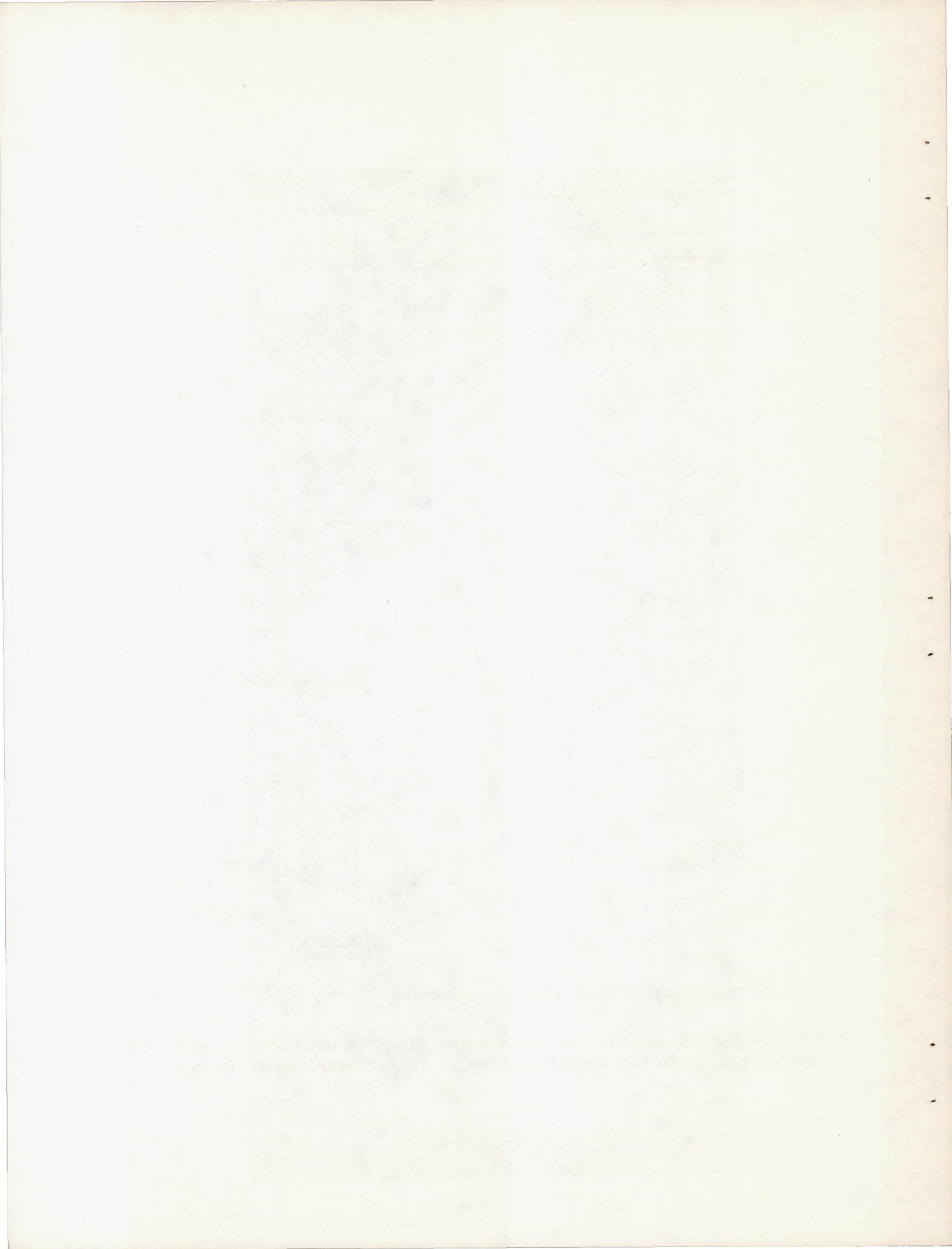


Figure 4.- Three-quarter rear view of the model of the NACA 65₂-415 airfoil section with two boundary-layer control slots on a 0.25c plain flap.



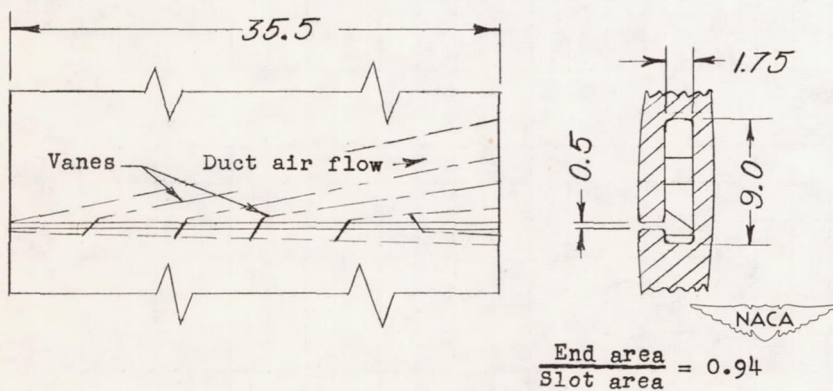
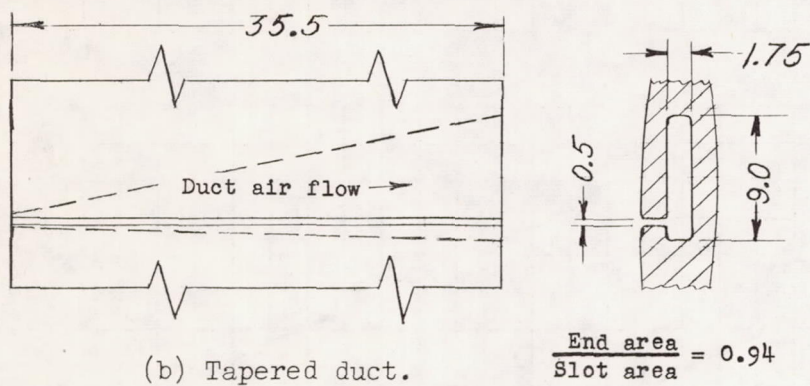
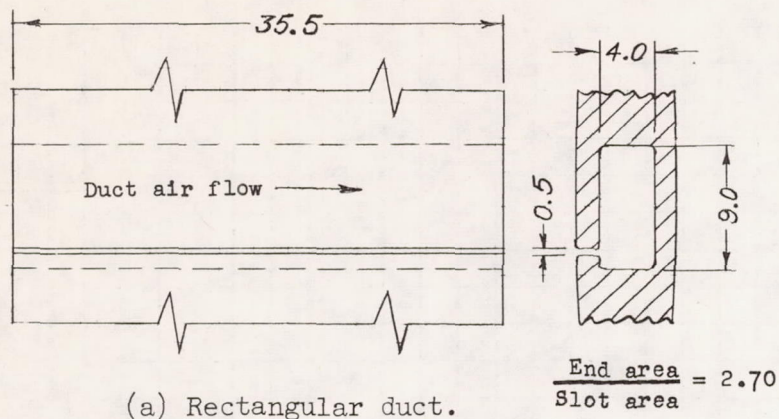
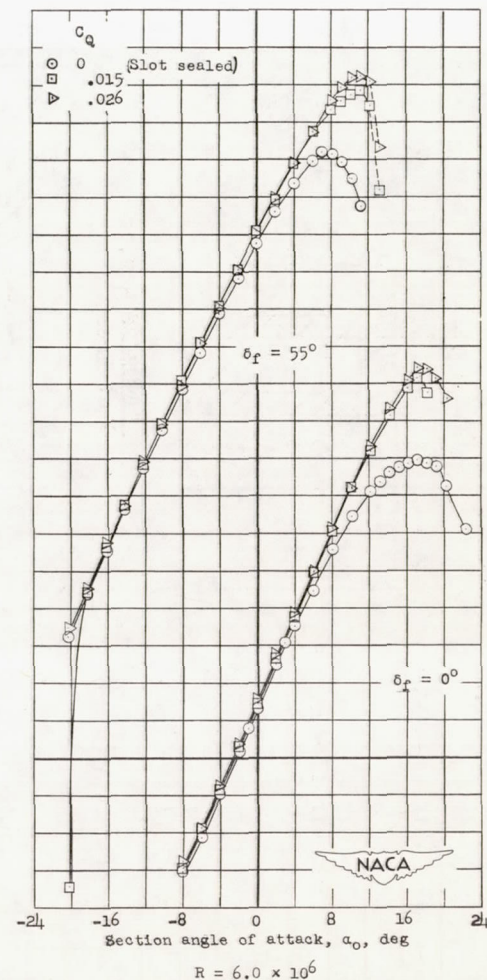
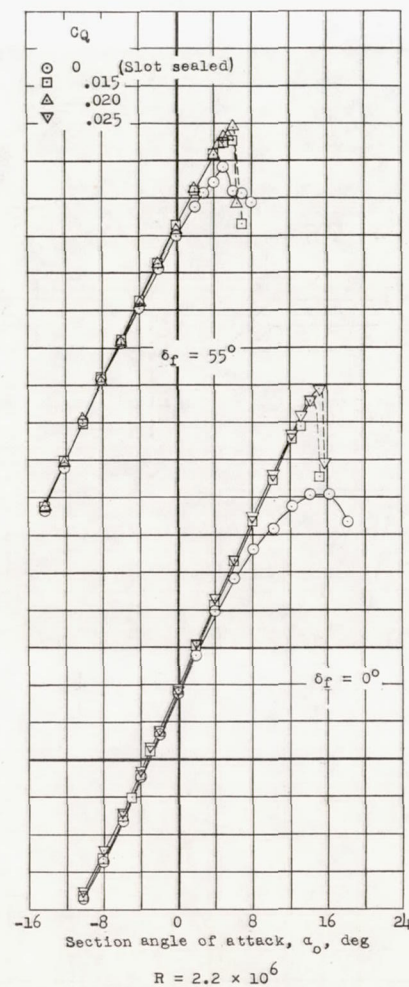
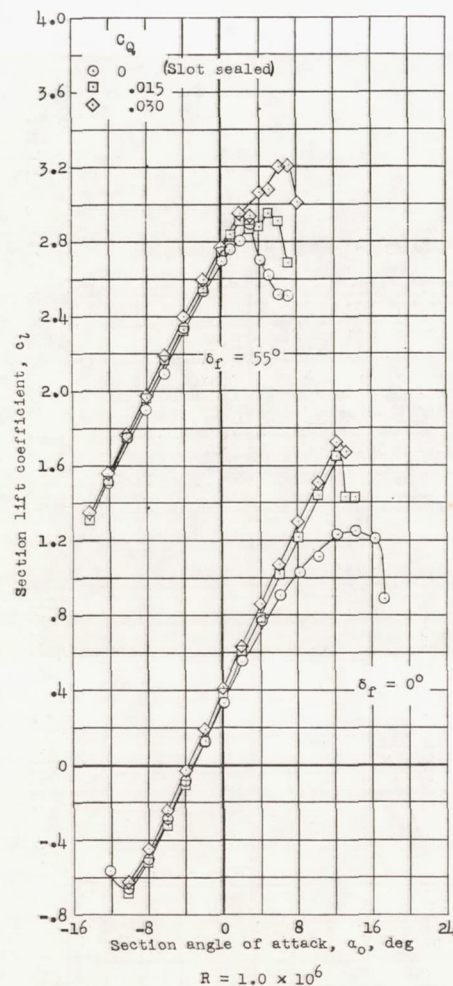
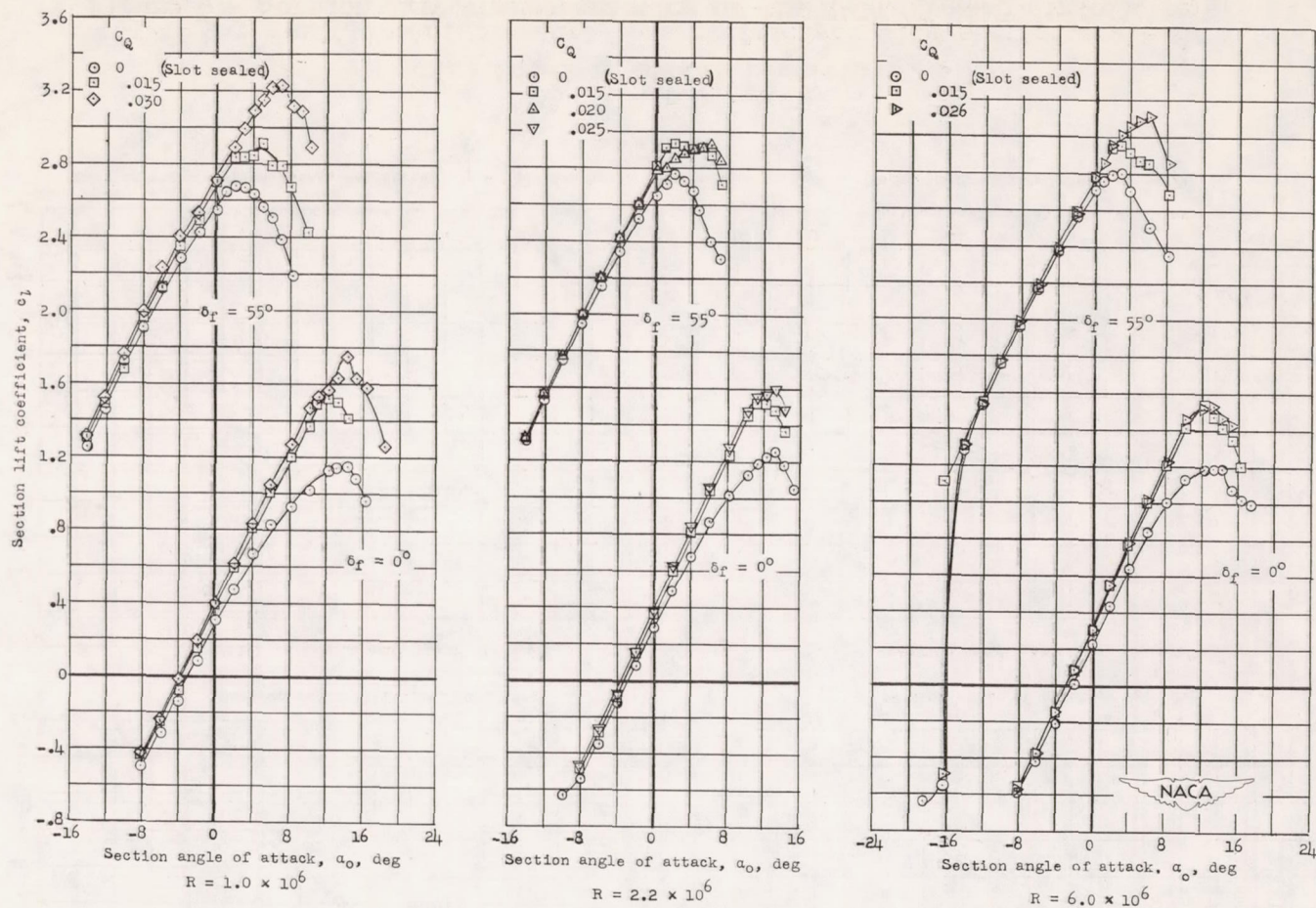


Figure 5.- Sketch showing the three types of ducts used with a rectangular spanwise slot in the airfoil surface. (All dimensions in inches.)



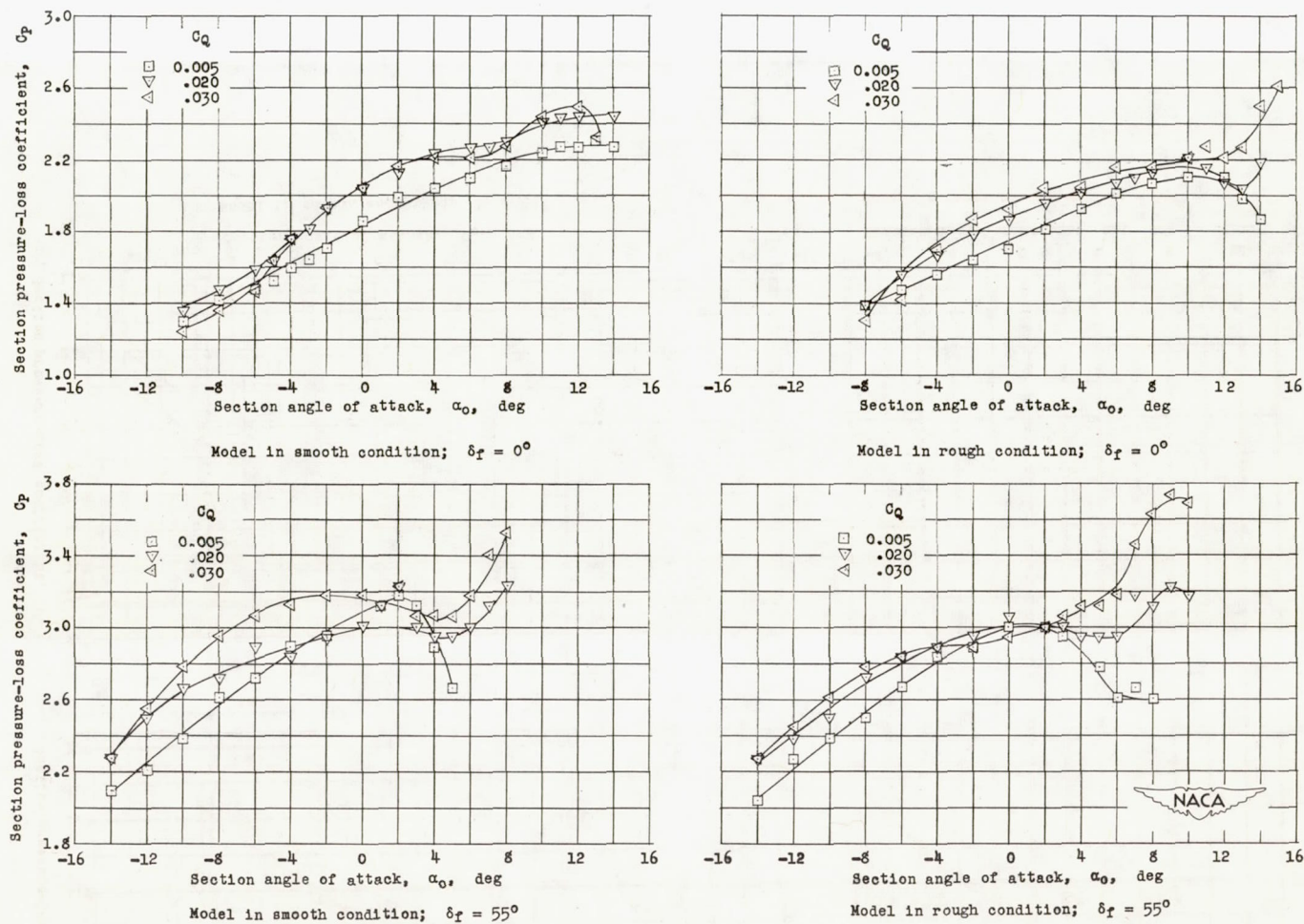
(a) Model in smooth condition.

Figure 6.- Section lift characteristics of the NACA 65₂-415 airfoil section with a double slotted flap and a boundary-layer control slot at 0.45c.



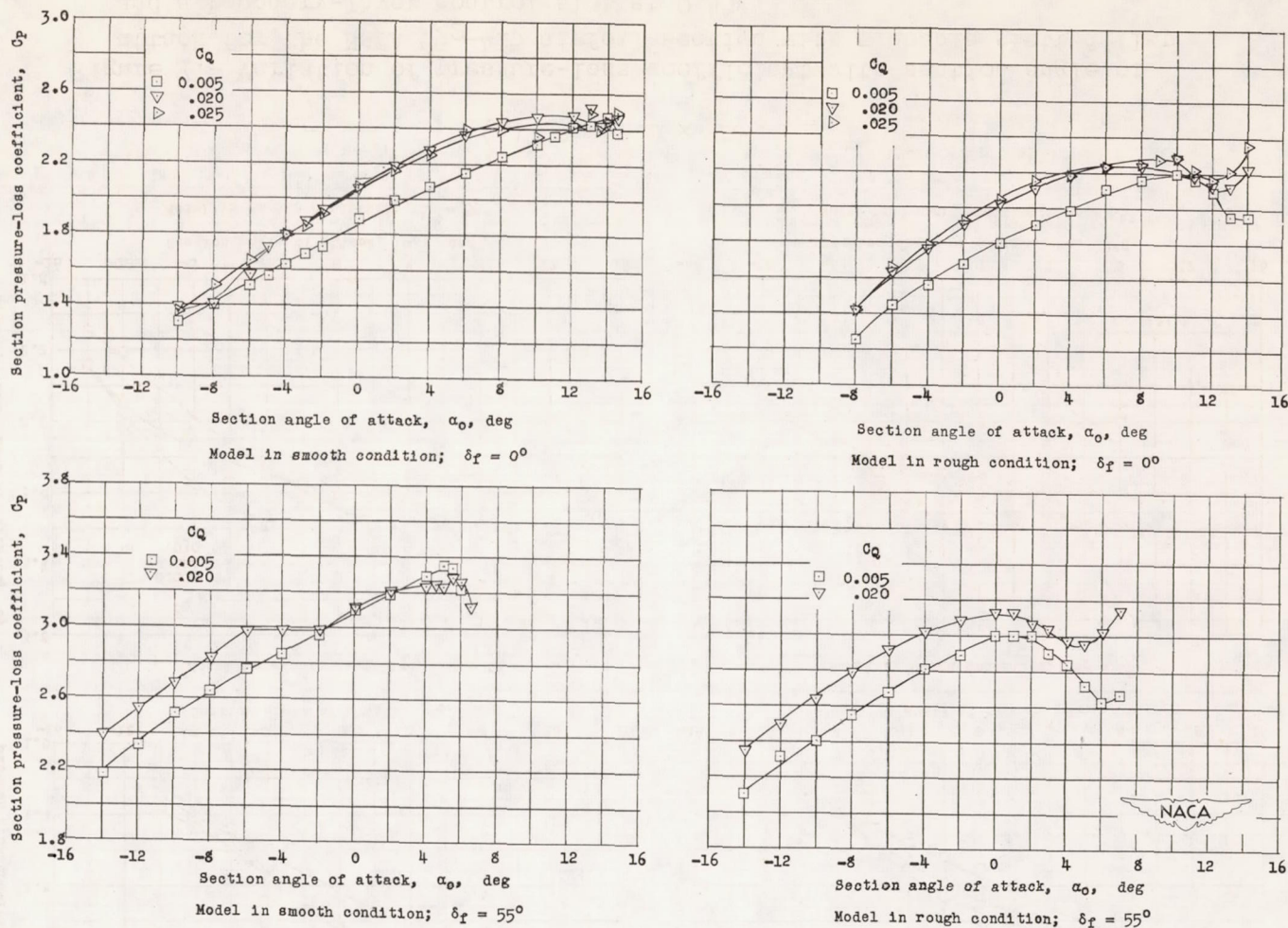
(b) Model in rough condition.

Figure 6.- Concluded.



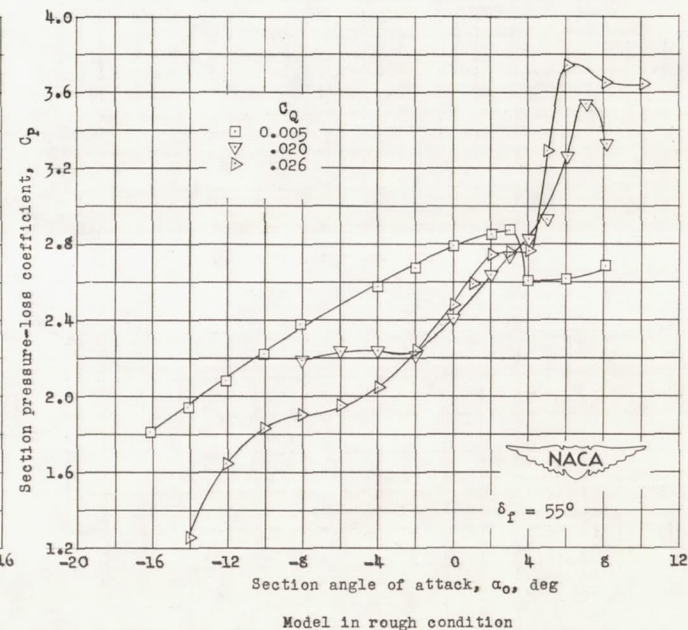
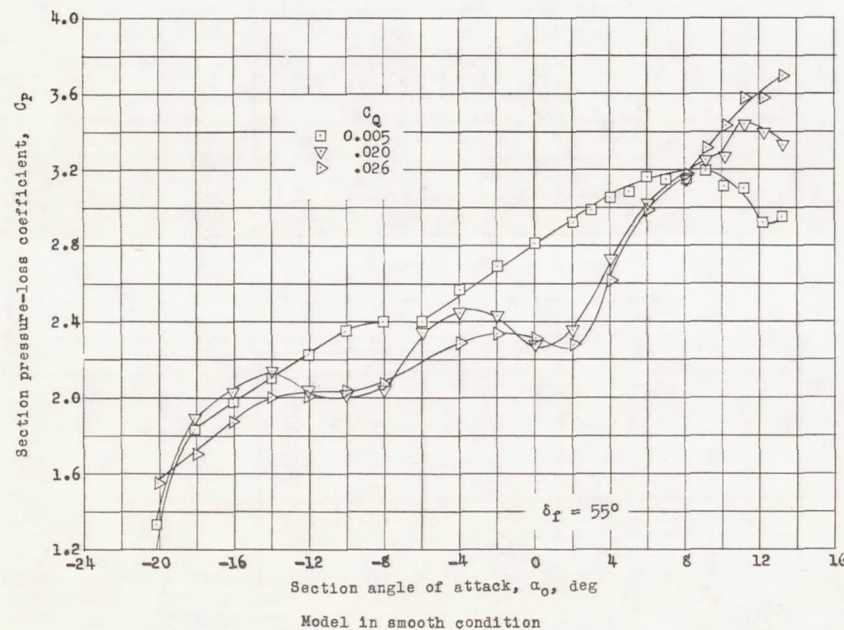
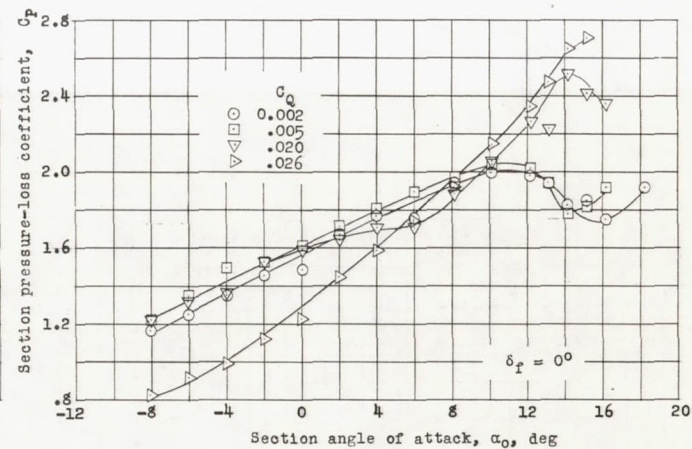
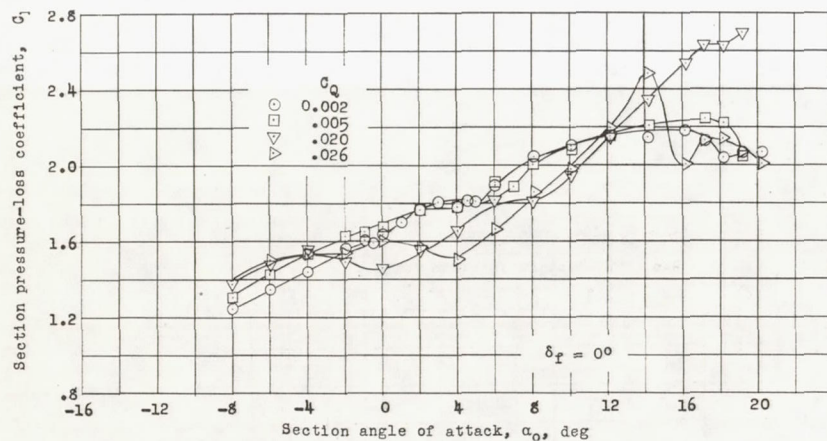
(a) $R = 1.0 \times 10^6$.

Figure 7.- Variation of pressure-loss coefficient with section angle of attack for the NACA 65₂-415 airfoil section with a double slotted flap and a boundary-layer control slot at 0.45c.



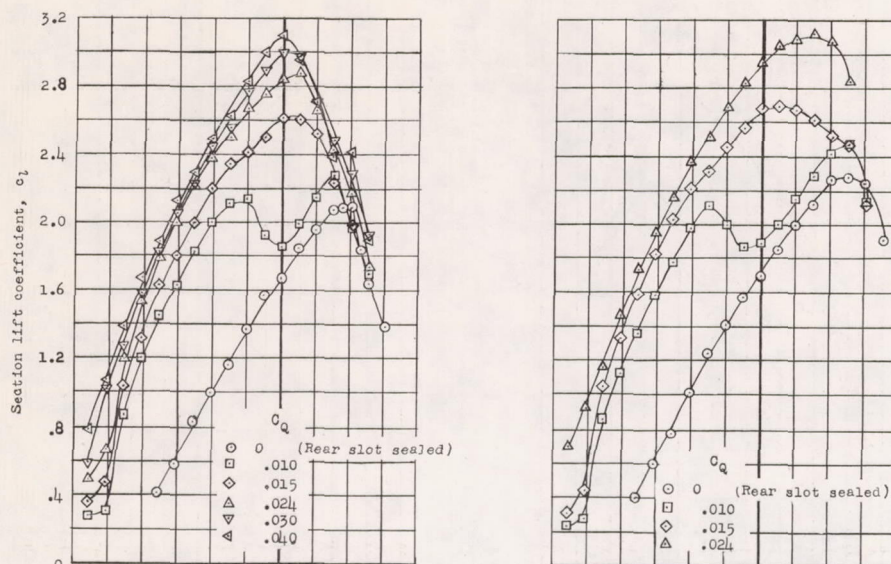
(b) $R = 2.2 \times 10^6$.

Figure 7.- Continued.

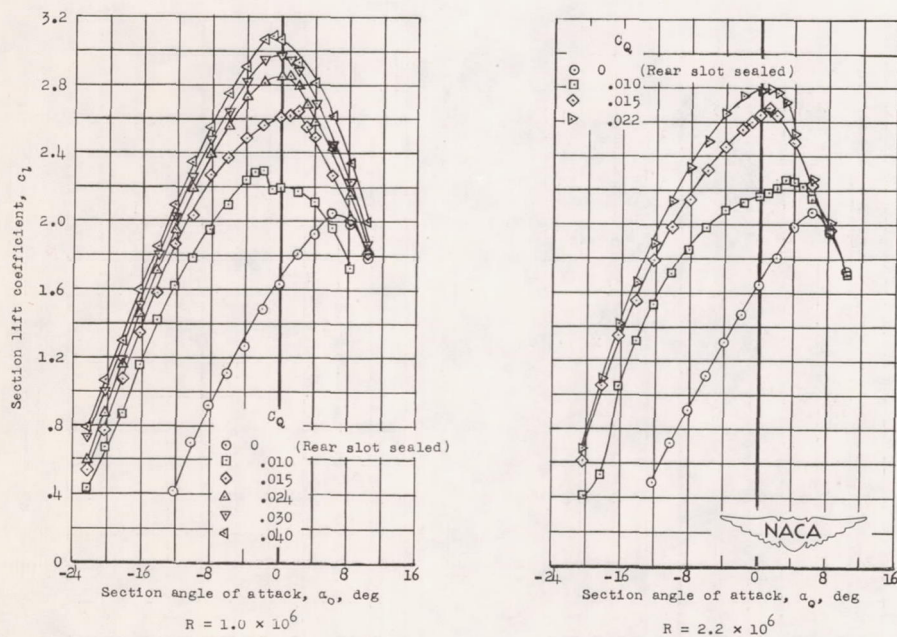


(c) $R = 6.0 \times 10^6$.

Figure 7.- Concluded.



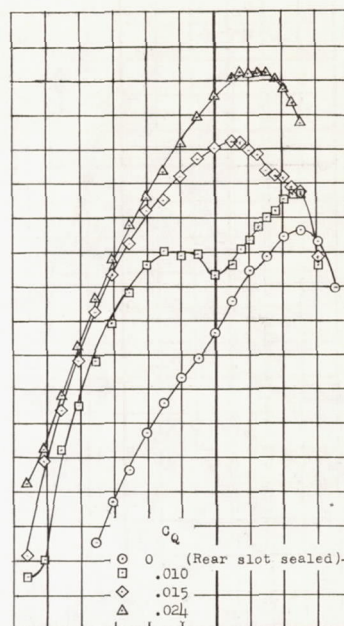
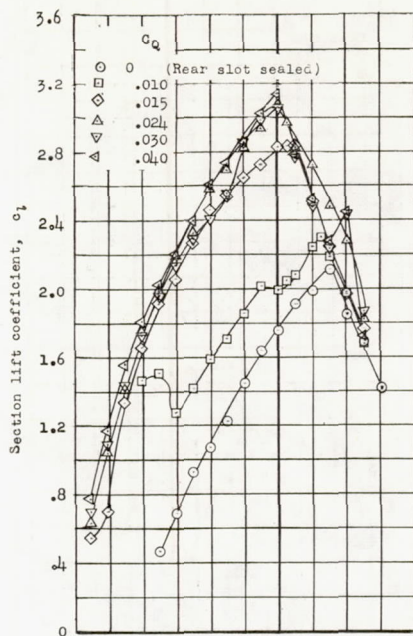
Model in smooth condition



Model in rough condition

(a) $\delta_f = 50^\circ$.

Figure 8.- Section lift characteristics of the NACA 65₂-415 airfoil section with two boundary-layer control slots on a plain flap.



Model in smooth condition

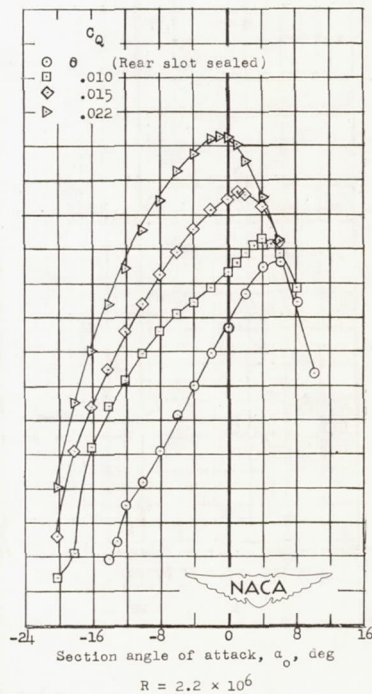
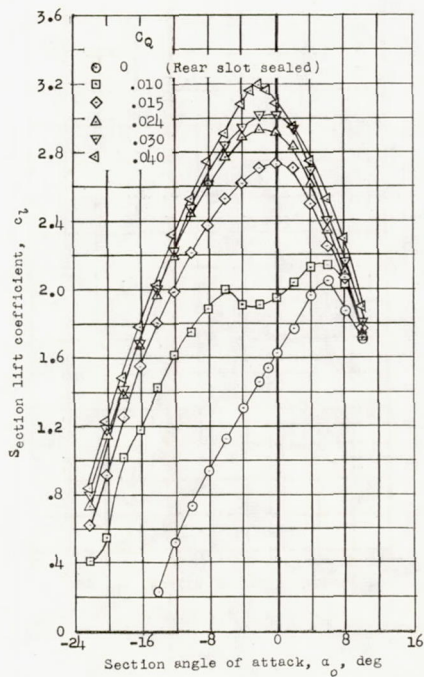
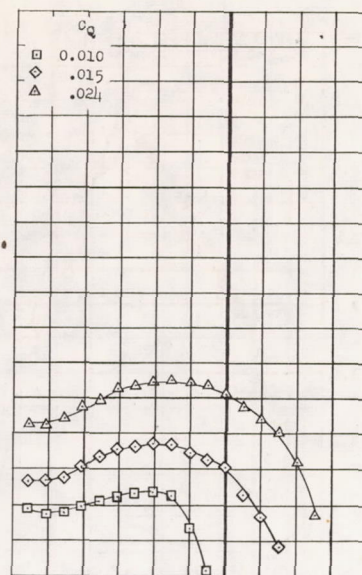
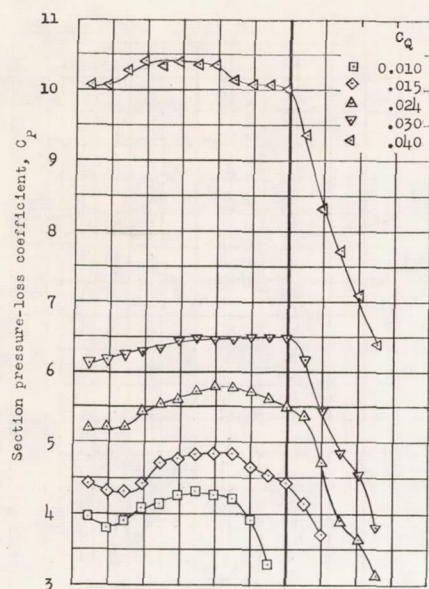
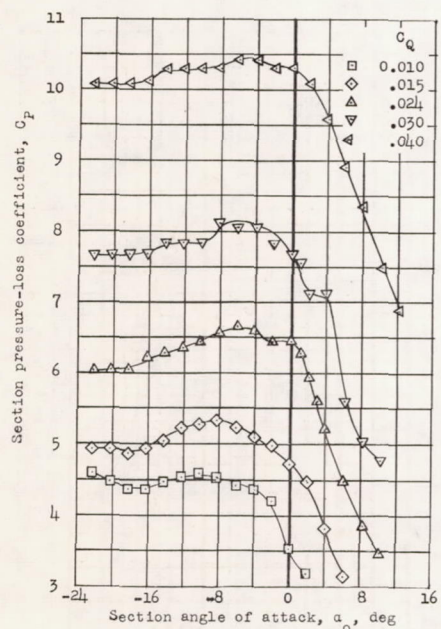
(b) $\delta_f = 55^\circ$.

Figure 8.- Concluded.



Model in smooth condition

 $R = 1.0 \times 10^6$

Model in rough condition

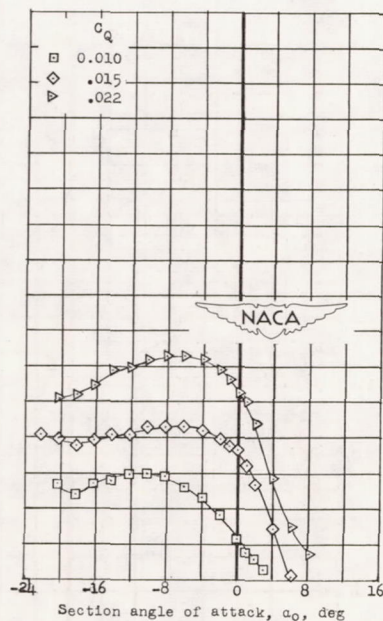
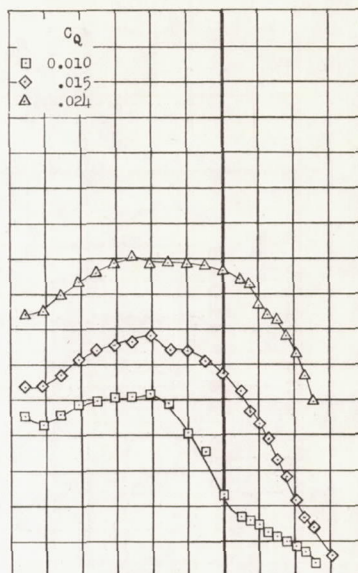
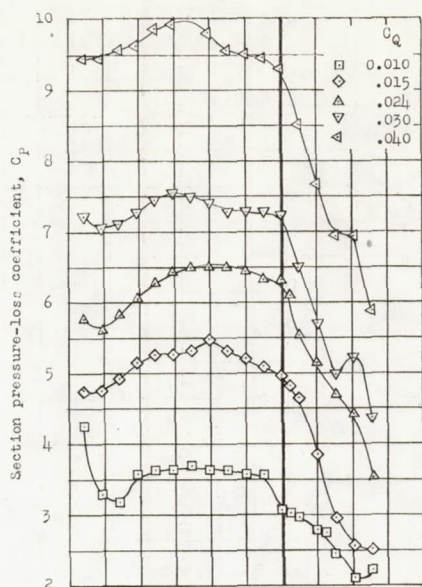
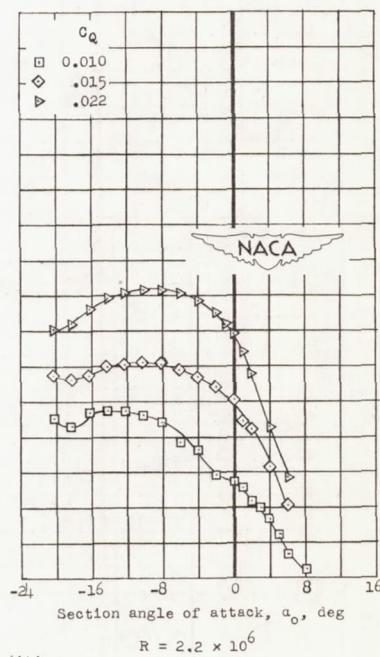
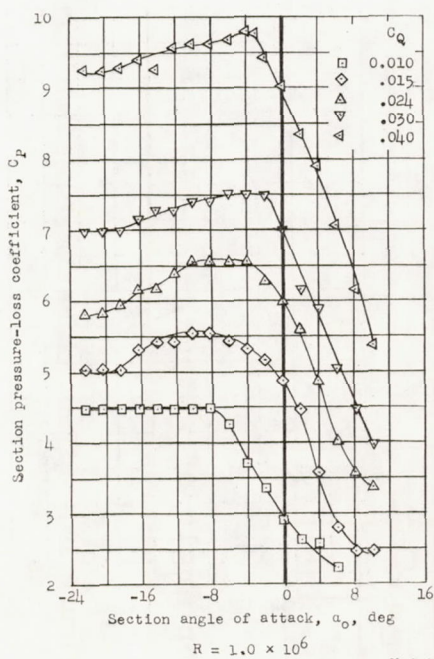
 $R = 2.2 \times 10^6$ (a) $\delta_f = 50^\circ$.

Figure 9.- Variation of pressure-loss coefficient with section angle of attack for the NACA 652-415 airfoil section with two boundary-layer control slots on a plain flap.



Model in smooth condition



Model in rough condition

(b) $\delta_f = 55^\circ$.

Figure 9.- Concluded.

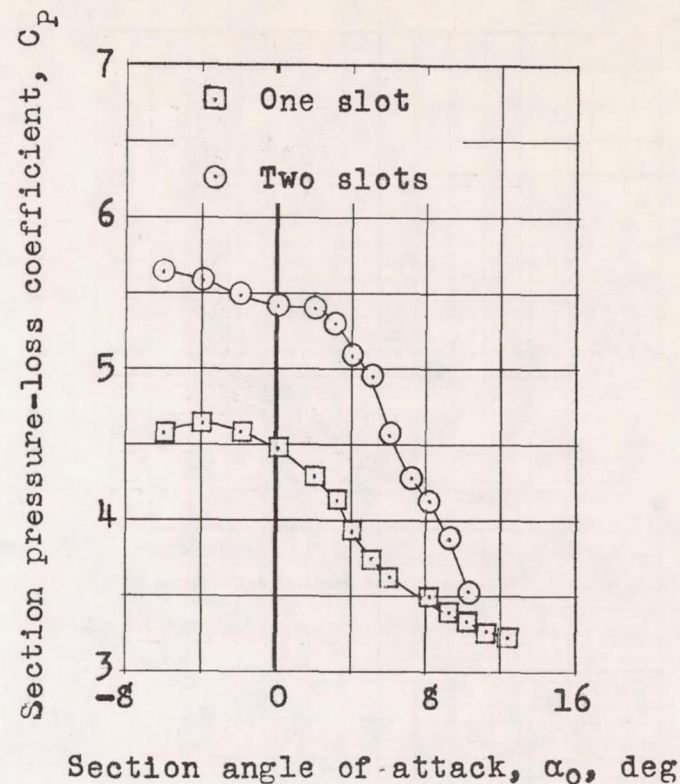
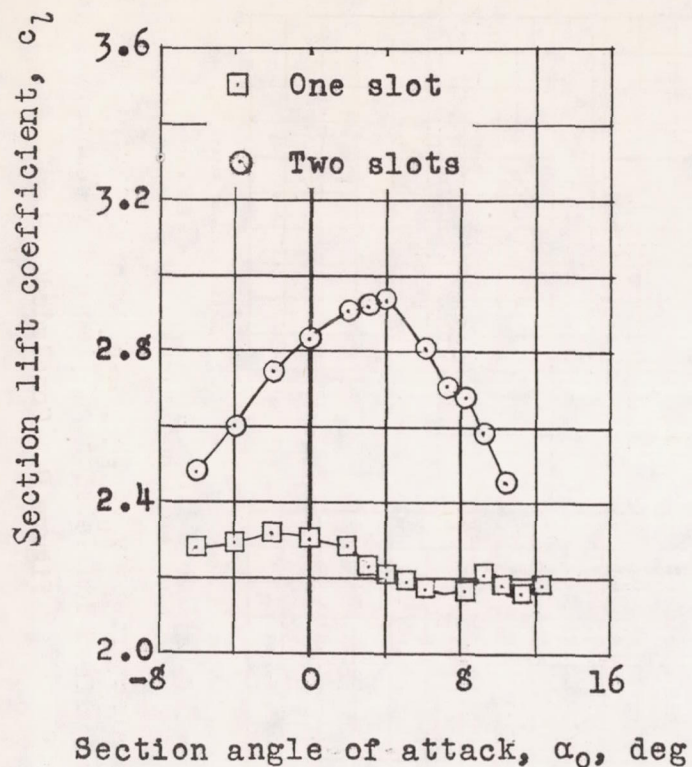
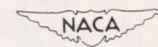
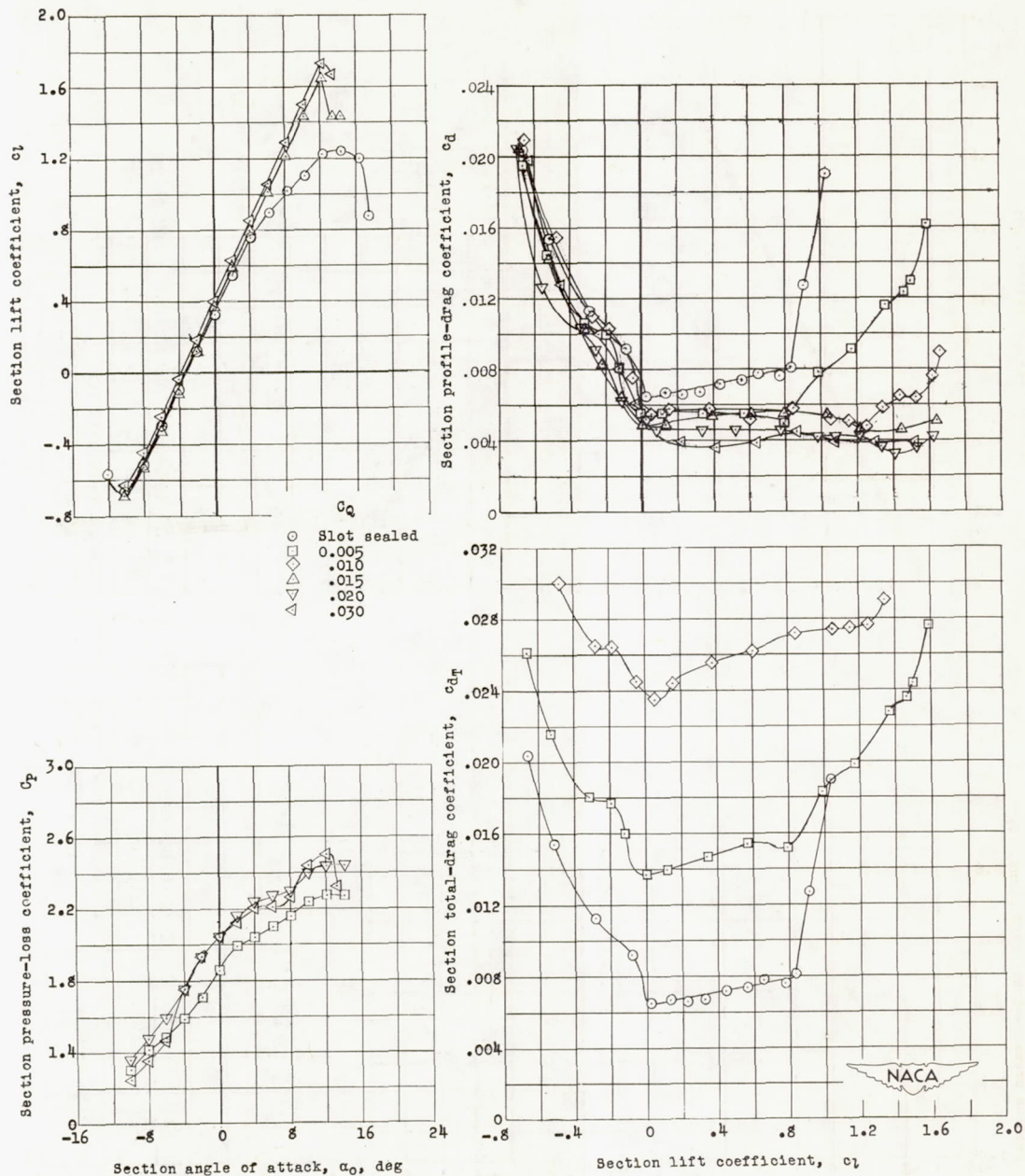


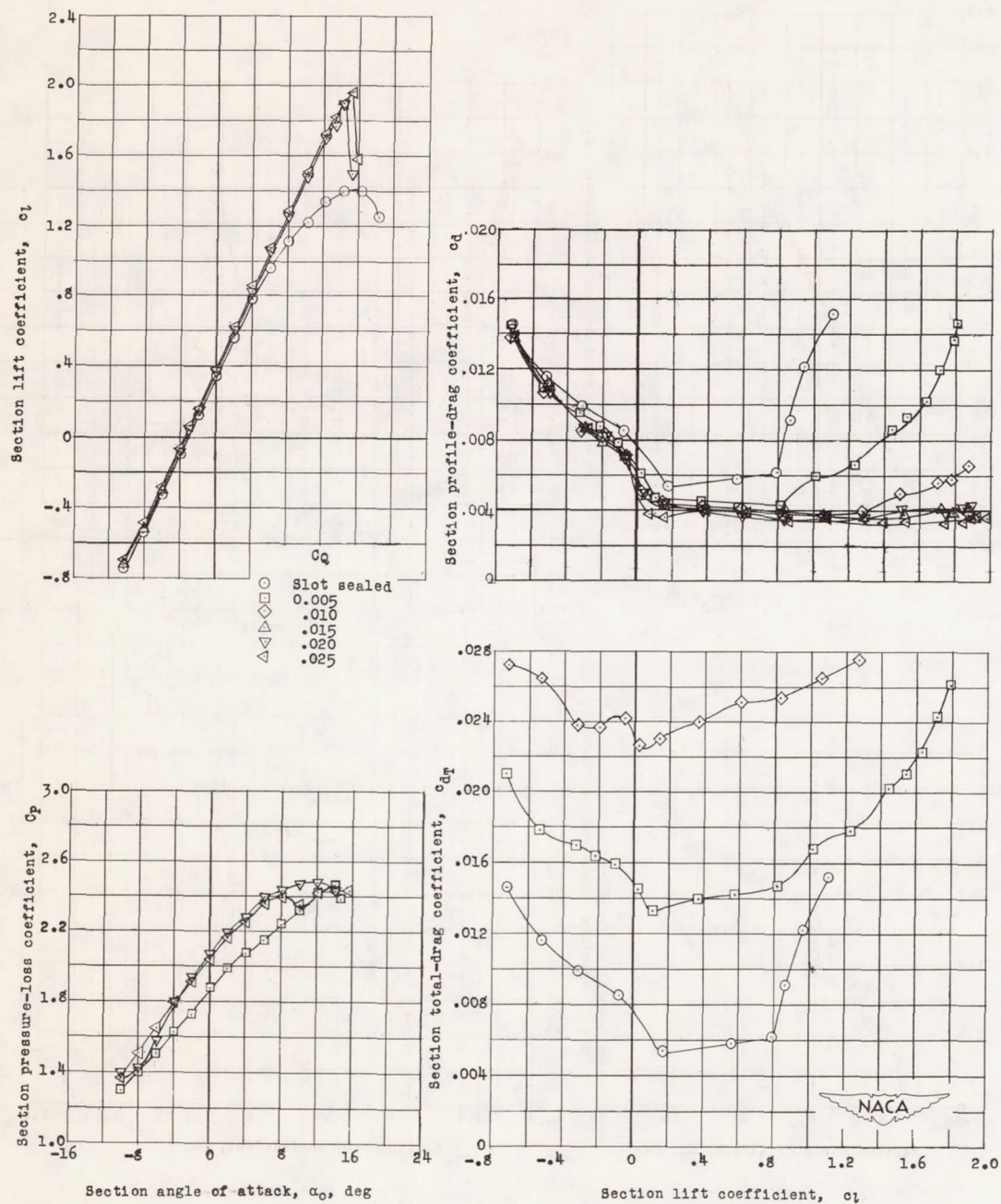
Figure 10.- Effect on maximum section lift coefficient and section pressure-loss coefficient of sealing the rear slot of the NACA 65₂-415 airfoil section in the smooth condition with two boundary-layer control slots on a 0.25c plain flap. $\delta_f = 50^\circ$; $C_Q = 0.020$; $R = 2.2 \times 10^6$.





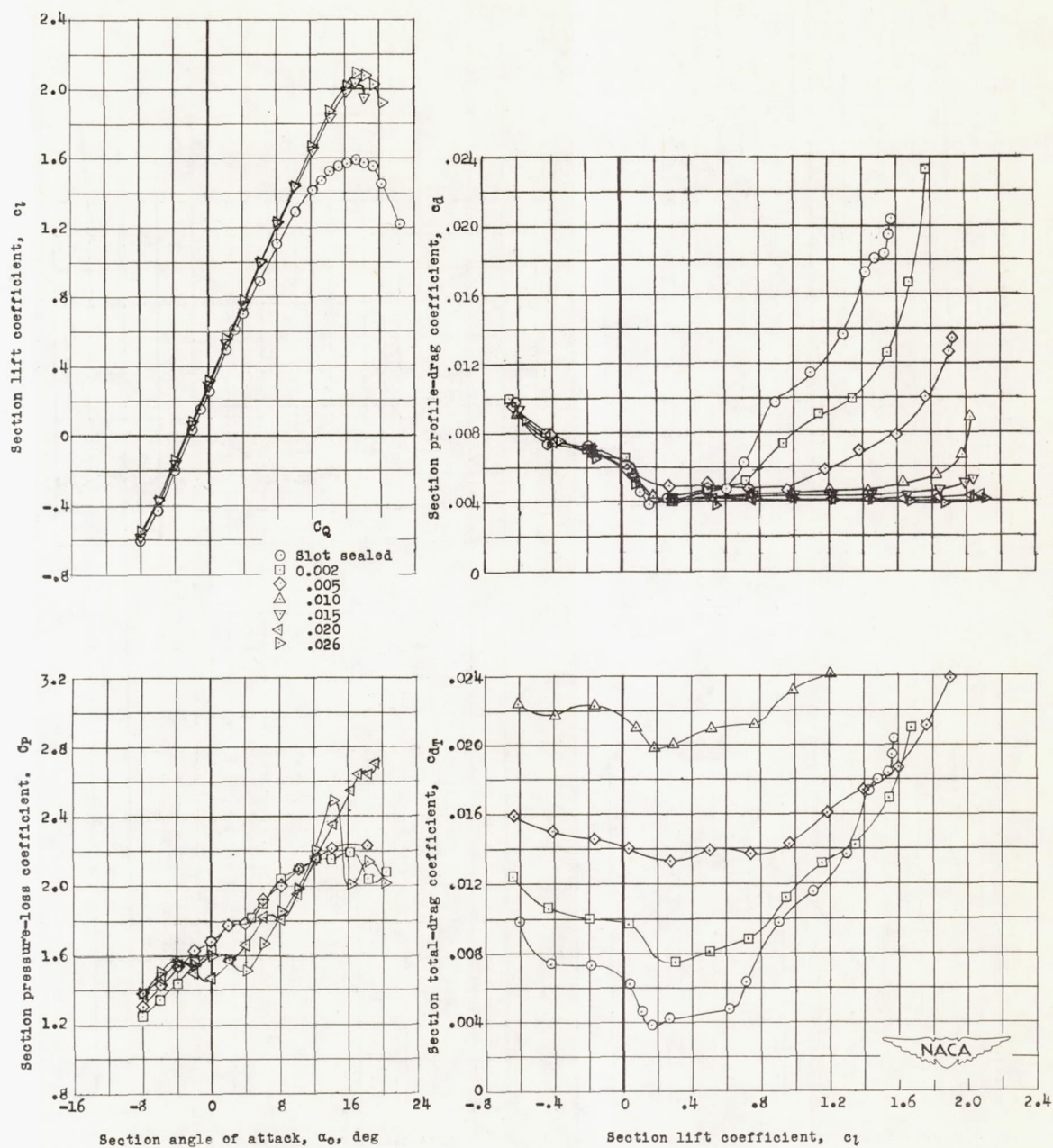
(a) $R = 1.0 \times 10^6$.

Figure 11.- Section characteristics of the NACA 652-415 airfoil section in the smooth condition with a double slotted flap and a boundary-layer control slot at $0.45c$. $\delta f = 0^\circ$.



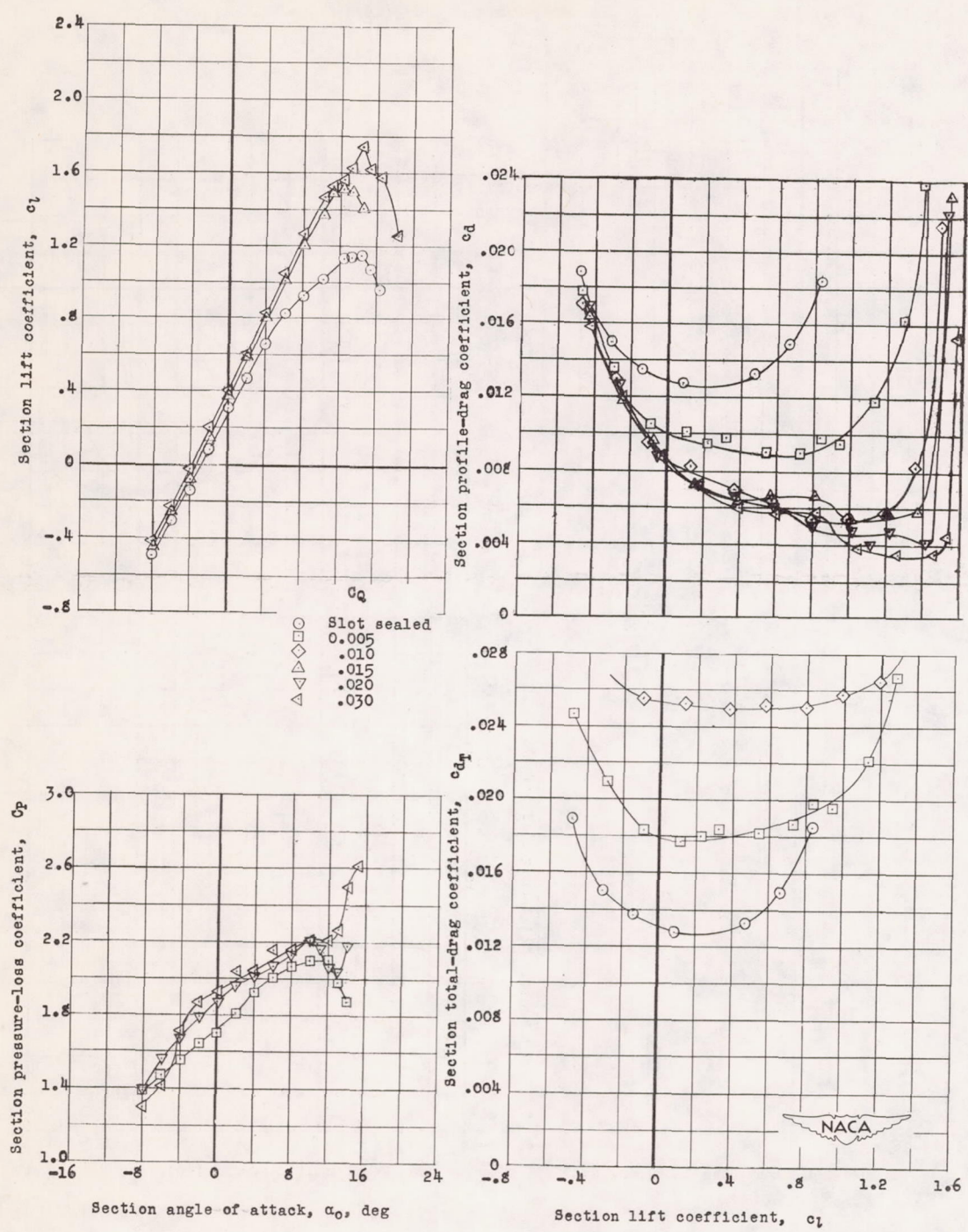
(b) $R = 2.2 \times 10^6$.

Figure 11.- Continued.



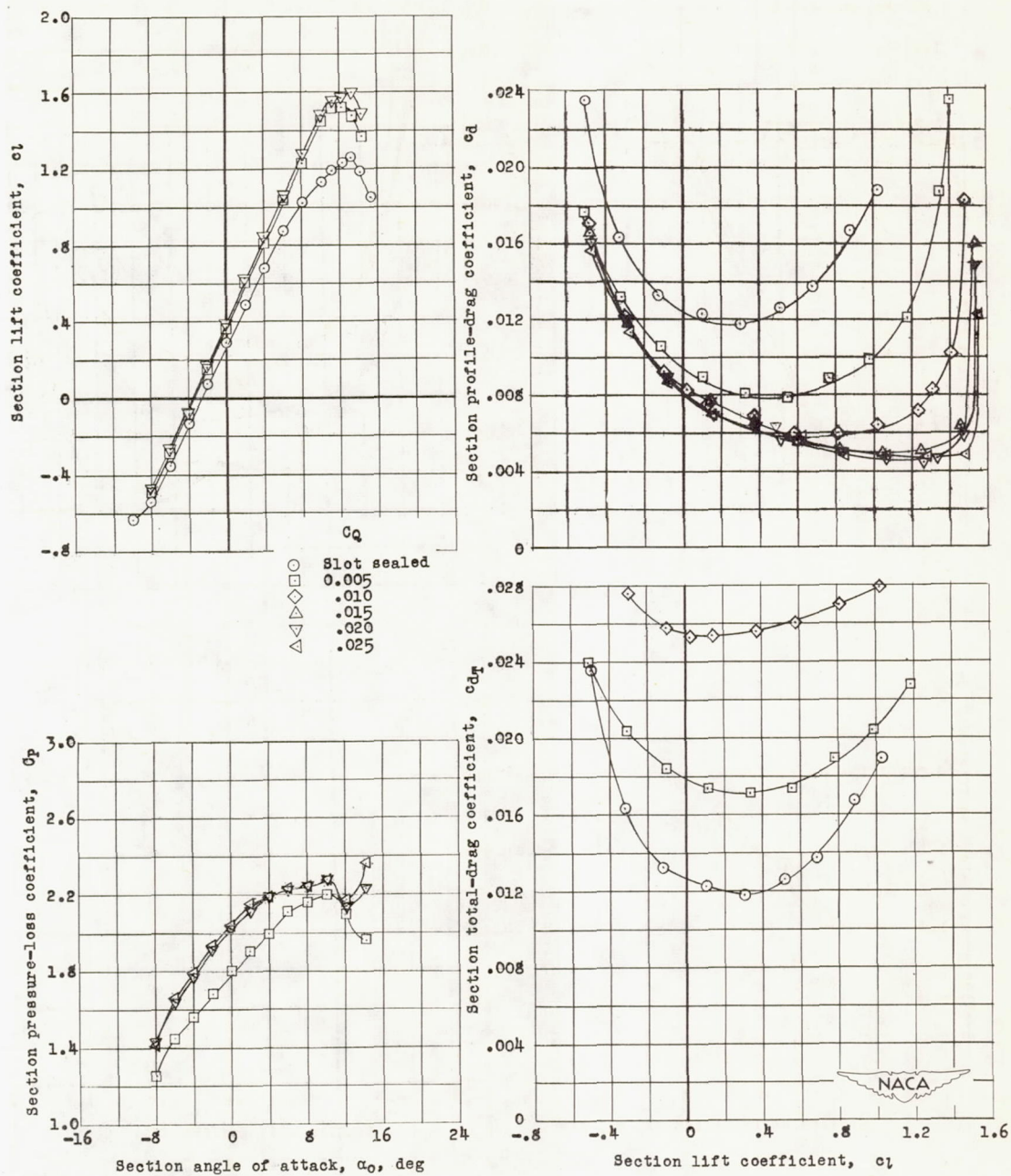
(c) $R = 6.0 \times 10^6$.

Figure 11.- Concluded.



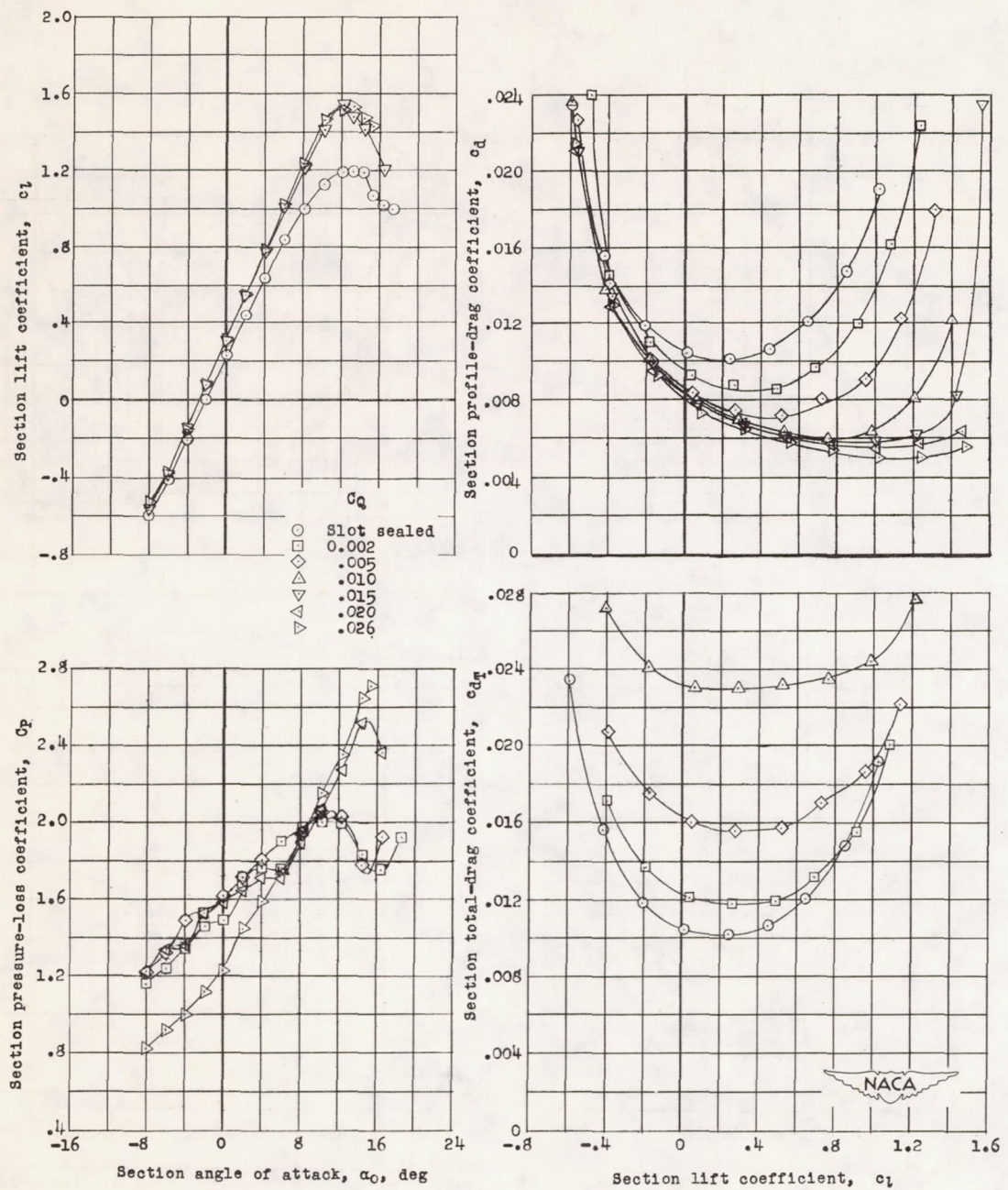
(a) $R = 1.0 \times 10^6$.

Figure 12.- Section characteristics of the NACA 65₂-415 airfoil section in the rough condition with a double slotted flap and a boundary-layer control slot at 0.45c. $\delta_f = 0^\circ$.



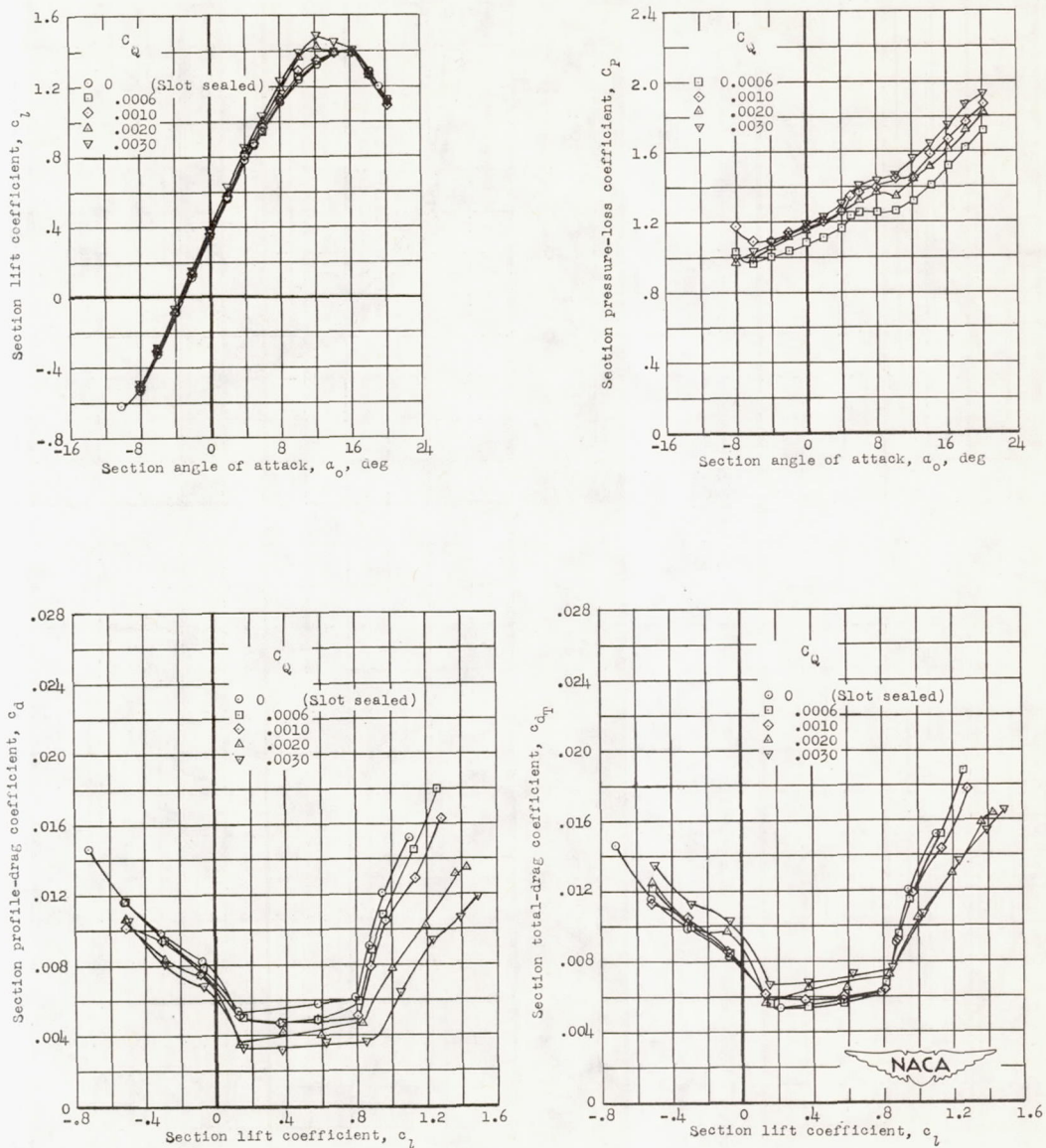
(b) $R = 2.2 \times 10^6$.

Figure 12.- Continued.



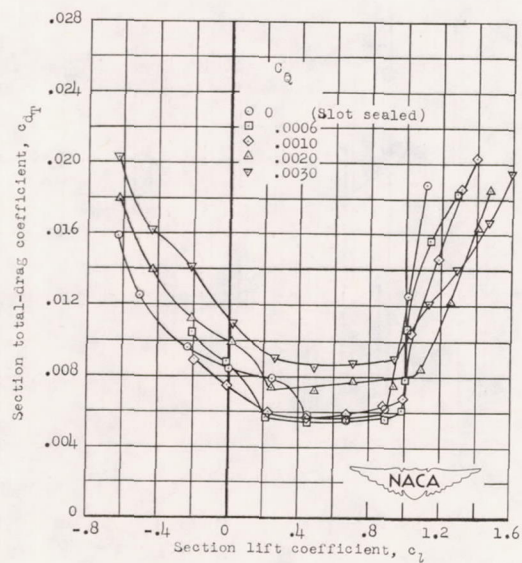
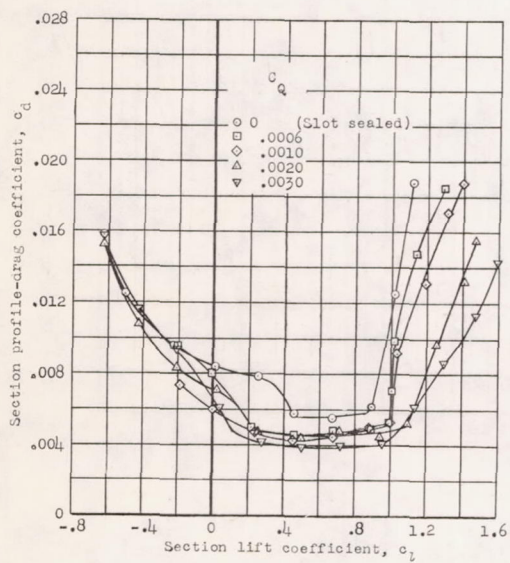
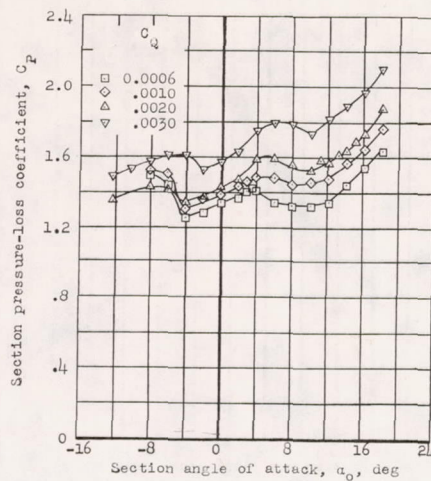
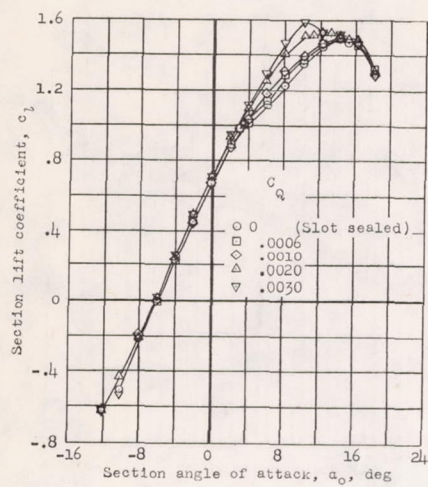
(c) $R = 6.0 \times 10^6$.

Figure 12.- Concluded.



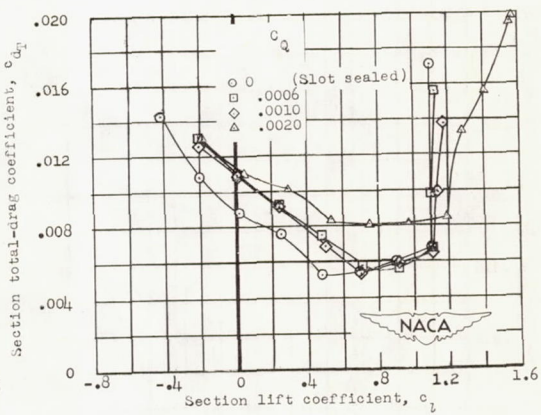
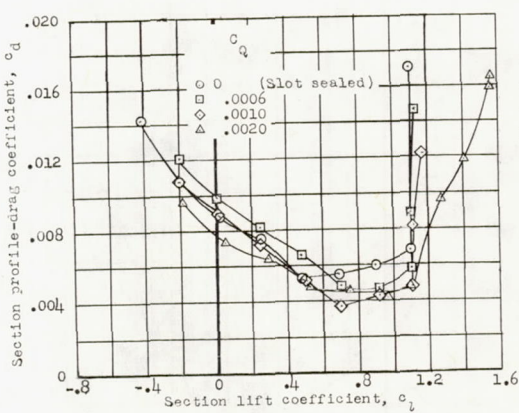
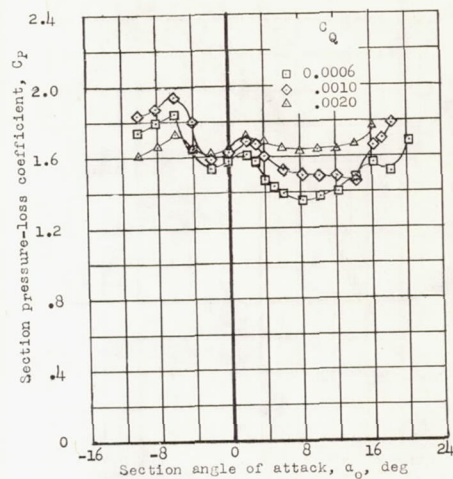
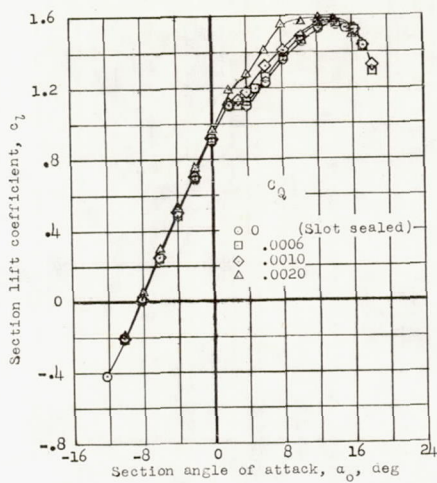
(a) $\delta_F = 0^\circ$.

Figure 13.- Section characteristics of the NACA 652-415 airfoil section in the smooth condition with a 0.25c plain flap and a boundary-layer control slot at 0.76c. $R = 2.2 \times 10^6$.



(b) $\delta_F = 5^\circ$.

Figure 13.- Continued.



(c) $\delta_f = 10^\circ$.

Figure 13.- Continued.

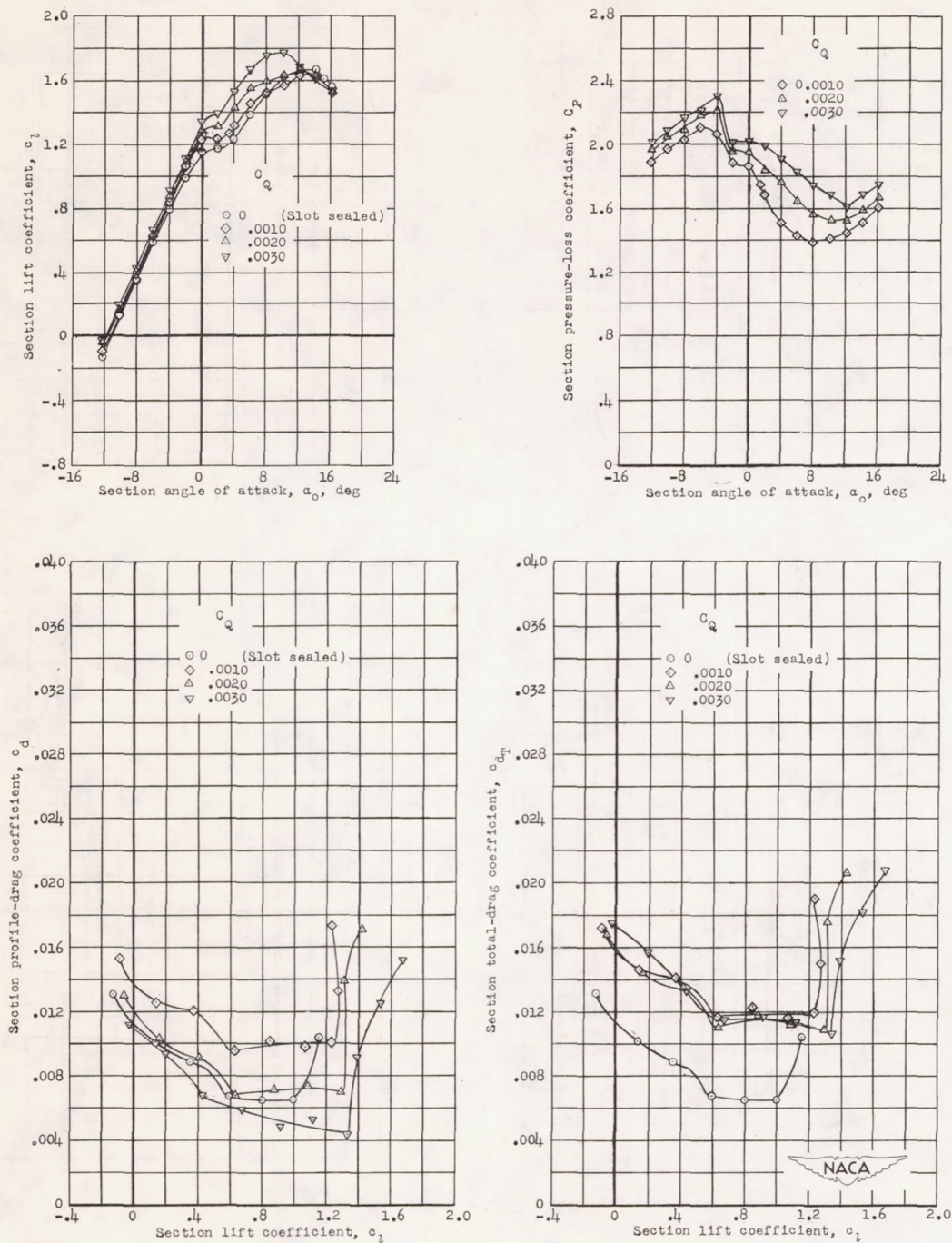
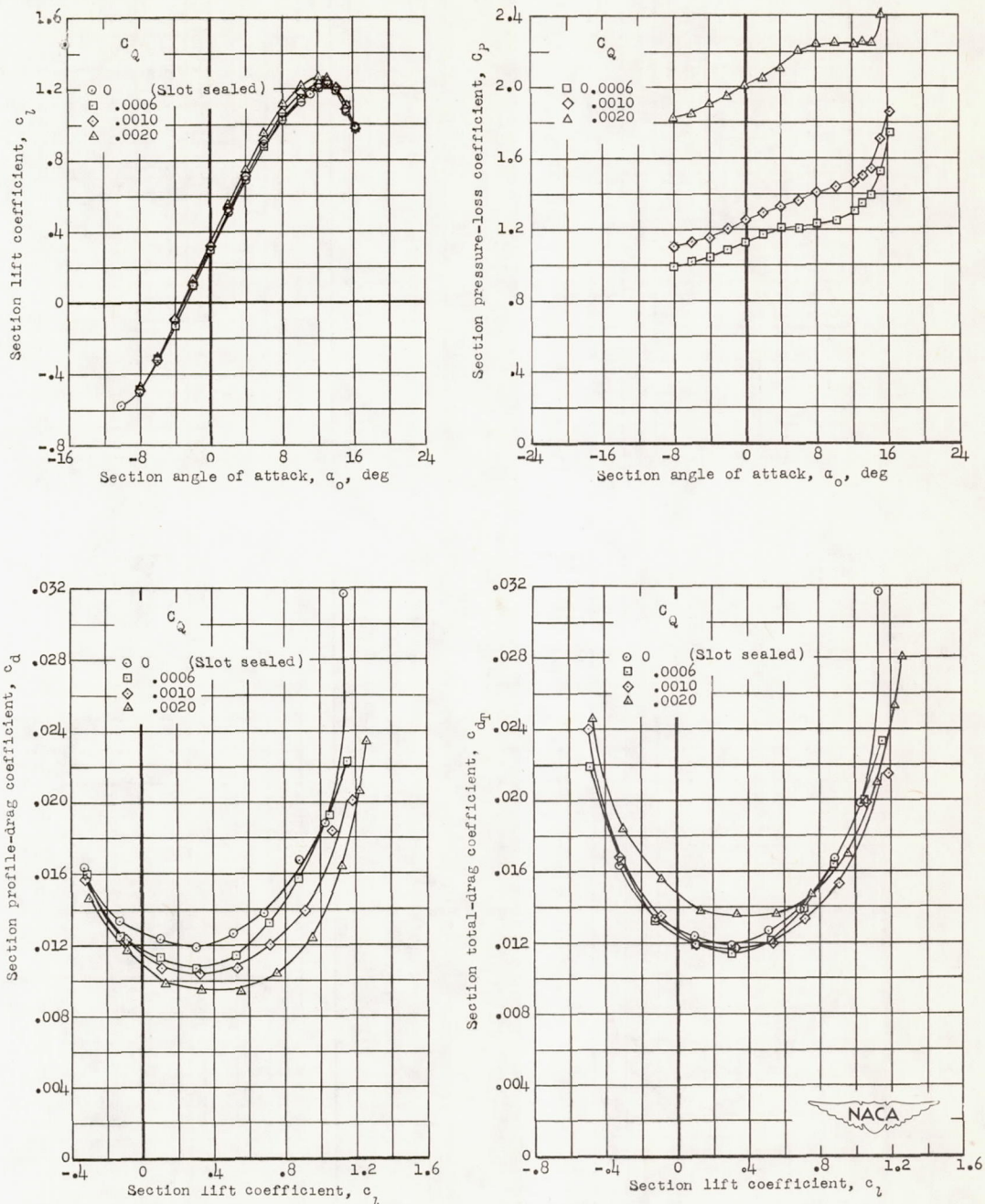
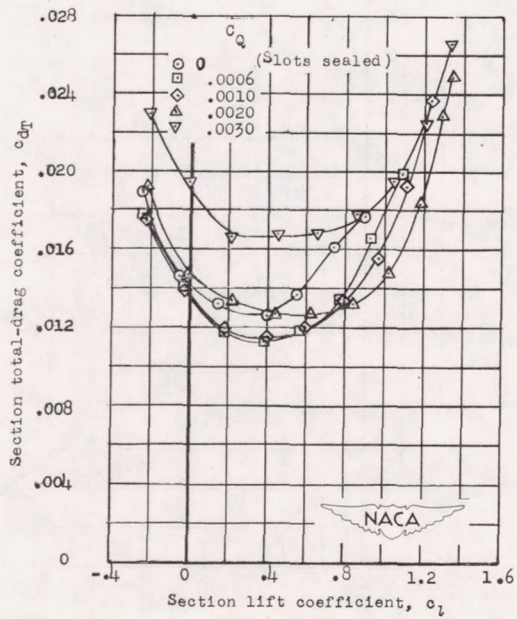
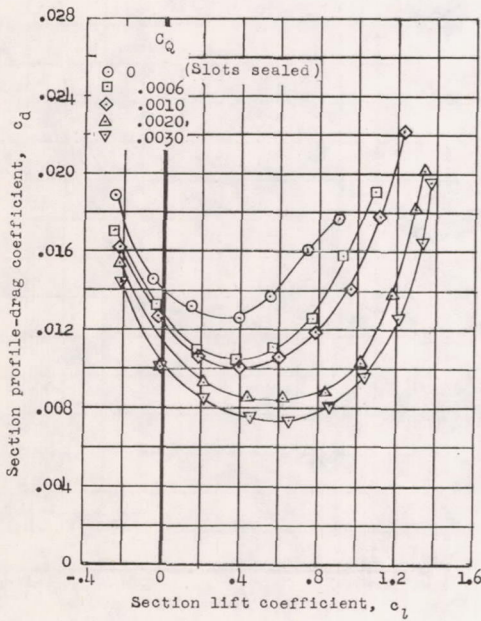
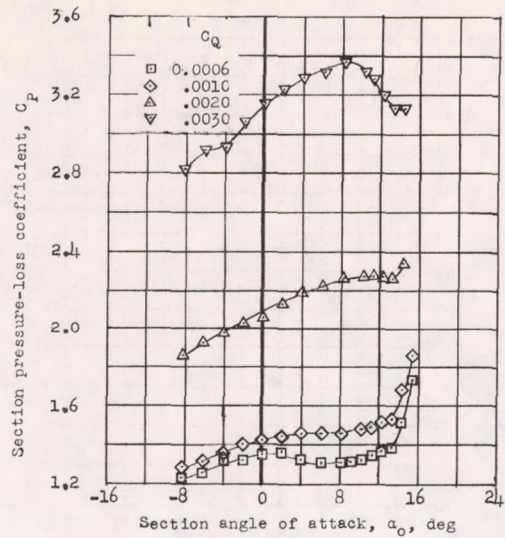
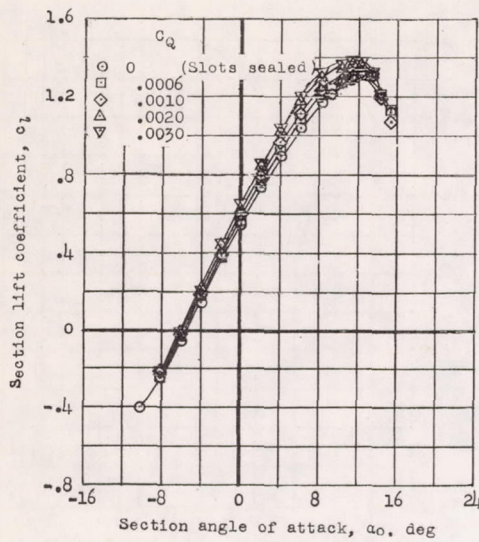
(d) $\delta_F = 15^\circ$.

Figure 13.- Concluded.



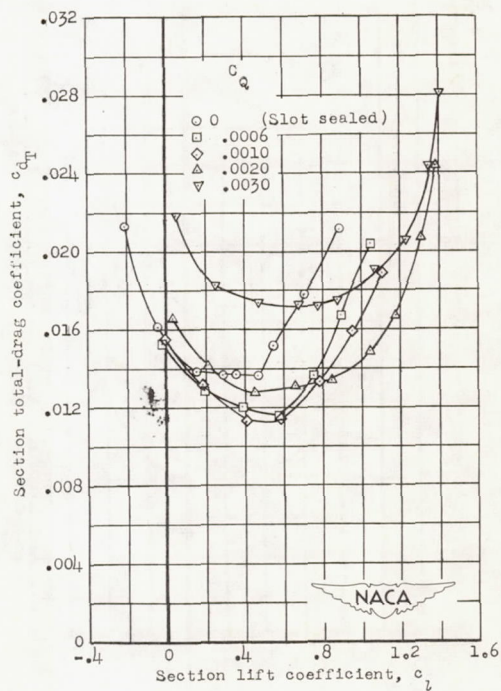
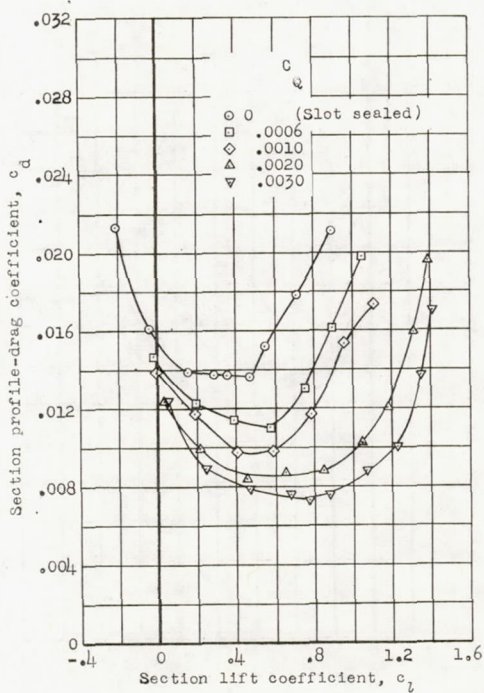
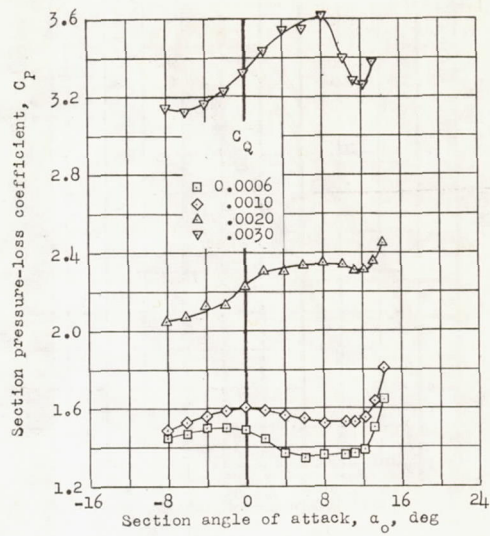
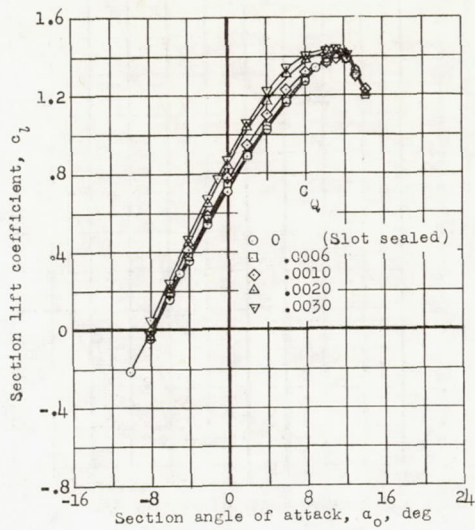
(a) $\delta_f = 0^\circ$.

Figure 14.- Section characteristics of the NACA 652-415 airfoil section in the rough condition with a 0.25c plain flap and a boundary-layer control slot at 0.76c. $R = 2.2 \times 10^6$.



(b) $\delta_f = 5^\circ$.

Figure 14.- Continued.



(c) $\delta_f = 10^\circ$.

Figure 14.- Continued.

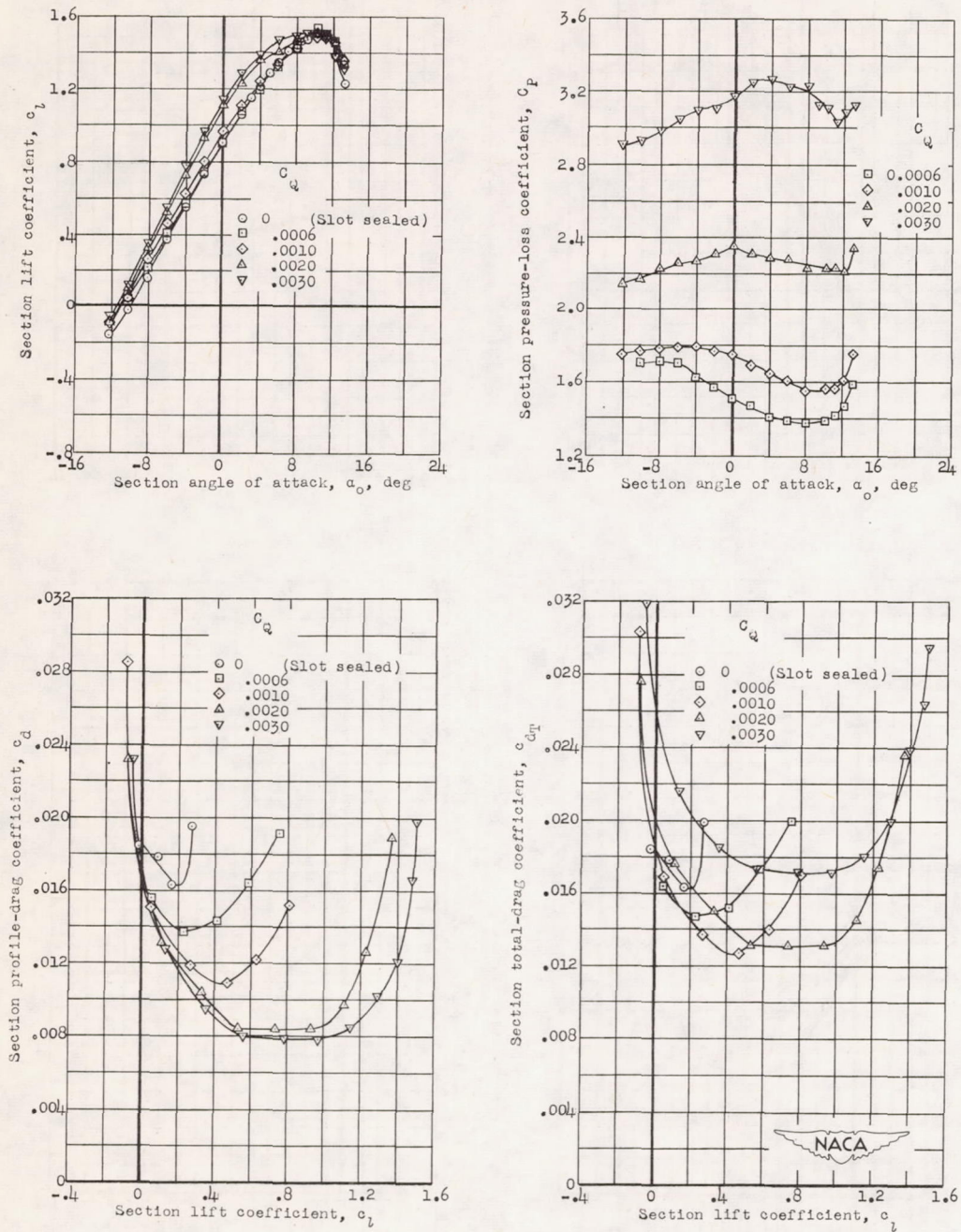
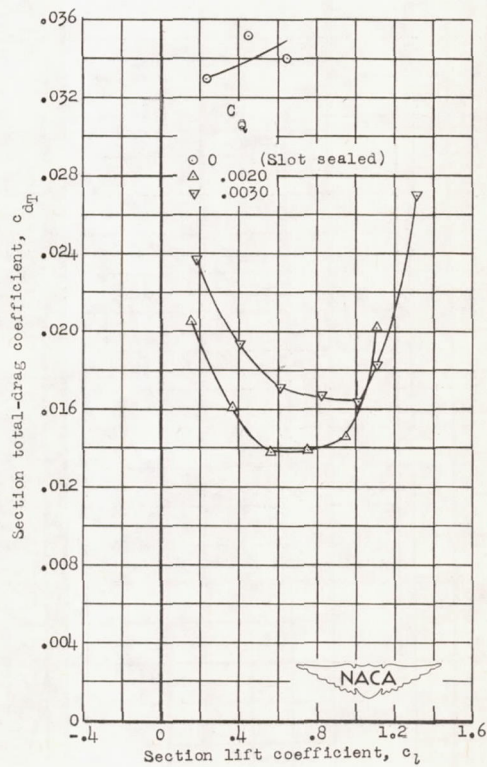
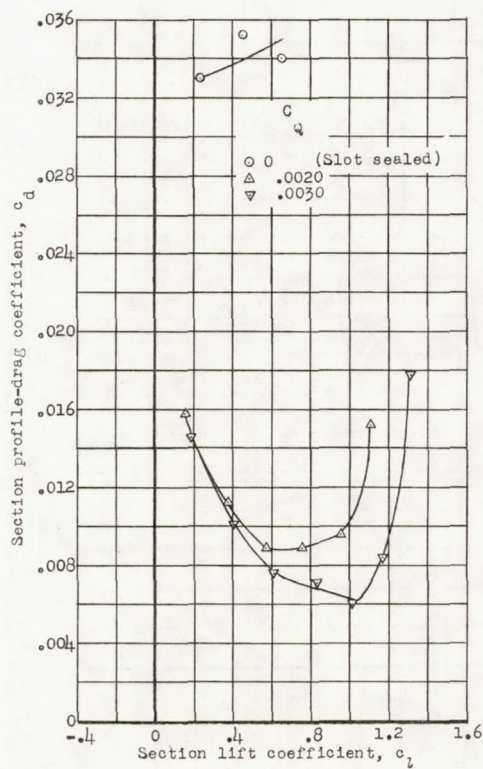
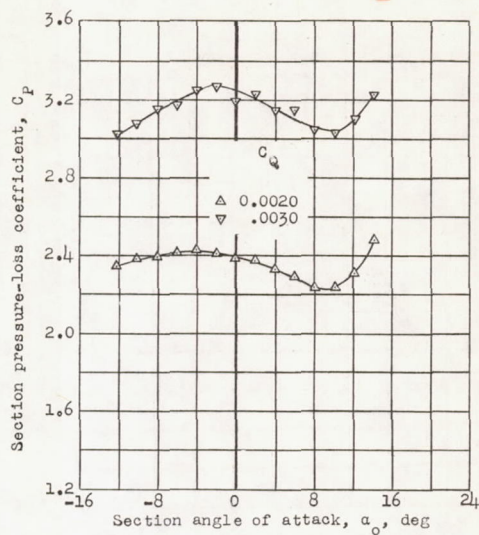
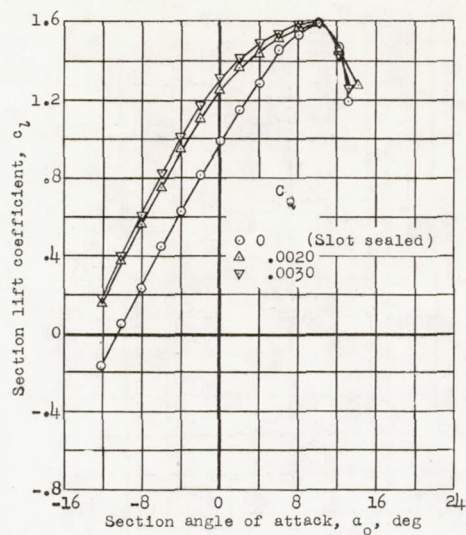
(d) $\delta_f = 15^\circ$.

Figure 14.- Continued.



(e) $\delta_f = 20^\circ$.

Figure 14.- Concluded.

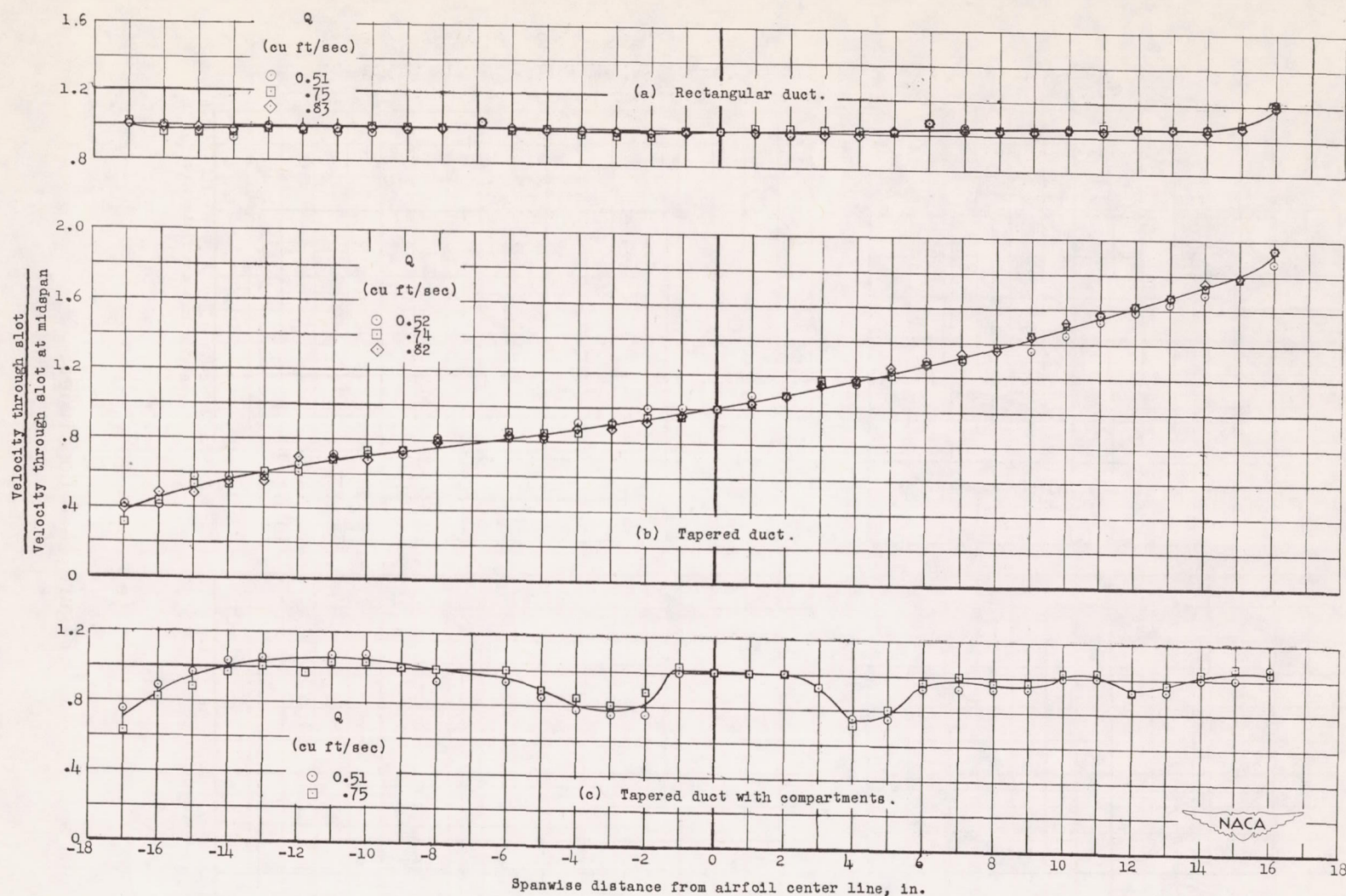
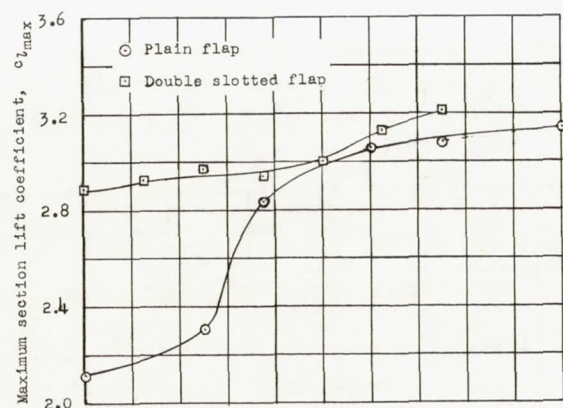
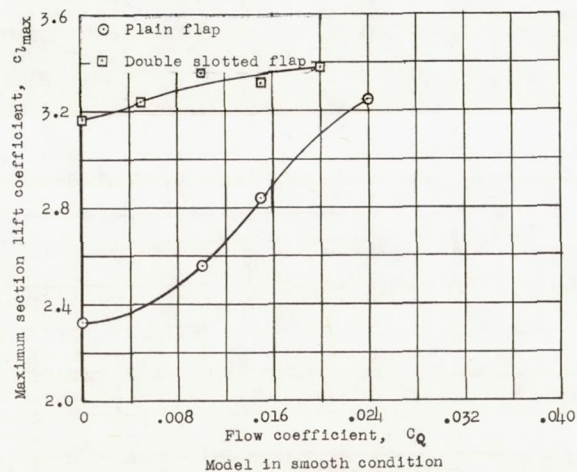
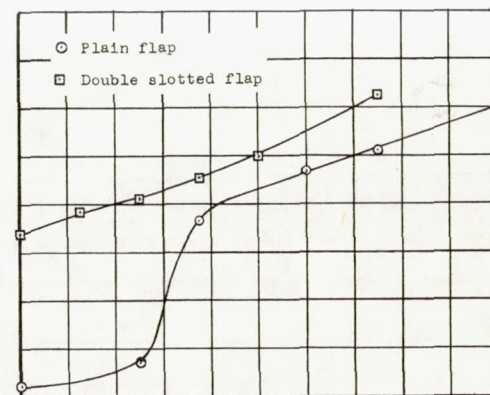


Figure 15.- Spanwise distribution of flow along a rectangular slot connected to three different types of ducts.



$R = 1.0 \times 10^6$



$R = 2.2 \times 10^6$

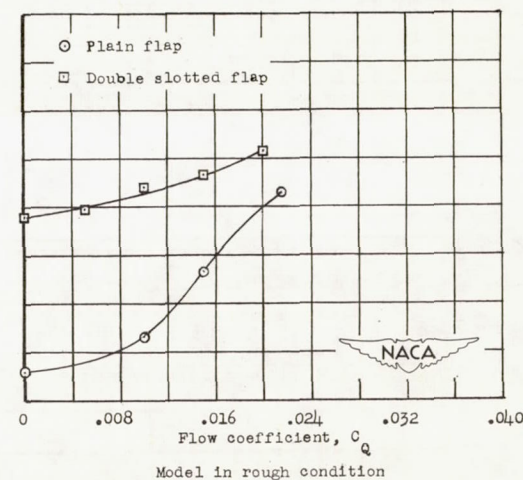


Figure 16.- Variation of maximum section lift coefficient with flow coefficient for the NACA 65₂-415 airfoil section with boundary-layer control. $\delta_f = 55^\circ$.

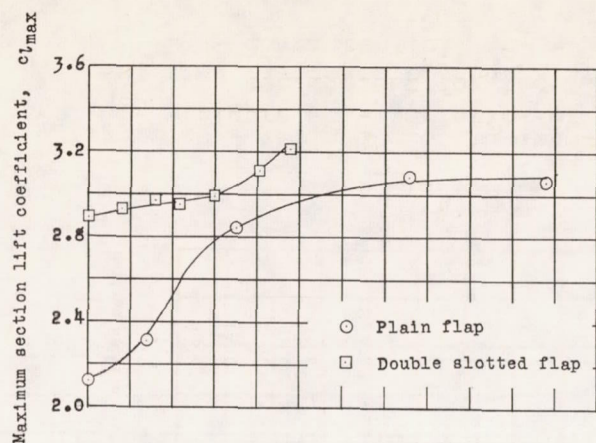
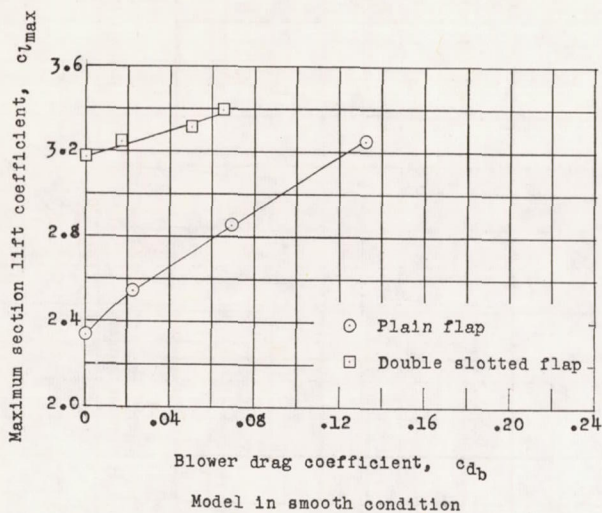
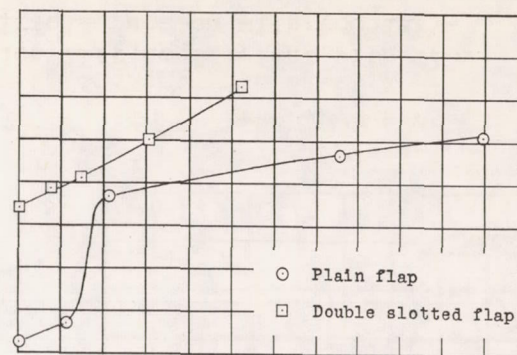
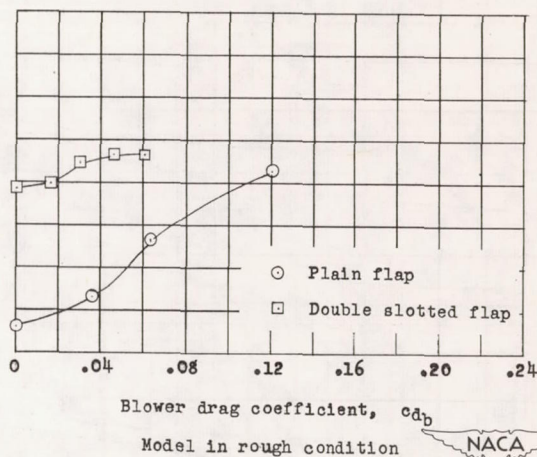
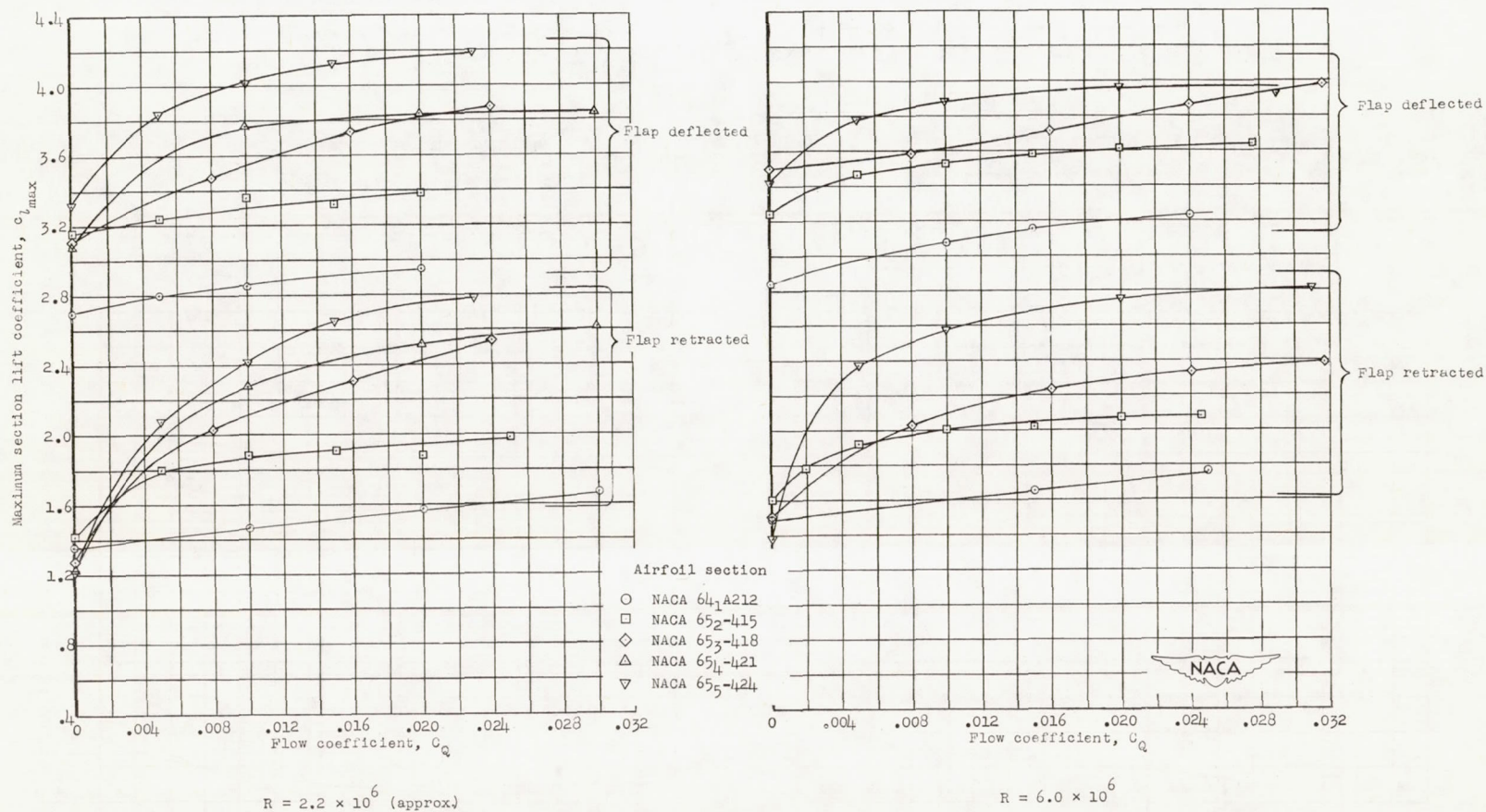
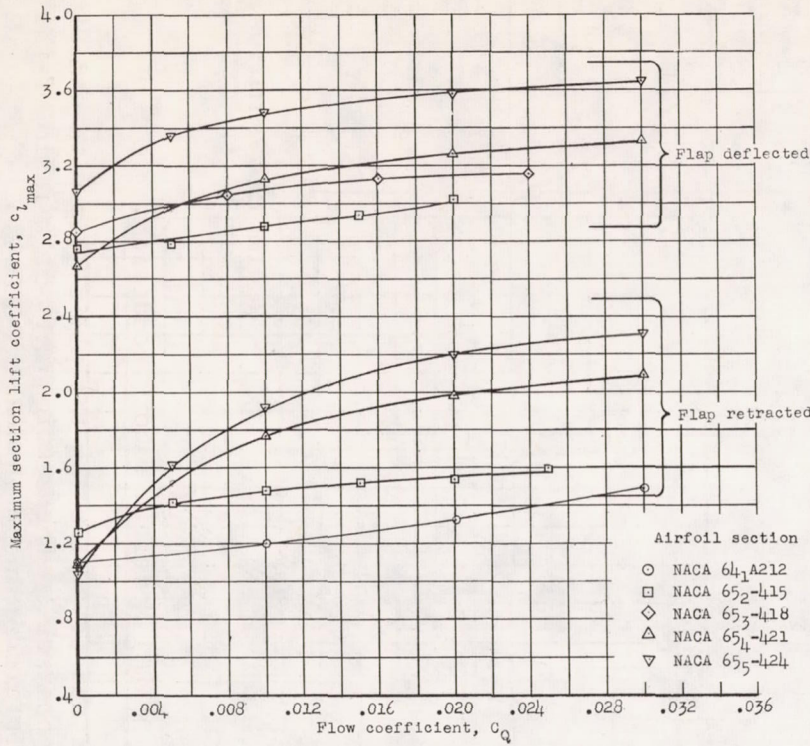
 $R = 1.0 \times 10^6$  $R = 2.2 \times 10^6$ 

Figure 17.- Variation of maximum section lift coefficient with blower drag coefficient for the NACA 65₂-415 airfoil section with boundary-layer control. $\delta_f = 55^\circ$.

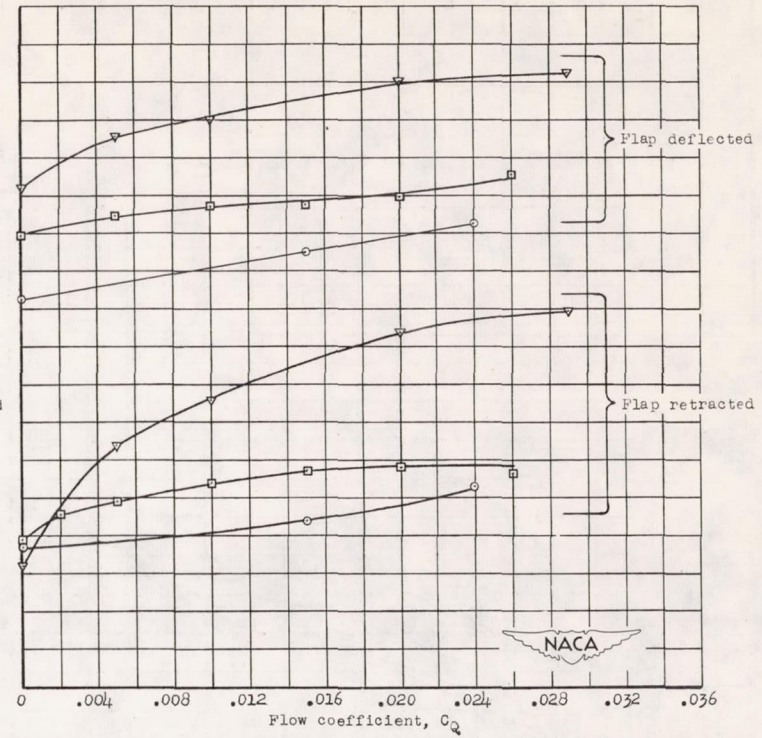


(a) Model in smooth condition.

Figure 18.- Variation of maximum section lift coefficient with flow coefficient for several NACA 6-series airfoil sections with double slotted flaps and boundary-layer control slots at approximately 0.45c.



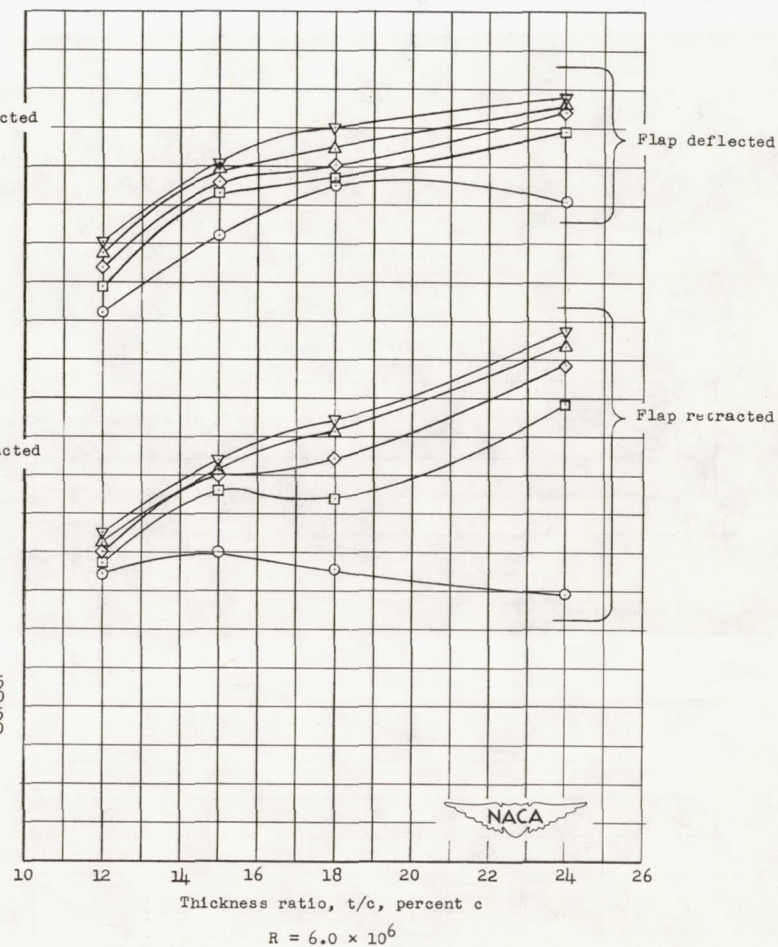
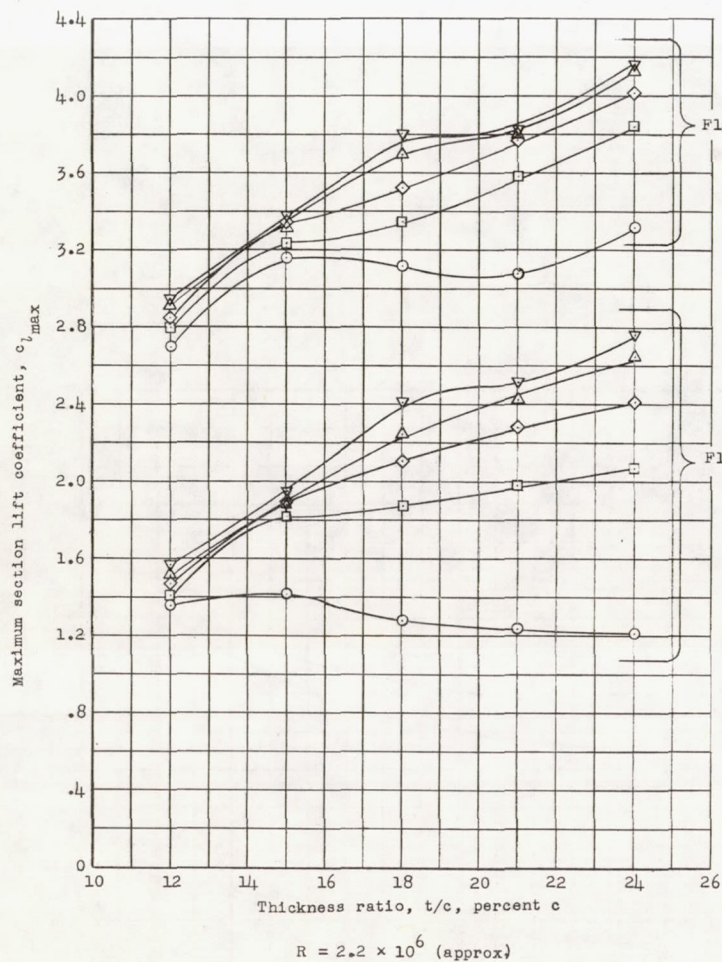
$R = 2.2 \times 10^6$ (approx.)



$R = 6.0 \times 10^6$

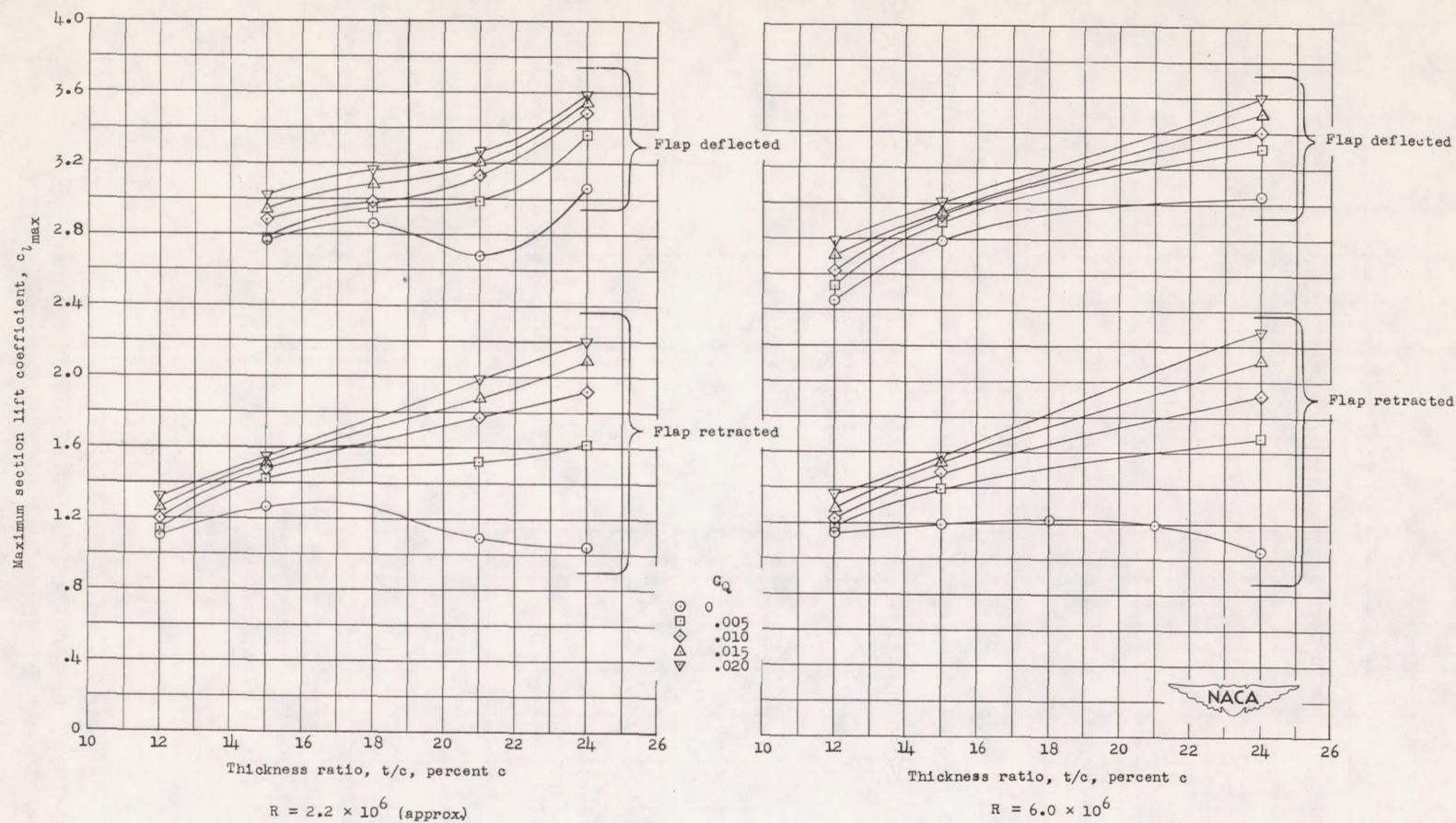
(b) Model in rough condition.

Figure 18.- Concluded.



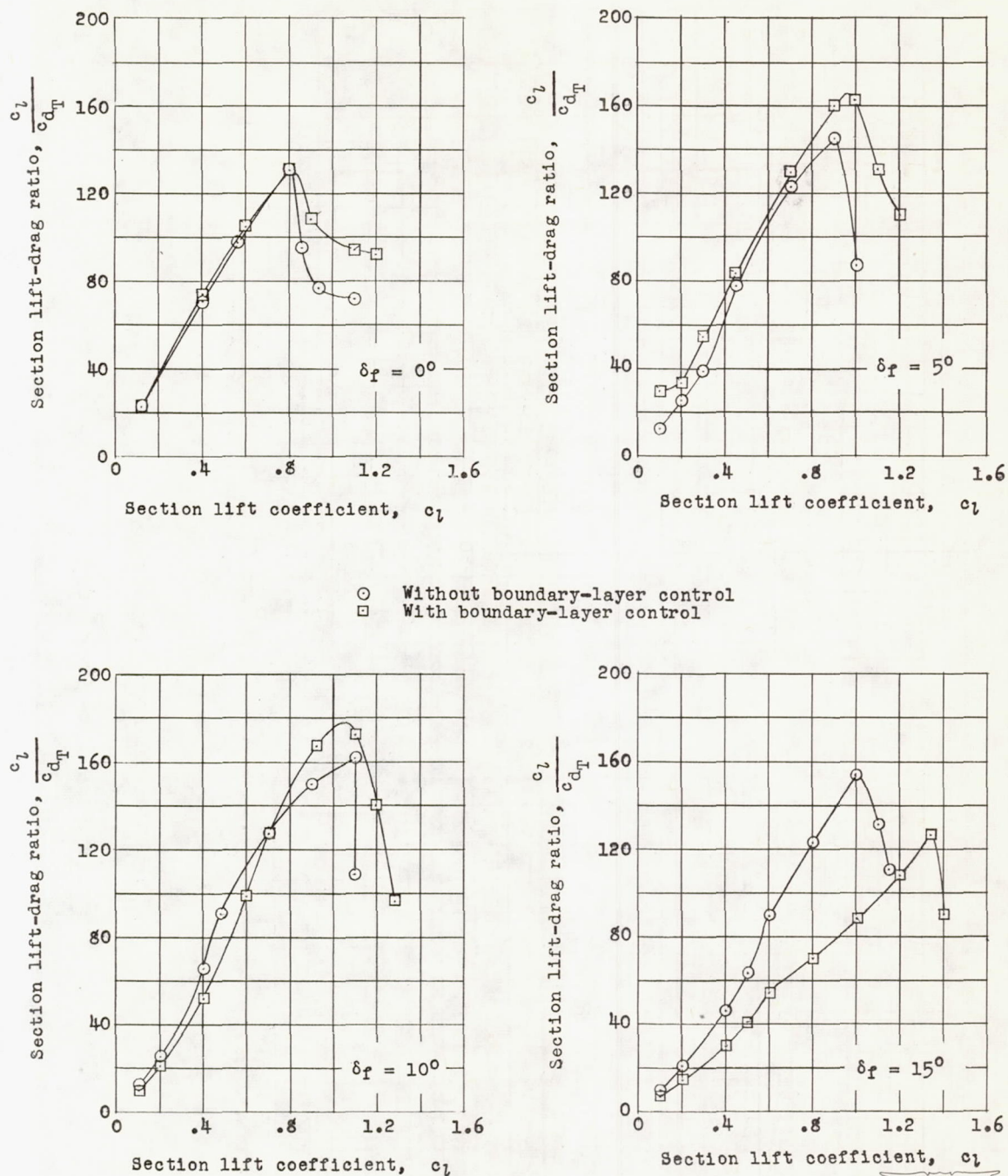
(a) Model in smooth condition.

Figure 19.- Variation of maximum section lift coefficient with airfoil thickness for NACA 6-series airfoil sections with double slotted flaps and boundary-layer control slots at approximately $0.45c$.



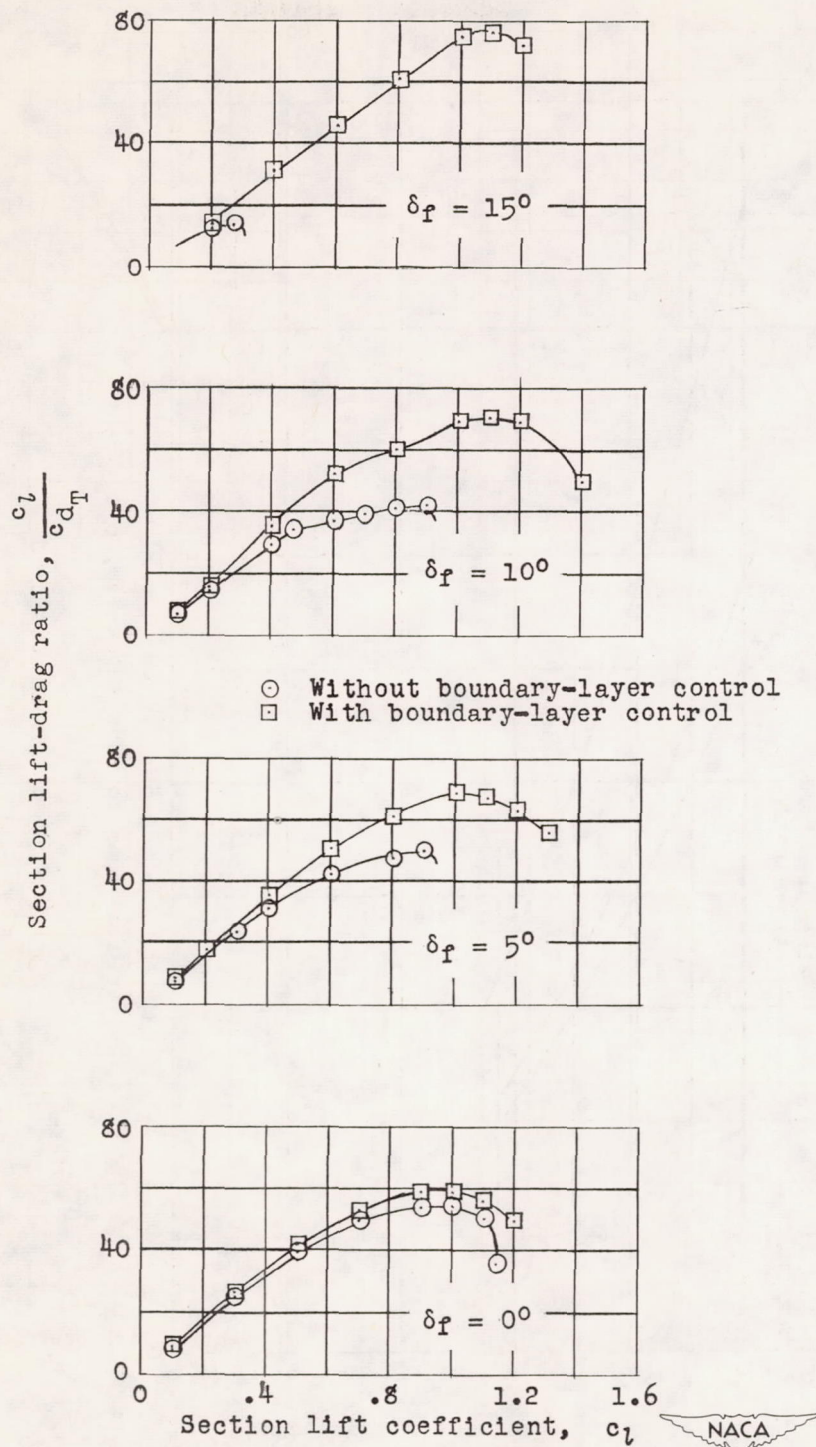
(b) Model in rough condition.

Figure 19.- Concluded.



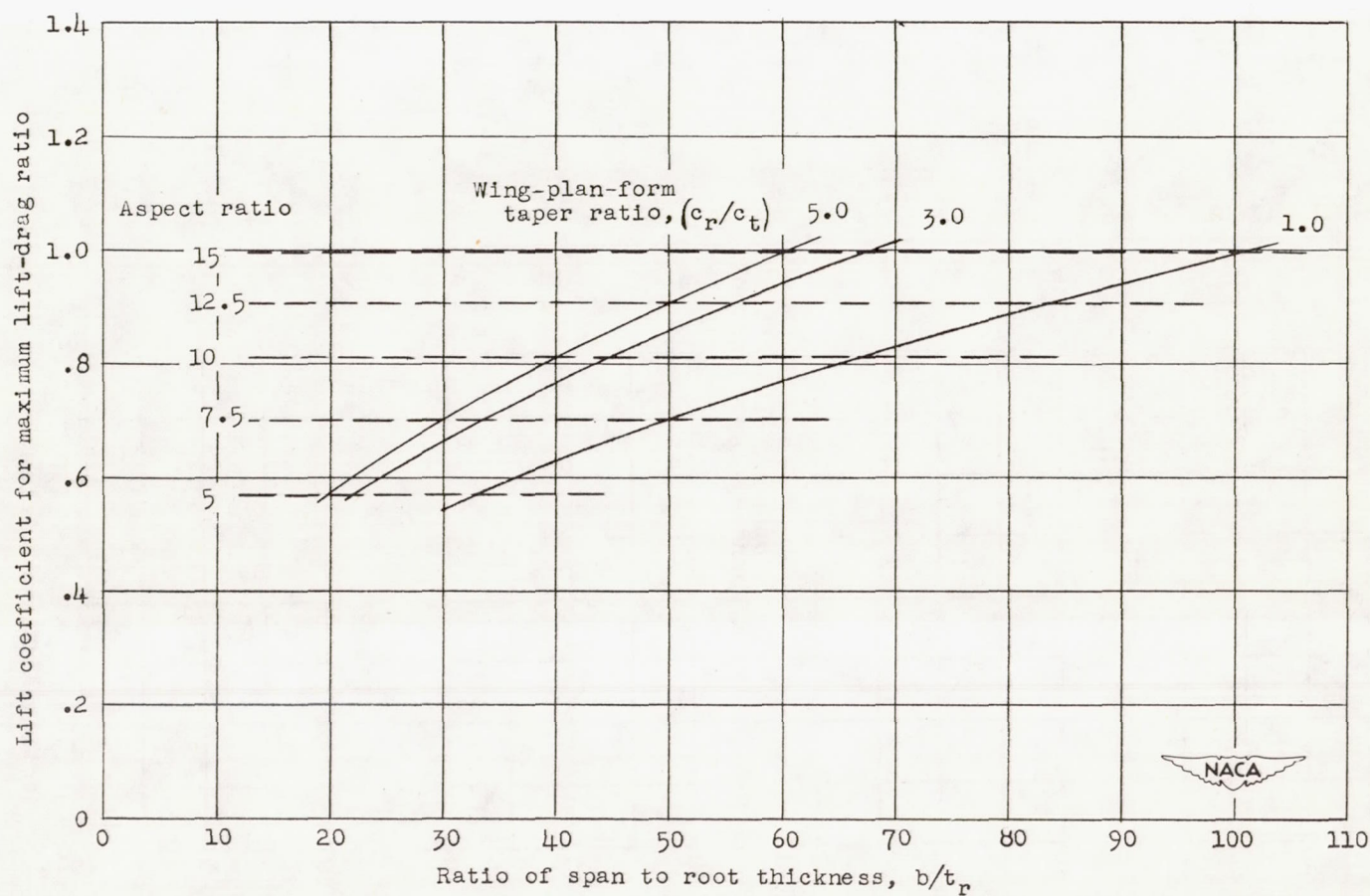
(a) Model in smooth condition.

Figure 20.- The effect of deflecting the plain flap with and without boundary-layer control on the section lift-drag ratio of the NACA 65₂-415 airfoil section. $R = 2.2 \times 10^6$.



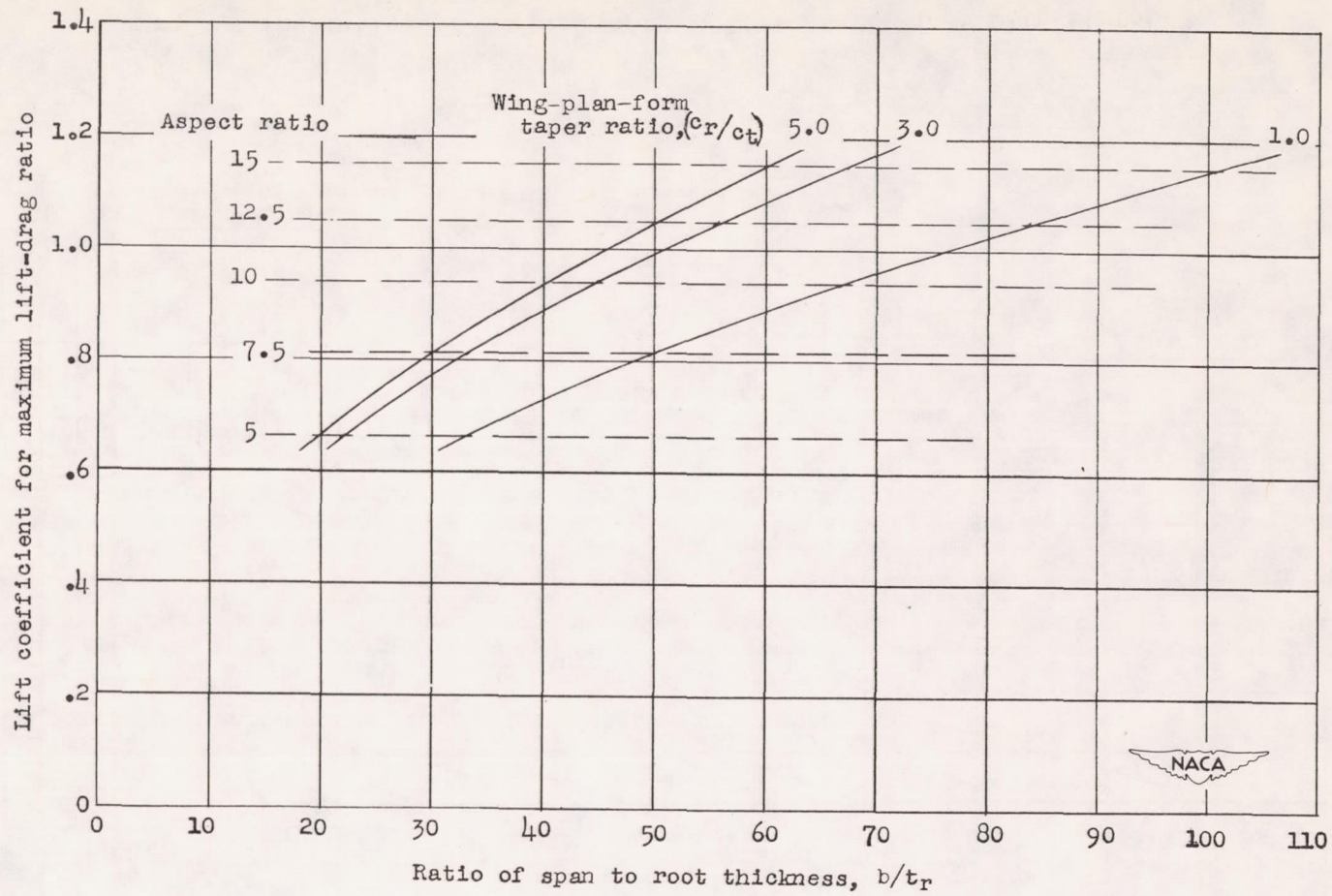
(b) Model in rough condition.

Figure 20.- Concluded.



(a) Smooth condition.

Figure 21.- Lift coefficient for maximum lift-drag ratio as a function of ratio of span to root thickness for various taper ratios and aspect ratios of a 15-percent-thick wing.



(b) Rough condition.

Figure 21.- Concluded.