ADVANCE COPY

NACA

RESEARCH MEMORANDUM

TWO-DIMENSIONAL WIND-TUNNEL INVESTIGATION OF MODIFIED NACA $65_{(112)}$-111 AIRFOIL WITH 35-PERCENT-CHORD SLOTTED FLAP AT REYNOLDS NUMBERS UP TO 25 MILLION

By

Stanley F. Racisz

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

TWO-DIMENSIONAL WIND-TUNNEL INVESTIGATION OF MODIFIED NACA $65_{(112)}$-111 AIRFOIL WITH 35-PERCENT-CHORD SLOTTED FLAP AT REYNOLDS NUMBERS UP TO 25 MILLION

By Stanley F. Racisz

SUMMARY

An investigation has been made in the Langley two-dimensional low-turbulence tunnels to develop the optimum configuration of a 0.35-chord slotted flap on an NACA $65_{(112)}$-111 airfoil section modified by removing the trailing-edge cusp. Included in the investigation were measurements to determine the scale effects on the section lift and drag characteristics of the airfoil with the flap retracted for Reynolds numbers ranging from 3.0×10^6 to 25.0×10^6. The scale effects on the lift characteristics were also determined for the same range of Reynolds numbers for the flap deflected in the position found to be the optimum at a Reynolds number of 9.0×10^6.

The optimum flap configuration at high Reynolds numbers was found to be a flap deflection of 35° with the flap located 1.98-percent chord behind and 3.21-percent chord below the slot lip. The flap deflection was lower and the flap was located rearward and upward from the position found to be the optimum at a Reynolds number of 2.4×10^6. Shifts in the linear portion of the lift curve caused by variation of Reynolds number, which occurred only for the condition with the flap deflected, were either eliminated or reduced considerably by altering the flap position. The maximum section lift coefficient of the airfoil with the flap deflected in the position found to be the optimum at a Reynolds number of 9.0×10^6 increased from 2.15 to 2.71 as the Reynolds number increased from 2.4×10^6 to 12 or 13.0×10^6 and then decreased to 2.62 as the Reynolds number was increased up to 25.0×10^6. The maximum section lift coefficient of the airfoil with the flap retracted increased from 1.17 to 1.35 as the Reynolds number was increased from 3.0×10^6 to 18.0×10^6 and

then decreased to 1.30 as the Reynolds number was increased to 24.9×10^6. The increment of maximum section lift coefficient increased from 1.24 to 1.36 as the Reynolds number was increased from 3.0×10^6 to about 12.0×10^6 and then decreased to 1.31 as the Reynolds number increased up to 25.0×10^6. The section drag coefficient at lift coefficients beyond the low-drag range continued to decrease with increase in Reynolds number although the minimum section drag coefficient began to increase at a Reynolds number slightly higher than 12.0×10^6.

INTRODUCTION

The modern high performance airplane with its increased wing loading requires the use of thin wing sections equipped with high-lift flaps. Experimental investigations, such as those reported in reference 1, have been made to develop 0.250-chord slotted flaps suitable for use on thin airfoil sections. Such investigations, however, have been made for only a small range of Reynolds numbers (2.4×10^6 to 9.0×10^6) and a very limited amount of data for Reynolds numbers greater than 9.0×10^6 are available for thin airfoils equipped with slotted flaps. From data presented in reference 1, it is seen that large changes in the lift characteristics of a thin airfoil with a slotted flap may occur as the Reynolds number is increased. Some question also exists as to whether or not a flap configuration that is the optimum for high lift at low Reynolds numbers is still the optimum configuration at much higher Reynolds numbers.

An investigation is therefore being conducted in the Langley two-dimensional low-turbulence tunnels in order to develop the optimum configuration of a 0.35-chord slotted flap on a modified NACA $65_{(112)}$-111 airfoil section and to determine whether or not the developed optimum flap configuration is dependent upon the Reynolds number. Measurements to determine the section pitching-moment characteristics, the effects of leading-edge roughness on the lift characteristics, and the lift characteristics for the flap deflected through a developed flap path are also included in this investigation.

The results of the first phase of this investigation which covered the development of the optimum flap configuration at a Reynolds number of 2.4×10^6 have been reported in reference 2. This paper presents the results of tests of the airfoil at Reynolds numbers up to 25.0×10^6 for the condition with the flap retracted and for the condition with the flap deflected. The development of the optimum flap configuration at a Reynolds number of 9.0×10^6 was also included in this phase of the investigation.

SYMBOLS

α_o	section angle of attack, degrees
c	airfoil chord
c_d	section drag coefficient
$c_{d_{min}}$	minimum section drag coefficient
c_l	section lift coefficient
$c_{l_{max}}$	maximum section lift coefficient
$\Delta c_{l_{max}}$	increment of maximum section lift coefficient
R	Reynolds number
x,y	horizontal and vertical positions, respectively, of the flap leading-edge radius center with respect to upper lip of slot in percent c, positive forward of and below slot lip, respectively (fig. 1)
δ_f	flap deflection, degrees, angle between airfoil chord line in flap retracted position and airfoil chord line in flap deflected position (fig. 1)

MODEL AND TESTS

The 2-foot chord model tested in this investigation was a modified NACA $65_{(112)}$-111 airfoil section with a 0.35c slotted flap.

The airfoil section had been modified by removing the trailing-edge cusp and was therefore similiar to an NACA $65_{(112)}$-111 airfoil section. Ordinates for the plain airfoil section and the slotted flap are given in tables I and II, respectively. Figure 1 is a sketch of the airfoil and flap and also shows the reference points defining the flap position. The model was constructed of aluminum alloy and completely spanned the 3-foot-wide tunnel test section. Provisions were made for attaching the flap to the main part of the model by fittings at the ends which also permitted independent variation of the flap position and deflection.

Tests were made in the Langley two-dimensional low-turbulence pressure tunnel to determine the scale effects on the lift and drag characteristics of the airfoil section with the flap retracted and slot sealed for Reynolds numbers ranging from 3.0×10^6 to 25.0×10^6. Lift measurements were made at a Reynolds number of 9.0×10^6 to determine the flap position and deflection for highest maximum lift (optimum configuration). The scale effects on the lift characteristics of the optimum flap configuration were then investigated for the same range of Reynolds numbers covered in the tests of the airfoil with the flap retracted and slot sealed. The test methods and the methods used in correcting the test data to free-air conditions are discussed in reference 3. The magnitude of the corrections used in correcting the test data to free-air conditions was of the order of a few percent. The maximum free-stream Mach number attained during any of the tests did not exceed 0.18.

RESULTS AND DISCUSSION

Flap Retracted and Slot Sealed

The section lift characteristics of the airfoil section with the flap retracted and slot sealed are presented in figure 2. From the data presented in figure 2, it is seen that increasing the Reynolds number from 3.0×10^6 to 18.0×10^6 increased the maximum section lift coefficient from 1.17 to 1.35. Increasing the Reynolds number beyond approximately 18.0×10^6 up to 24.9×10^6, however, resulted in a slight decrease in the maximum section lift coefficient. The data presented in figure 2 indicate that within the range of Reynolds numbers tested, increasing the Reynolds number had no important effects on the section lift coefficient at low absolute values of the section angle of attack.

The angle of attack at which the stall occurred was increased by about 2° as the Reynolds number was increased from 3.0×10^6 to approximately 12.0×10^6 (fig. 2). At Reynolds numbers above approximately 12.0×10^6, the section angle of attack for maximum section lift coefficient remained nearly the same. The increase in the section angle of attack for maximum section lift coefficient with increase in Reynolds number was accompanied by a more gradual stall as indicated by the data presented in figure 2.

The drag polars for the airfoil section with the flap retracted and the slot sealed are presented in figure 3. These data indicate that increasing the Reynolds number up to about 13.0×10^6 decreased the minimum section drag coefficient whereas increasing the Reynolds number beyond approximately 13.0×10^6 up to approximately 24.7×10^6 resulted in increases in the minimum section drag coefficient. The section drag coefficient at lift coefficients beyond the low-drag range, however, continued to decrease with increase in Reynolds number within the test range of Reynolds number. The low-drag range continuously decreased with increase in Reynolds number until at a Reynolds number somewhat below 24.7×10^6, the low-drag region was no longer defined by a "bucket" (fig. 3).

Airfoil with Flap Deflected

Optimum configuration at high Reynolds numbers.- The results of tests made to develop the optimum flap configuration at a Reynolds number of 9.0×10^6 are presented in figures 4 and 5. These data indicate that at a Reynolds number of 9.0×10^6 the optimum flap deflection is 35° or 10° less than that indicated by the data obtained for a Reynolds number of 2.4×10^6 (reference 2). Tests of the positions found to be the optimum at a Reynolds number of 2.4×10^6 indicated downward shifts of the lift curve with increasing Reynolds number similiar to that shown for a flap deflection of 40° (fig. 5). Although the gain in maximum section lift coefficient obtained by altering the flap configuration was generally less than 0.1, the increase in the section lift coefficient at low angles of attack was 4 or 5 times as much as the increase in maximum section lift coefficient. The original optimum configurations (those optimum at $R = 2.4 \times 10^6$) were therefore less suitable at a Reynolds number of 9.0×10^6 than some of the other configurations tested. The data presented in figure 4(a) indicate that the optimum position of the flap leading-edge radius center moves rearward and upward as the Reynolds number is increased. Tests to develop the optimum configuration for Reynolds numbers higher than 9.0×10^6 are not feasable inasmuch as the air pressure within the tunnel prohibits personnel from entering the tunnel to alter the flap configuration. It was therefore estimated from the data presented in figure 4(a) that the optimum position of the flap leading-edge radius center at Reynolds numbers of 18.0×10^6 and 25.0×10^6 would be approximately 1.98 percent c behind and 3.21 percent c below the slot lip. The use of this optimum flap position gave almost as high a value of $c_{l_{max}}$ as the highest obtained at a Reynolds number of 9.0×10^6, and would also permit the use of a simpler flap path. The lift characteristics at Reynolds numbers up to 25.0×10^6 were therefore determined for this optimum configuration.

Effect of Reynolds number on lift.- The section lift characteristics of the configuration found to be the optimum at a Reynolds number of 9.0×10^6 are presented in figure 6. Increasing the Reynolds number from 3.0×10^6 to approximately 12.1×10^6 increased the maximum section lift coefficient from 2.41 to 2.71, increased the angle of attack for maximum section lift coefficient from 2° to 7°, and caused the stall to be more gradual. Increasing the Reynolds number beyond approximately 12.1×10^6 up to 25.3×10^6, however, resulted in a slight decrease in the maximum section lift coefficient accompanied by only small changes in the type of stall and the angle of attack at which the stall began. (See fig. 6.) The variation of maximum section lift coefficient with Reynolds number is shown in figure 7. This curve is extended to a Reynolds number of 2.4×10^6 where the value of $c_{l_{max}}$ (2.15) was obtained from reference 2. The highest maximum section lift coefficient obtained for the flap deflected condition, as shown in figure 7, was 2.71 at a Reynolds number of approximately 12.1×10^6. At a Reynolds number of 9.0×10^6 the maximum section lift coefficient (2.69) is approximately 0.24 higher and the increment of maximum section lift coefficient (1.36) is approximately 0.30 higher than the values obtained for the NACA 65-210 airfoil section with the 0.25c slotted flap designated as slotted flap 1 in reference 1.

The increment of maximum section lift coefficient increased from 1.24 to 1.36 as the Reynolds number was increased from approximately 3.0×10^6 to approximately 11.0×10^6 as shown in figure 7. The variation of increment of maximum section lift coefficient with Reynolds number, however, was less than the variation of maximum section lift coefficient with Reynolds number. The increment of maximum section lift coefficient for Reynolds numbers ranging from 3.0×10^6 to 25.0×10^6 was approximately 1.3.

<u>Lift at low angles of attack</u>.- From the data presented in figure 6 it is seen that throughout the range of Reynolds number at which the model was tested, the change in section lift coefficient at low angles of attack with variation of Reynolds number was small. The variation of section lift coefficient at a constant section angle of attack within the linear portion of the lift curve is shown in figure 8. It is seen from figure 8 that only slight downward shifts of the lift curves for the flap deflected condition were obtained as the Reynolds number was increased beyond approximately 12.0×10^6 whereas for the flap retracted condition the section lift coefficient at an angle of attack of 0° remained substantially independent of the Reynolds number. In no case, however, was the downward shift in the lift curve with increase in Reynolds number as much as that obtained for one of the configurations included in tests of the 40° flap deflection when the Reynolds number was increased from 2.4×10^6 to 9.0×10^6 (fig. 5(b)), even though that flap position was found to be the optimum for that flap deflection at the lower Reynolds number. It therefore appears that a downward shift in the lift curves at low angles of attack with increasing Reynolds number may be caused by changes in the flow through the slot which alter the optimum configuration as the Reynolds number is varied.

CONCLUSIONS

The results of tests of a modified NACA $65_{(112)}$-111 airfoil section with a 0.35-chord slotted flap indicate the following conclusions.

1. The optimum flap configuration at high Reynolds numbers was found to be a flap deflection of 35° with the flap leading-edge radius center located 1.98-percent chord behind and 3.21-percent chord below the slot lip. The flap deflection was lower and the flap was located rearward and upward from the position found to be the optimum at a Reynolds number of 2.4×10^6.

2. Shifts in the linear portion of the lift curve caused by variation in Reynolds number, which occurred only for the condition with the flap deflected, were either eliminated or reduced considerably by altering the flap position.

3. The maximum section lift coefficient of the airfoil with the flap deflected in the position found to be the optimum at a Reynolds number of 9.0×10^6 increased from 2.15 to 2.71 as the Reynolds number

increased from 2.4×10^6 to 12 or 13.0×10^6 and then decreased to 2.62 as the Reynolds number was increased up to 25.3×10^6.

4. The maximum section lift coefficient of the airfoil with the flap retracted increased from 1.17 to 1.35 as the Reynolds number was increased from 3.0×10^6 to 18.0×10^6 and then decreased to 1.30 as the Reynolds number was increased 24.9×10^6.

5. The increment of maximum section lift coefficient increased from 1.24 to 1.36 as the Reynolds number was increased from 3.0×10^6 to about 12.0×10^6 and then decreased to 1.31 as the Reynolds number increased up to 25.0×10^6.

6. The section drag coefficient at lift coefficients beyond the low-drag range continually decreased with increase in Reynolds number although the minimum section drag coefficient began to increase at a Reynolds number slightly higher than 12.0×10^6.

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

Stanley F. Racisz
Stanley F. Racisz
Aeronautical Engineer

Approved: Clinton H. Dearborn
Clinton H. Dearborn
Chief of Full-Scale Research Division
mpc

REFERENCES

1. Cahill, Jones F.: Two-Dimensional Wind-Tunnel Investigation of Four Types of High-Lift Flaps on an NACA 65-210 Airfoil Section. NACA TN No.   , 1947.

2. Racisz, Stanley F.: Two-Dimensional Wind-Tunnel Investigation Of Modified NACA $65_{(112)}$-111 Airfoil With 35-Percent Chord Slotted Flap To Determine Optimum Flap Configuration at a Reynolds Number Of 2.4 Million. NACA RM No. L7A02, 1946.

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

TABLE I

ORDINATES FOR THE MODIFIED

NACA $65_{(112)}$-111 AIRFOIL SECTION

[Stations and ordinates given in percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.463	.871	.538	-.821
.708	1.050	.792	-.979
1.204	1.325	1.292	-1.217
2.450	1.813	2.550	-1.625
4.942	2.546	5.054	-2.229
7.442	3.117	7.558	-2.696
9.942	3.600	10.058	-3.083
14.942	4.371	15.054	-3.700
19.950	4.958	20.050	-4.163
24.958	5.404	25.042	-4.508
29.967	5.725	30.033	-4.754
34.975	5.933	35.025	-4.904
39.983	6.033	40.017	-4.963
44.992	6.000	45.008	-4.904
50.000	5.829	50.000	-4.725
55.008	5.508	54.992	-4.413
60.017	5.087	59.983	-4.017
65.021	4.575	64.979	-3.546
70.025	4.029	69.975	-3.054
75.025	3.429	74.975	-2.533
80.025	2.792	79.975	-1.996
85.025	2.146	84.975	-1.471
90.021	1.483	89.979	-.967
95.017	.796	94.983	-.479
100.004	.054	99.996	-.054
L.E. radius: 0.842			

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

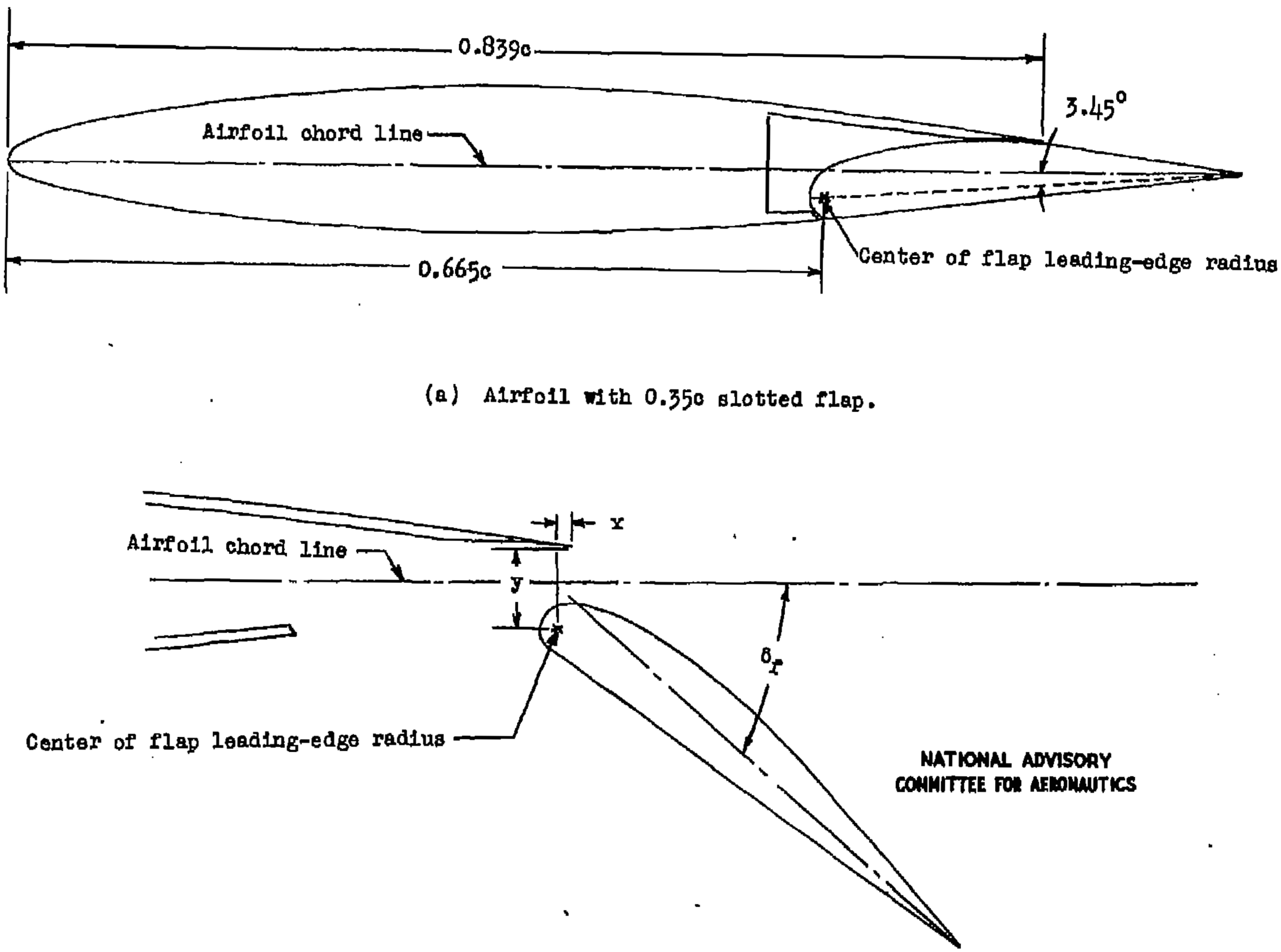
TABLE II

ORDINATES FOR 0.35-CHORD FLAP

[Lower surface of flap formed by lower surface of plain airfoil. Stations and ordinates given in percent airfoil chord]

Station	Ordinate
65.50	-0.863
66.00	-.367
67.00	.308
68.00	.792
70.00	1.442
72.00	1.846
74.00	2.104
76.00	2.267
78.00	2.346
80.00	2.354
82.00	2.300
84.00	2.183
86.00	2.000
Upper surface fairs into plain airfoil section at station 88.00	
L.E. radius: 1.404 L.E. radius center at station 66.50 and ordinate -1.971	

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS



(a) Airfoil with 0.35c slotted flap.

(b) Variables used to define flap configuration.

Figure 1.- Profile of the modified NACA $65_{(112)}$-111 airfoil section with 0.35c slotted flap.

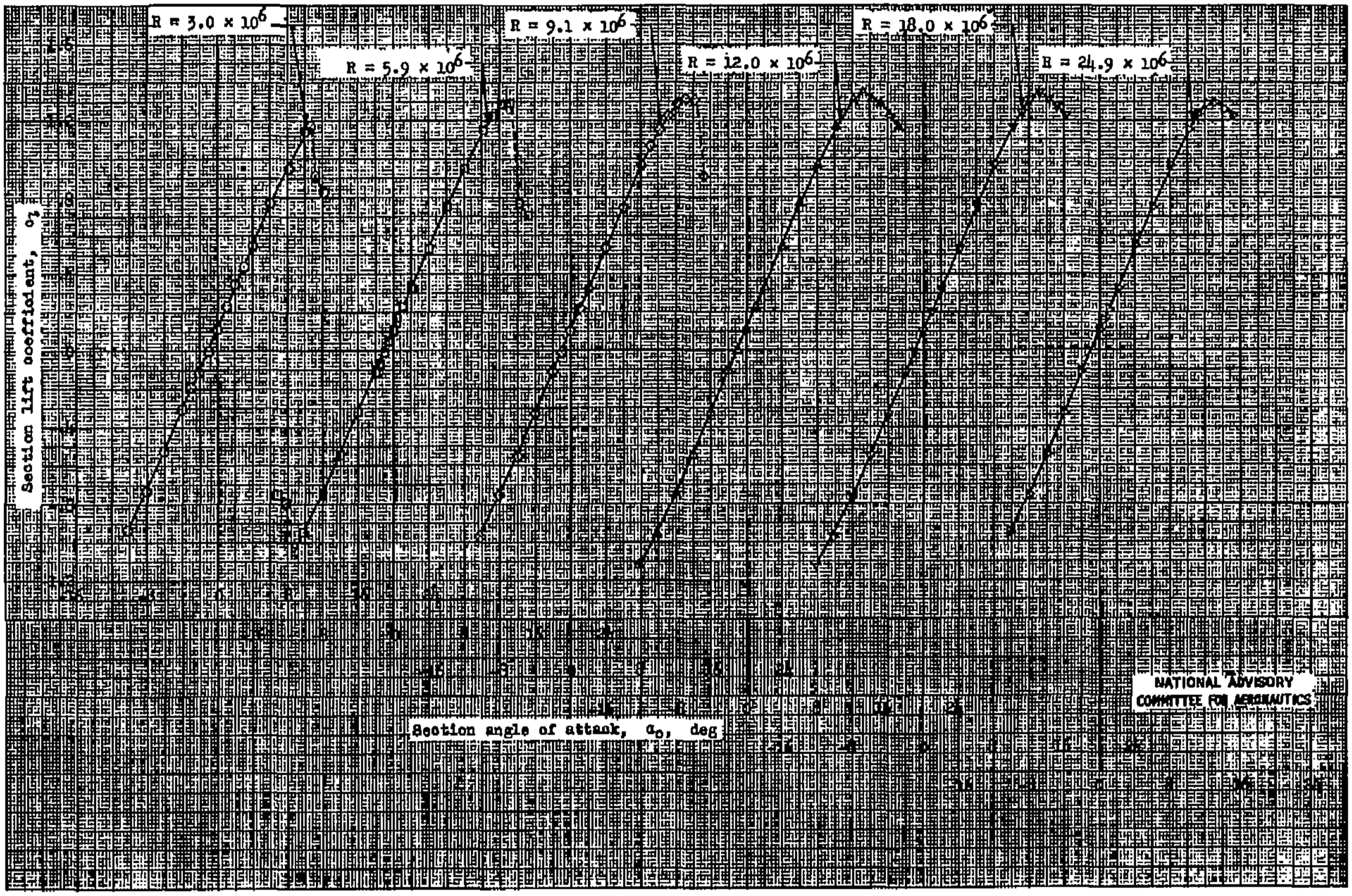


Figure 2 .- Section lift characteristics of a modified NACA $65_{(112)}$-111 airfoil section with flap retracted and slot sealed for several Reynolds numbers.

2021 3

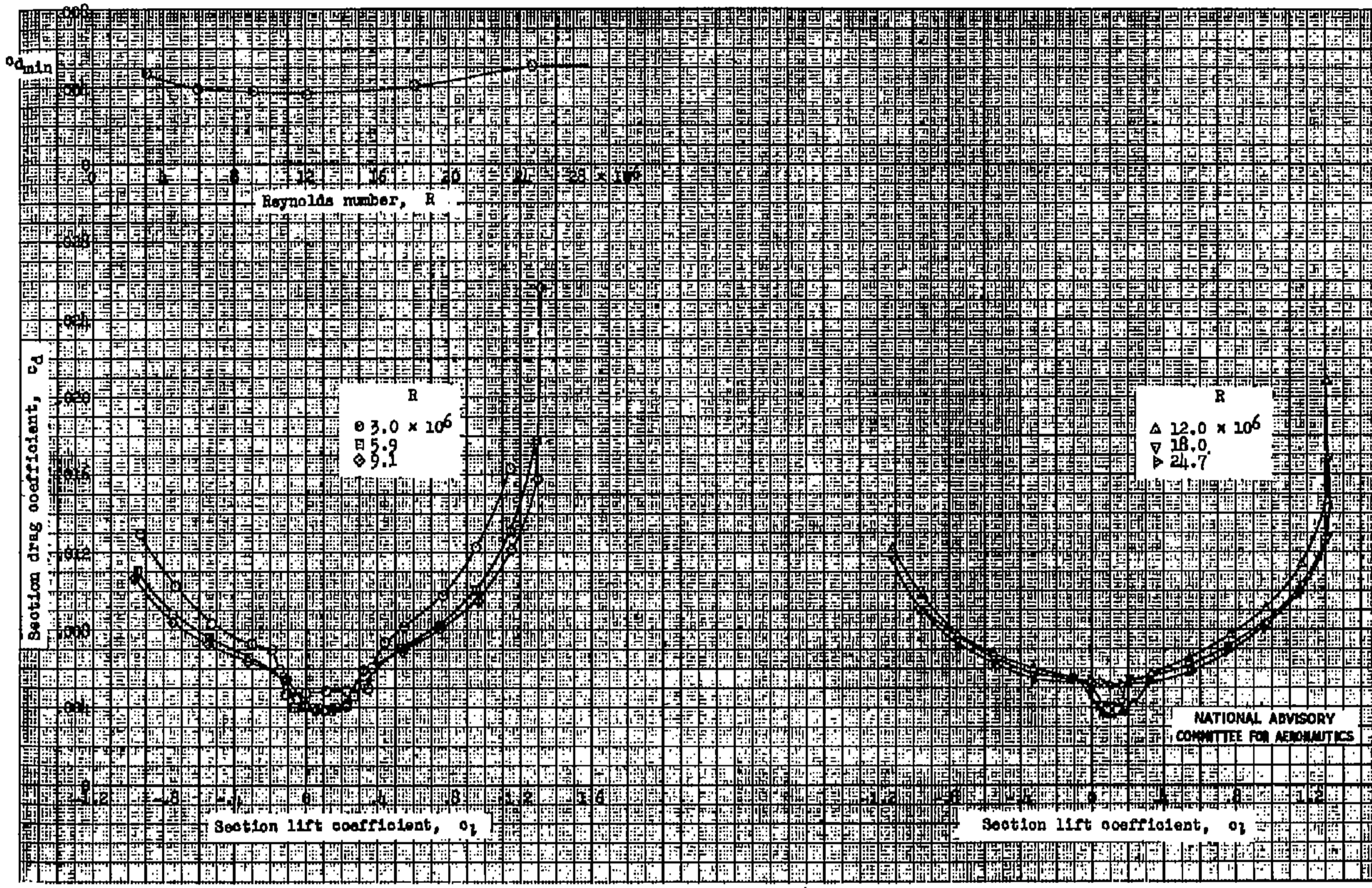
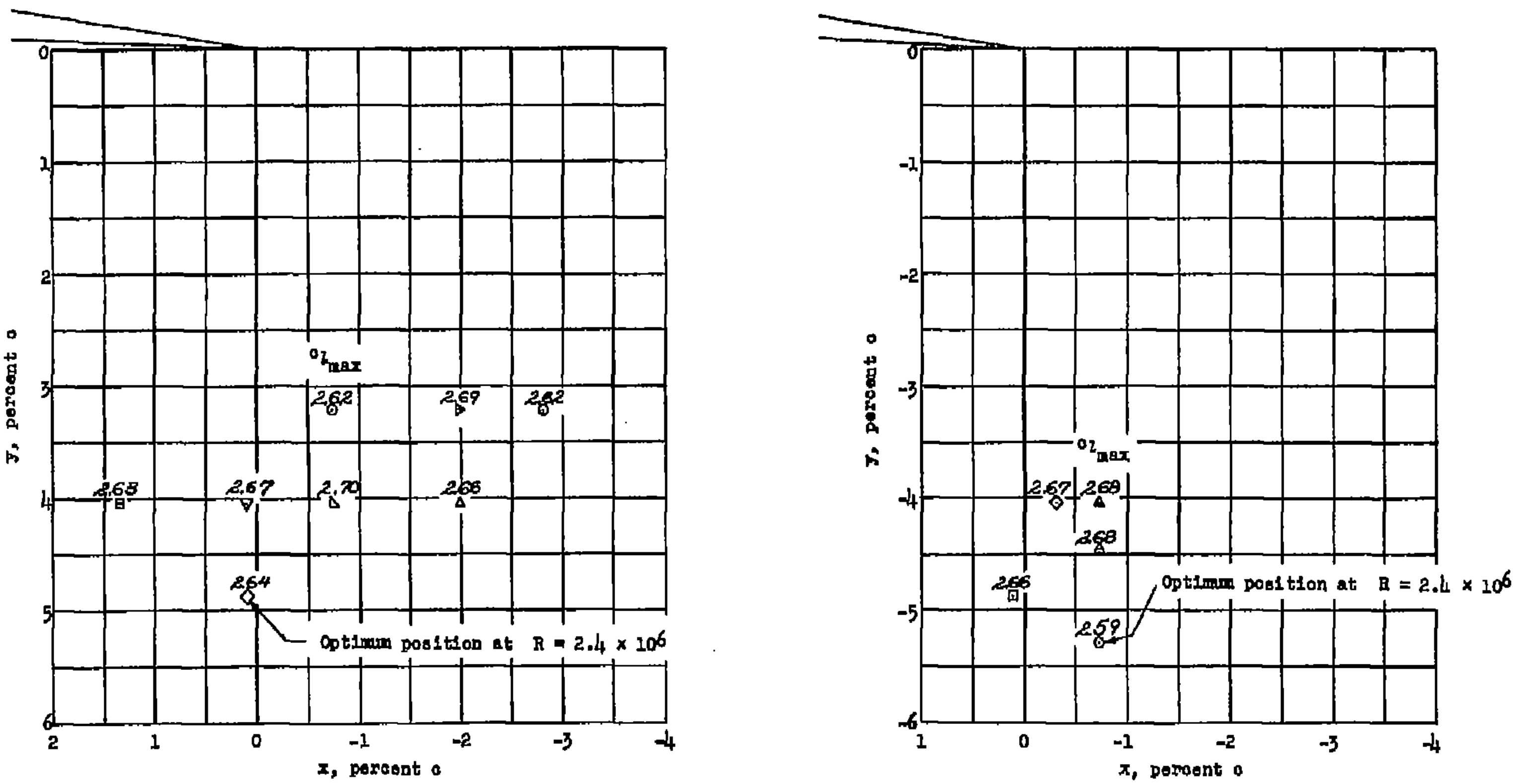


Figure 3 .- Section drag characteristics of a modified NACA $65_{(112)}$-111 airfoil section with flap retracted and slot sealed.



NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

(a) $\delta_f = 35^\circ$.

(b) $\delta_f = 40^\circ$.

Figure 4 .- Values of maximum section lift coefficient for various positions of the flap leading-edge radius center with respect to slot lip of a modified NACA $65_{(112)}$-111 airfoil section. 0.35c slotted flap; $R = 9.0 \times 10^6$ (approx.).

2021 5

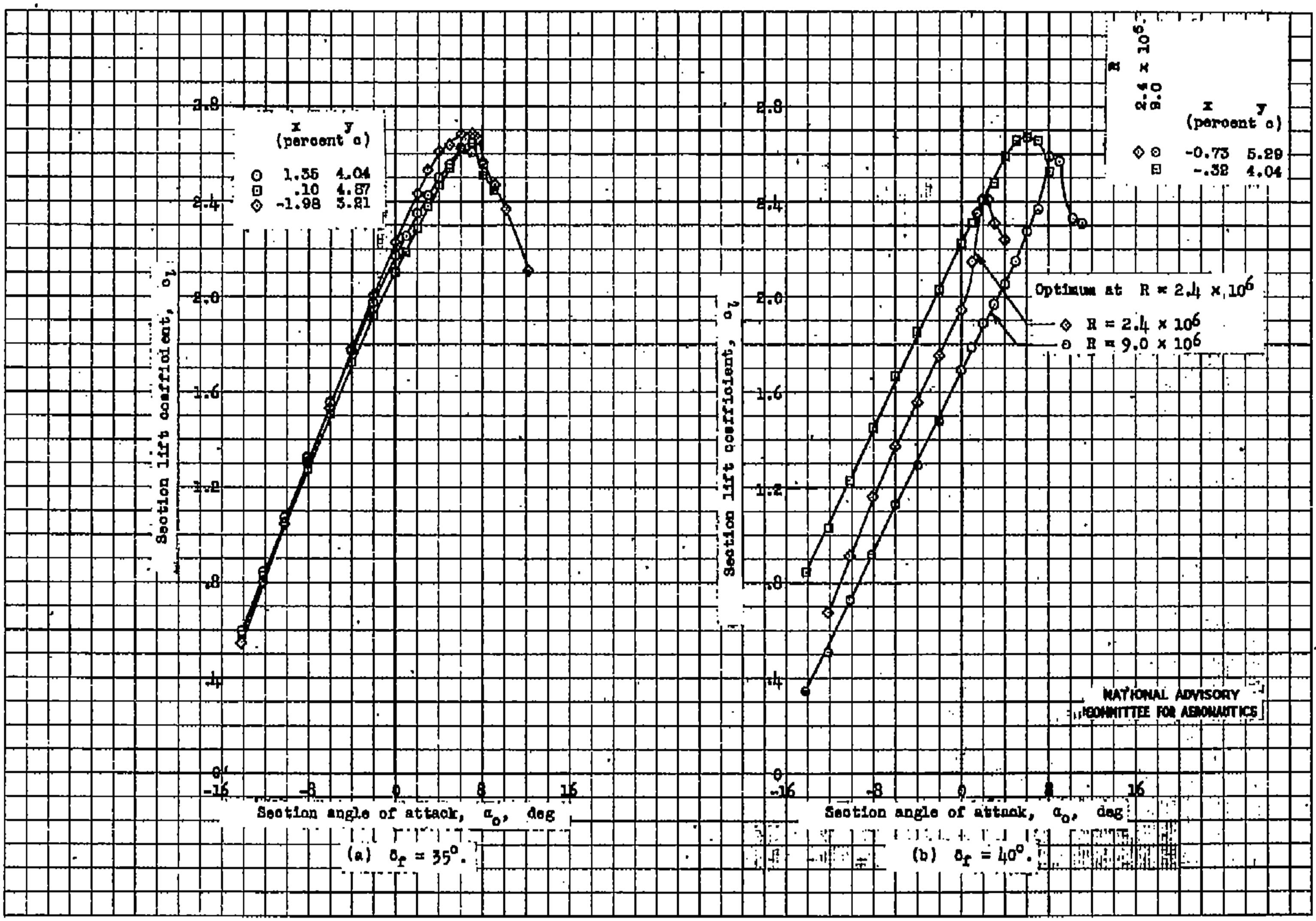


Figure 5.- Variation of section lift coefficient with section angle of attack for several positions of the flap leading-edge radius center with respect to slot lip of a modified NACA $65_{(112)}$-111 airfoil section. 0.35c slotted flap; $R = 9.0 \times 10^6$ (approx.), except as noted.

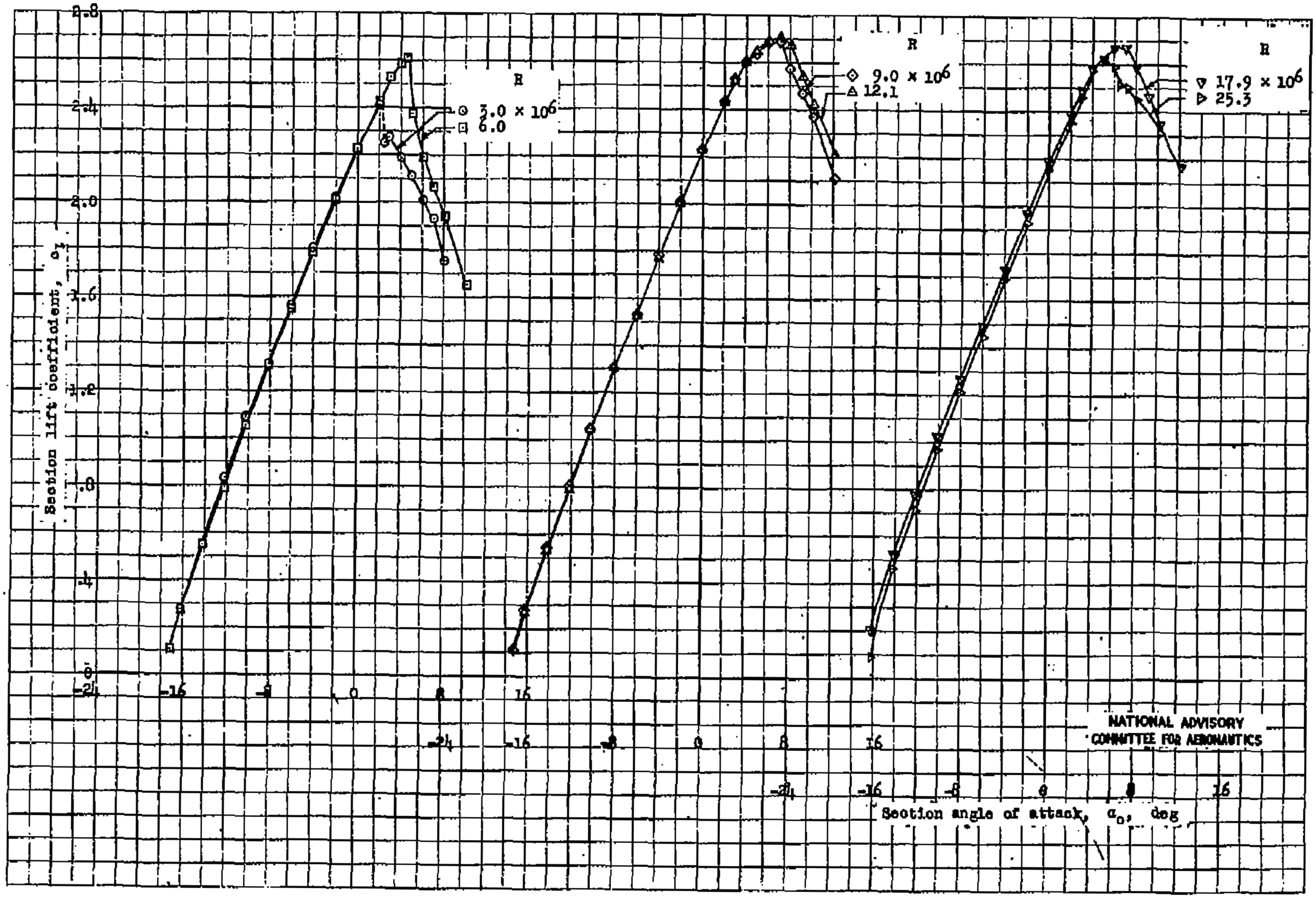


Figure 6 .- Section lift characteristics of a modified NACA $65_{(112)}$-111 airfoil section with a 0.35c slotted flap at several Reynolds numbers. $\delta_f = 35^0$; x = -1.98 percent c; y = 3.21 percent c.

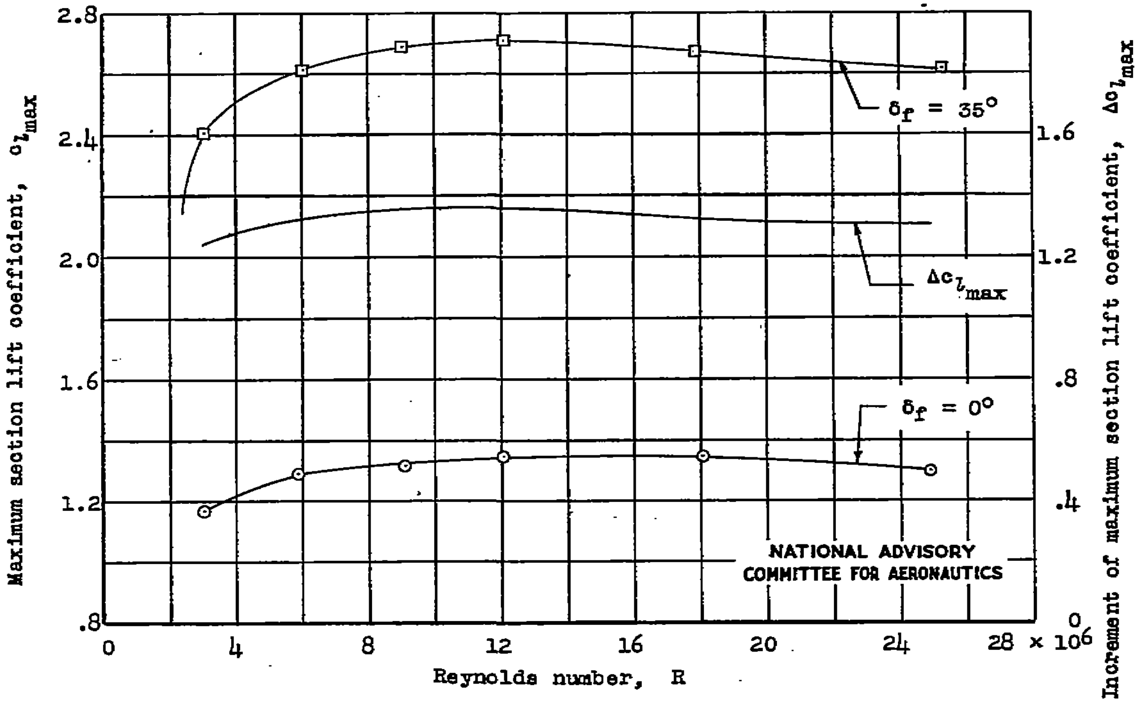


Figure 7 .- Variation of maximum section lift coefficient and increment of maximum section lift coefficient with Reynolds number for a modified NACA $65_{(112)}$-111 airfoil section with a 0.35c slotted flap.

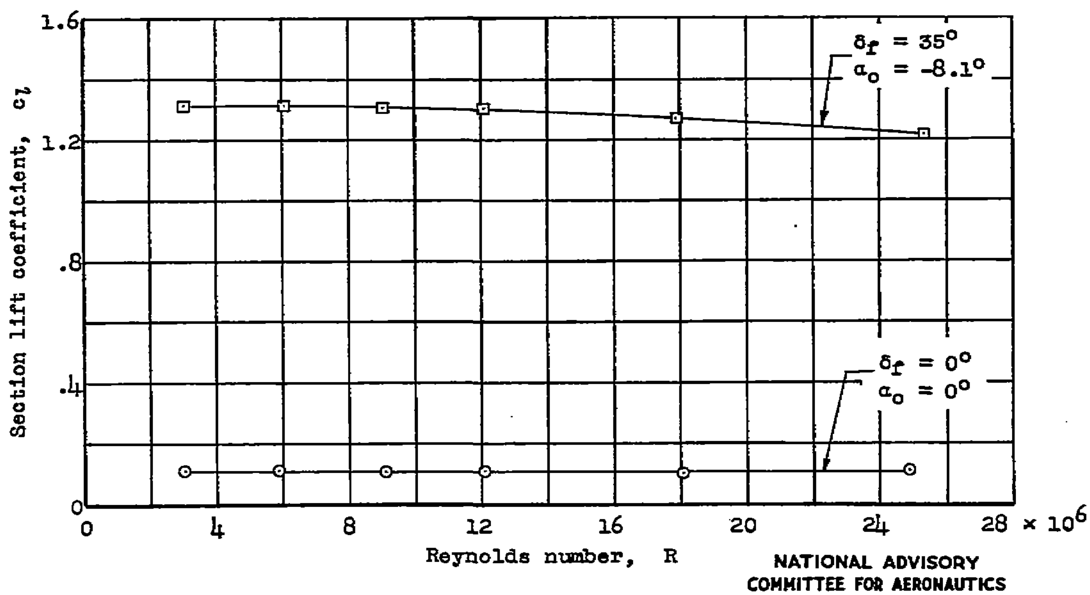


Figure 8 .- Variation of section lift coefficient at a constant angle of attack with Reynolds number for a modified NACA $65_{(112)}$-111 airfoil section with a 0.35c slotted flap.