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**SUBSONIC TWO-DIMENSIONAL WIND TUNNEL INV
OF THE HIGH LIFT CAPABILITY OF CIRCUI
CONTROL WING SECTIONS**

by

Robert J. Englar

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Two series of Circulation Control Wing airfoil sections, formed by the conversion of the sharp trailing edge into a circular bluff surface with tangential upper surface blowing, were evaluated subsonically to determine their high lift characteristics as potential STOL wing sections. Parameters investigated which had noticeable effect on the blown airfoil performance include leading edge devices (type of device and degree of deflection), trailing edge configuration (radius, slot location, deflection, etc.), Reynolds number, airfoil incidence, momentum coefficient, slot height, (continued on back)

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and nozzle pressure ratio. Maximum lift coefficients roughly triple those of the flapped conventional sections were generated at incidence slightly less than the conventional stall angles and at blowing rates obtainable from bleed of state-of-the-art turbojet engines. An experimental investigation into the lift augmenting effects of pulsed unsteady blowing was conducted on a smaller radius trailing edge configuration. An additional investigation was conducted to determine the effects of spoilers or similar disturbances ahead of the jet exit. The results of the above investigations provide a data base for the prediction of the aerodynamic characteristics of aircraft employing Circulation Control trailing edges to increase their STOL capability.



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SYMBOLS

A_j	jet exit area, ft ²
c	airfoil undeflected chord, ft*
c'	deflected, rotated, or effective chord, ft*
C_a	section axial force coefficient
C_d	section drag coefficient
$C_{d_{rake}}$	section drag coefficient from integrated momentum loss on wake rake
C_l	section lift coefficient
\bar{C}_l	mean section lift coefficient during pulsed blowing
$C_{l_{clean}}$	section lift coefficient of airfoil with spoiler retracted
$C_{l_{max}}$	section maximum lift coefficient
$C_{L_{max}}$	aircraft maximum lift coefficient
C_{l_α}	lift curve slope, per degree
$C_{m_{25}}$	section quarter-chord pitching moment coefficient
C_n	section normal force coefficient
C_p	pressure coefficient, $\frac{P-P_\infty}{q}$
C_μ	section momentum coefficient, $\frac{\dot{m}V_j}{qS}$
\bar{C}_{μ_1}	mean momentum coefficient during pulsed blowing as measured by venturimeter
\bar{C}_{μ_2}	calculated mean momentum coefficient during pulsed blowing
h	jet exit nominal slot height, ft*
h_t	tunnel height, ft
\dot{m}	measured jet mass efflux, slugs/sec

* unless otherwise noted

\bar{I}	mean jet mass efflux during pulsed blowing, slugs/sec
p	local static pressure, psfa
P_d	plenum (duct) total pressure, psfa
\bar{P}_d	mean plenum total pressure during pulsed blowing, psfa
$P_{d_{max}}$	maximum plenum total pressure during pulsed blowing, psfa
P_v	line pressure upstream of venturimeter, psia
P_∞	freestream static pressure, psfa
q	freestream dynamic pressure, psf
R	universal gas constant, 1715 ft ² /(sec ² °R)
r	trailing edge radius, ft*
Re	Reynolds number based on undeflected chord
S	wing or airfoil planform area, ft ²
t	airfoil thickness, ft*
T_d	plenum total temperature, °R
u_{max}	maximum velocity in the wall jet velocity profile, ft/sec
v_j	isentropic jet velocity, ft/sec
v_∞	freestream velocity, ft/sec
x	distance from undeflected leading edge, ft*
x_{slot}	slot location from undeflected leading edge, ft*
α_c	corrected incidence; α_g corrected for tunnel boundary constraints, deg
α_{eff}	effective incidence; α_c corrected for induced downwash effects, deg
α_g	geometric incidence relative to chord, deg
α_{stall}	stall incidence, deg

* unless otherwise noted

γ	ratio of specific heats
δ	mean line maximum camber relative to chord line, ft
δ_f	flap deflection angle relative to chord, deg
δ_j	jet deflection angle relative to chord, deg
δ_{LE}	leading edge deflection angle relative to chord, deg
δ_s	spoiler deflection angle relative to chord, deg
ϵ	solid blockage correction factor
λ_2	two-dimensional airfoil shape factor
ρ	freestream density, slugs/ft ³
ρ_j	density in the jet throat (exit), slugs/ft ³
ω	pulsed blowing frequency, cycles/sec

SUMMARY

Two series of Circulation Control Wing airfoil sections, formed by the conversion of the sharp trailing edge into a circular bluff surface with tangential upper surface blowing, were evaluated subsonically to determine their high lift characteristics as potential STOL wing sections. Parameters investigated which had noticeable effect on the blown airfoil performance include leading edge devices (type of device and degree of deflection), trailing edge configuration (radius, slot location, deflection, etc.), Reynolds number, airfoil incidence, momentum coefficient, slot height, and nozzle pressure ratio. Maximum lift coefficients roughly triple those of the flapped conventional sections were generated at incidence slightly less than the conventional stall angles and at blowing rates obtainable from bleed of state-of-the-art turbojet engines. An experimental investigation into the lift augmenting effects of pulsed unsteady blowing was conducted on a smaller radius trailing edge configuration. An additional investigation was conducted to determine the effects of spoilers or similar disturbances ahead of the jet exit. The results of the above investigations provide a data base for the prediction of the aerodynamic characteristics of aircraft employing Circulation Control trailing edges to increase their STOL capability.

INTRODUCTION

Recent investigation into the application to helicopter rotors of Circulation Control elliptical airfoils employing tangential blowing over bluff trailing edges has demonstrated the simultaneous generation of high lift and drag at low blowing rates and low angles of incidence (Reference 1). The concept offers promise of considerable payoff in STOL performance when applied to the more conventional airfoil sections of fixed wing aircraft. Based on the well-known Coanda principle, this Circulation Control Wing (CCW) concept involves converting the sharp trailing edge of the high speed cruise airfoil into a rounded surface to which a jet of air, blown tangentially from the upper surface, adheres. The jet sheet is able to turn nearly 180 degrees around the bluff

afterbody, initially acting as a boundary layer control, but primarily controlling the airfoil stagnation points and thus the circulation. The resulting high augmentation of circulation lift is obtained at values of blowing or momentum coefficient (C_{μ}) well within the ranges of mass flow and pressure which can be bled from state-of-the-art turbojet and turbofan engines. A problem frequently encountered with blown flap concepts is the conversion of the blowing momentum into wing thrust, and thus reduction of drag needed to maintain a low equilibrium approach velocity at large glide path angles. This is avoided by the Circulation Control concept, as large jet turning produces viscous mixing with the lower surface freestream, and jet thrust recovery is significantly reduced.

Application of the CCW to fixed wing carrier-based Naval aircraft is expected to produce considerable reduction in approach velocities and/or landing distances, increased aircraft payload and wing loadings, and the independence of high speed wing design from compromise resulting from low speed landing and takeoff requirements. In addition, the generation of lift independent of incidence implies increased pilot visibility during carrier approach. The existence of an aft upper surface blowing source provides the additional possibility for increased transonic maneuverability.

A characteristic Circulation Control Wing configuration is shown in Figure 1, where a short chord flap is rotated through 180 degrees to expose the cylindrical Coanda surface. Replacement of the conventional half-span single slotted flap of a 1/5-scale model T-2C aircraft with a Coanda trailing edge very similar to this configuration resulted in increases of 96 percent in $C_{L_{max}}$ and 240 percent in the corresponding drag coefficient at $C_{\mu} = 0.156$ (References 2 and 3). However, full rotation of the flap in this configuration results in a loss in chord of about 11 percent; additional lift augmentation should result if this loss can be eliminated. The extended configuration of Figure 2 was thus proposed, where the Coanda surface translates aft to the trailing edge as a split flap is deployed to form the lower surface.

It is the primary objective of the present investigation to provide section aerodynamic data on the above and additional CCW configurations for use as input to analyses for prediction of three-dimensional performance. This report also documents a preliminary investigation conducted on a small chord airfoil model which was used to confirm the effectiveness of the Coanda trailing edges on relatively thin conventional airfoil sections. In addition, it was desired to investigate the effects of unsteady pulsed blowing on the lift augmentation of CCW airfoils, and the effects of deflecting a spoiler or similar disturbance upstream of the blowing slot. Further goals of this investigation were to identify a leading edge device capable of preventing laminar separation under conditions of high circulation, and to examine the effects of Reynolds number and trailing edge parameter variation on overall airfoil performance.

DESIGN CONSIDERATIONS

Airfoil sections to be modified included those thought to be characteristic of state-of-the-art fixed wing aircraft. For the preliminary investigation on the small chord airfoil, an NACA 66-210 profile was chosen. A larger chord NACA 64A-212 airfoil was constructed to provide section data to correspond to the T-2C/CCW model of Reference 2. Previous 2-D investigations of 15-percent thick elliptic CC airfoils (Reference 4) indicated a serious problem with leading edge separation at high lift, and a primary concern of the 66-210/CCW investigation was the determination of sufficient means to prevent that problem. A Krüger leading edge flap and a leading edge droop were alternately incorporated for this purpose. The trailing edge geometries for both small and large chord models were based on those parameters which had proven effective in CC rotor airfoil evaluations. References 5 and 6 suggest that strongly attached Coanda flow is maintained for a slot height-to-radius ratio in the range $0.01 \leq h/r \leq 0.05$, while effective Coanda jet turning and lift augmentation result from a trailing edge radius-to-chord ratio in the range $0.02 \leq r/c' \leq 0.05$. This produces a slot-height-to-chord ratio of approximately $0.0005 \leq h/c' \leq 0.0025$,

the lower limit being postulated as the point at which nozzle internal boundary layer thickness approaches the slot height (jet exit thickness) and seriously degrades the "potential core" characteristics of the jet. Once the trailing edge radius is chosen, the flap rotation point for the configuration of Figure 1 is determined by positioning the center of the radius at the airfoil chordwise location where the sum of radius plus slot height is equal to local airfoil thickness. This determines the length of the rotating flap chord and the slot longitudinal location. For most thinner airfoils, the resulting flap chord will be roughly 10 to 20 percent of the original or undeflected chord, c , and the slot location will be approximately $.80c$ to $.90c$, or aft of 93 percent of the rotated chord c' (defined as the distance from the undeflected leading edge to the furthest aft point on the Coanda surface). It is essential that this resulting slot location be slightly ahead of the adverse pressure gradient downstream of the suction peak produced by attached flow accelerating around the bluff trailing edge. A more forward slot location can delay section stall due to better boundary layer control on the upper surface, but a slightly more aft slot produces higher lift augmentation due to higher jet momentum at the airfoil trailing edge. For the extended configuration of Figure 2, the slot location is at the original trailing edge, the effective chord c' is $c + r$, and limits on h/r , r/c' and h/c' are the same as above. It should be noted that all nondimensional data in this report are referenced to the original undeflected chord c (or original planform area S) regardless of the value of the effective chord c' ; all data are thus directly comparable. Also, incidence is relative to the chord line through the undeflected leading and trailing edge points of the conventional airfoil.

MODELS AND EXPERIMENTAL APPARATUS

MODELS

Based on the design considerations of the previous section, two airfoil sections were modified into various configurations of the Circulation Control Wing. A small chord (undeflected $c = 8.0$ inches)

NACA 66-210 section was converted into the rotated flap configuration of Figure 1 and is shown in Figure 3. Krüger leading edge flaps of 5, 10 and 15 percent undeflected chord were initially employed for leading edge separation control, but due to their relative ineffectiveness, were replaced with a leading edge droop, hinged at the lower surface at .15c and deflected at angles of 0, 15.3, 29 and 43.6 degrees from the chord. These configurations are identified as CCW800, CCW815, CCW829, and CCW844 respectively. Additional details of the model are found in Appendix A, while geometric parameters are listed in Table 1.

A large chord ($c = 24.0$ inches) model NACA 64A-212 was converted to include the .15c leading edge droop and a number of trailing edge variations. Figure 4 depicts this model, with additional details found in Appendix A and geometric parameters in Table II. Configuration CCW241 was similar to CCW829, including a 30° droop and 180° rotated flap. CCW242 was similar except the flap deflection was 90° . An extended trailing edge configuration similar to that of Figure 2 and with 30° leading edge droop comprised CCW243, while CCW244 was the same as CCW243 but with a reduced trailing edge radius having roughly half the value of r/c' . An investigation of pulsed blowing was also performed with this model. Configuration CCW245 was CCW241 with no leading edge droop.

A third model was employed to investigate the effects of upper surface distortions or deflections of control surfaces such as spoilers ahead of the slot. This model was a 20.6-percent thick cambered ellipse section characteristic of a rotor blade airfoil, and is shown in Figure 5. A 9.82-percent-chord spoiler with the hinge at 70-percent chord could be deflected up to 51 degrees relative to the chord line of the 10.18 inch model.

EXPERIMENTAL APPARATUS AND TECHNIQUE

The small chord 66-210/CCW model was installed and evaluated in the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) 15- x 20-inch subsonic tunnel. For this model, as well as all the others, lift and moment coefficients were obtained from integration of surface static pressures near the midspan as recorded by a 144-port scannivalve system. Drag coefficient was obtained from integration of wake momentum

deficit as measured on a total head wake rake. Additional details relating to model installation; test apparatus and technique; data reduction and corrections; and control of tunnel two-dimensionability are presented in Appendix A. The 64A-212/CCW airfoil and the cambered ellipse section were installed in the two-dimensional parallel wall insert which converted the DTNSRDC 8- x 10-foot subsonic tunnel into a 3- x 8-foot 2-D channel. Figure 6 shows this installation, while Figures 7 and 8 show configuration CCW243 installed within the inserts, and details of the wall blowing slots and wake rake. Again, Appendix A presents further details of installation and technique, and references additional sources of explanation.

A fourth series of investigations was conducted to determine the effects of pulsed (unsteady) trailing edge blowing upon lift augmentation. Modifications made to the air supply system and data acquisition and reduction are explained in Appendix A. The model used was the CCW244 configuration of the 64A-212 airfoil.

RESULTS AND DISCUSSION

NACA 66-210/CCW AIRFOIL

As mentioned previously, the investigation of this smaller chord airfoil was primarily intended to confirm the effectiveness of Coanda type trailing edges applied to thin, cambered conventional airfoils for high lift generation, and to identify satisfactory leading edge devices to prevent flow separation caused by rapid flow acceleration around rather small leading edge radii. The following data shows that, indeed, lack of proper leading edge devices can produce quite severe consequences in lift augmentation, drag generation and pitching moments.

Lift Augmentation

Section lift coefficients, as determined from static pressure integration, are presented as functions of momentum coefficient at constant corrected incidence (α_c) for four different nose droop angles in Figure 9. Here, the coefficients are corrected for solid blockage and

tunnel boundary interference, but not for any induced effect which might result from spanwise non-uniformity due to interaction between trailing edge adverse pressure gradient and tunnel wall boundary layer (see Reference 7). The corrected incidence α_c has been adjusted to account for tunnel boundary corrections. At low and negative incidence, all four configurations show a rapid rise in C_L with blowing. This initial rise is attributed to flow entrainment and boundary layer control, while the less steep slope at higher C_μ is characteristic of stagnation point movement by the Coanda jet and resulting supercirculation. However, at low droop angles, as higher incidence is approached, a noticeable break in the curve occurs. The pressure distributions in Figure 10 for $\alpha_c = 8.4^\circ$ and $C_\mu \approx 0.11$ very clearly show leading edge separation at 0° droop and reattachment of the flow at higher droop. Furthermore, attached leading edge flow results in considerably higher trailing edge suction peaks at a constant C_μ , indicating greater jet turning, flow entrainment, and lift augmentation. The inset plot shows an increase of over 1.5 in C_L produced by applying a 43.6° nose droop. As Figures 9 (c) and (d) show, the lift break is delayed by nose droop to much higher values of incidence.

Insight into the mechanism of lift augmentation due to blowing is given by Figure 11. With no blowing, the leading edge stagnation point is on the upper surface of the 43.6° drooped nose, but as C_μ is increased, it moves to the lower surface, which approaches full stagnation ($C_p \rightarrow 1.0$) along the entire bottom. On the upper surface, a suction spike at the droop knee is followed by a moderate adverse pressure gradient which leads, at higher C_μ , to a long favorable gradient terminating somewhere aft of $0.97c'$. This high upper surface suction and lower surface overpressure result in high C_L at quite low C_μ . Figures 12 and 13 present the effect of incidence on airfoil pressure distributions and lift with and without nose droop. At $C_\mu \approx .088$ and $\delta_{LE} = 0^\circ$, Figure 12 shows serious leading edge separation at incidence of -0.68 degrees and higher. This corresponds to the lift breaks in Figure 9 (a). For 29° droop and $C_\mu \approx .173$ (Figure 13), higher incidence produces only slight separation at the leading edge but the major effect is gradual reduction in the suction peak at the knee of the droop, and much more pronounced reduction

in the trailing edge suction peak. Small changes in the leading edge flow apparently can quite strongly affect the boundary layer and downstream pressure distributions. As soon as the trailing edge peak begins to reduce (at incidence above 3.2 degrees for $C_{\mu} \approx .17$) the lift break in Figure 9 (c) begins.

Figure 14 presents lift curves at constant C_{μ} , obtained as crossplots of Figure 9. For all leading edge droop angles, stall occurs at progressively lower incidence with increased blowing; for no droop, α_{stall} takes on negative values. As droop is increased, stall occurs at higher incidence, and lift augmentation due to blowing is supplemented by lift due to positive incidence. Figure 15 is a summary plot of this data, showing $C_{l_{max}}$ and α_{stall} as functions of blowing rate and droop angle. A comparison is made to the conventional NACA 66-210 with a 60° split flap (from Reference 8) operating at five times the test Reynolds number of the CCW airfoil. An increase of 250 percent in $C_{l_{max}}$ is seen for the blown airfoil with $\delta_{LE} = 43.6^{\circ}$ and $C_{\mu} = 0.24$; operating at the same Reynolds number would produce an even larger increase. Figure 14 (d) shows a similar comparison of the blown and conventional airfoil. Also shown is the data resulting from the 0.15c Krüger leading edge flap at $C_{\mu} = .142$; the loss of effectiveness due to lack of leading edge flow control is evident. Figure 16 presents maximum lift coefficient as a function of C_{μ} ; in both this figure and Figure 15, it appears that the additional benefits of increasing droop from 29 to 43.6° are minimal. In fact, at lower blowing, higher droop reduces $C_{l_{max}}$ due to suction on the lower surface of the leading edge. A droop of roughly 30 degrees appears to be more optimum over the entire C_{μ} range, but a more effective use of droop would be to schedule δ_{LE} as a function of C_{μ} and incidence. However, the pressure distributions of Figure 13 suggest that, in spite of the droop's effectiveness, a device offering stronger control of the leading edge boundary layer (such as a slat or tangential leading edge blowing) might further improve the lift augmentation of this type of airfoil.

Reynolds Number Effects

The majority of the preceding data was run at a nominal freestream dynamic pressure of 30 psf, yielding for this small chord model a Reynolds number of 0.64×10^6 (based on undeflected chord c and corrected for model blockage). Figure 17 shows the effects of Reynolds number on lift for two incidences and two blowing rates for dynamic pressure from 10 to 57 psf. At $C_{\mu} = 0$, increase in R_e produces a slight increase in C_L , but above 0.7×10^6 the difference appears negligible. However, with blowing, the increase in C_L with R_e is greater. The magnitude of this trend with higher C_{μ} and R_e is not evident from this data. Additional evaluation will have to be achieved using the larger chord 64A-212 section data. It should also be mentioned here that maintaining a constant C_{μ} requires higher jet pressure ratios and velocities (P_d/p_{∞} and V_j) at higher Reynolds number. The kinetic energy of the jet (proportional to V_j^3) and jet turning thus increases with Reynolds number at constant C_{μ} so that increments in the Figure 17 curves with blowing may not be due solely to R_e .

In the data of Figure 9, air supply limitations produced an upper C_{μ} limit of roughly 0.12 at $q = 30$ psf. Additional C_{μ} up to 0.20 was obtained by reducing the dynamic pressure to 20 psf. The flagged data points of Figure 9 are obtained at this reduced Reynolds number, but the curves are faired slightly above these points using the increments of Figure 17, so that they are indicative of data for $R_e \approx 0.64 \times 10^6$.

Drag

Drag measurements taken by a rake employing 54 total head probes and 8 static probes were integrated using the methods of Betz and Jones (Reference 9) and modified (see References 5, 7, and 10) to account for the additional momentum of the jet so that

$$C_d = C_{d_{\text{rake}}} - \frac{\dot{m} V_{\infty}}{qc} = C_{d_{\text{rake}}} - C_{\mu} \frac{V_{\infty}}{V_j}$$

where \dot{m} is slugs/sec/ft of span in this case.

For most blown airfoil concepts, the jet momentum is converted into thrust, and drag is reduced with blowing. As Figure 18 shows, the same is true of the CCW at low blowing rates and moderate incidence. However, as higher C_u is reached, the jet turns further around the bluff trailing edge and into the oncoming freestream, producing a large viscous wake and increased profile drag. Also, as Figure 18 (a) in particular shows, as soon as the lift break due to leading edge separation occurs, drag rises very rapidly, even though lift drop-off has not occurred (i.e., no " C_u - stall" has developed). Also to be noted are the high values of zero blowing drag at low and negative incidence for increased nose droop, due primarily to separation from the underside of the nose.

Pitching Moment

As is typical of most blown airfoil schemes, the increased suction spike far aft on the airfoil generates rather large nose-down pitching moments about the quarter chord (0.25 undeflected chord). Figure 19 shows this to be the case with CCW sections as well, with largest values of nose-down moment occurring for low incidence and high blowing. Higher incidence of course adds leading edge suction peaks which oppose those at the trailing edge, and $C_{m_{25}}$ becomes less negative when flow remains attached. A similar result occurs with little or no droop, but is caused by the separated flow reducing the jet effectiveness of the aft surface and thus the nose-down pitching moment. In general, however, the conditions of highest jet efficiency are also those of largest nose-down moment.

NACA 64A-212/CCW AIRFOIL

Based on the initial confirmation by the 66-210/CCW section of high lift and drag generation at low incidence and blowing, and on the identification of roughly 30° droop as an effective leading edge device, the 64A-212/CCW section was tested to investigate: additional trailing edge configurations; effects of higher Reynolds number and slot height variations; and the aerodynamic properties of the airfoil section employed in the T-2C/CCW investigations of Reference 2. The configurations have

been identified in the previous section on models and in Figure 4, and the geometric parameters are listed in Table II.

Lift Augmentation

Figure 20 presents lift as a function of C_{μ} at constant corrected incidence for five configurations, all run at a dynamic pressure of 30 psf and slot height of 0.027 inches. The lift break due to leading edge problems at higher incidences on the 66-210/CCW is still observed, although for similar configuration (CCW829 and CCW241) it now appears to be occurring at much higher incidence and greater C_L for the larger chord model. Figure 21 shows a clearer comparison of these airfoils. At zero incidence, the relatively small difference in C_L is probably due to Reynolds number, while at 9° geometric incidence, the much larger differences are probably due to more severe separation on the smaller leading edge radius of the 66-210 airfoil. Leading edge separation control on CCW241 allows this airfoil to generate $C_L = 5.75$ at $C_{\mu} = 0.19$ and $\alpha_g = 9^\circ$ with a chord that is shortened 11.4 percent from the undeflected value. The pressure distributions for the 64A-212 airfoils show trends very similar to Figures 11, 12, and 13 for the smaller airfoil. In Figure 20 (e), CCW245 (no leading edge droop) displays separation problems similar to CCW800 in Figure 9 (a). Increased Reynolds number and nose radius appear to produce little improvement for the undrooped airfoils.

Configurations 242, 243, and 244 display the effects of trailing edge geometry variation, Figure 20 (b), (c), and (d). The 90° flap, an intermediate rotation angle for the shortened chord configuration of Figure 1, generates high C_L due primarily to the large effective camber and the fact that no chord loss exists in this partially rotated configuration. However, at higher C_{μ} , operation at incidence above 0 degrees produces stall (i.e., decreased C_L with increased α). The reduced radius trailing edge configuration (CCW 244, $r/c' = .021$) shows rather interesting trends when compared to the larger radius ($r/c' = .041$) of CCW241 for incidence of 6 degrees and less. Figure 22 (a) indicates that for no blowing and $\alpha_g = 3^\circ$, the aft lower surface camber produced by the rotated flap produces additional C_L for the larger radius trailing edge. However

at higher C_{μ} , the reduced radius trailing edge sustains pressure coefficients roughly twice that of CCW241 at the same blowing; this increased jet turning and entrainment produces significant additional C_L . At higher incidence, Figure 22 (b) shows the larger radius produces greater C_L in all cases. The aft camber predominates at low blowing, and the slightly farther forward slot (in terms of actual deflected chord) of CCW241 provides better upper surface boundary layer control at high incidence and higher C_{μ} , even though the smaller radius still provides better jet turning. The extended trailing edge configuration (CCW243 of Figure 4) shows significant lift increase over CCW241 by regaining the chord lost during the airfoil's flap rotation. A C_{μ} limit of roughly 0.08 was imposed by the model's long unsupported upper plenum surface between the adjustment screws; this expanded under pressure and consequently closed the blowing slot. However, based on similarity to CCW241, it is felt that the extrapolation to higher C_{μ} in Figure 20 (c) is valid.

The more conventional lift curves (C_L vs α_c at constant C_{μ}) are plotted in Figure 23, where the conventional 64A-212 data from Reference 8 is compared in Figure 23 (a). All configurations except CCW245 produce increases of at least 215 percent in $C_{L_{max}}$ at $C_{\mu} = .16$ over the conventional split flap airfoil at $Re = 6 \times 10^6$. Configurations 241, 243, and 244 all possess the conventional lift curve shapes with parallel slopes and positive stall angles, decreasing somewhat with increased C_{μ} (analogous to increased conventional flap deflection). However, CCW242 and 245 possess low or negative stall angles at higher C_{μ} , both apparently experiencing leading edge problems. The 90° flap data shows very little parallelism in lift curve slope. The operation of both airfoils seem to suggest problems in areas of positive α -operation (such as gusts or conventional landing flares) and in systems to control blowing and incidence schedules in these regions of operation.

In Figure 23, additional dashed curves are provided which correspond to the actual effective incidence, α_{eff} , at which the airfoil operates. These values are obtained from curves similar to Figure 24 for each airfoil. The effective incidence is α_c modified as described in Appendix A

to account for the induced downwash field due to vorticity shed at the tunnel wall intersection with the model, and is a function of lift coefficient (i.e., trailing edge suction peak). As can be seen, the corrections are significant. At zero blowing, $\alpha_{\text{eff}} = \alpha_c$ since no trailing edge peak is present. Using the effective incidence, Figures 25 and 26 summarize the data of Figure 23 in terms of C_L obtained at a higher value of C_μ over the α_{eff} range, and $C_{L_{\text{max}}}$ as a function of C_μ . Figure 27 plots $C_{L_{\text{max}}}$ versus effective stall angle for the five configurations at various values of C_μ .

Slot Height Variation

The momentum coefficient is a function of the parameters P_d/P_∞ , T_d , A_j , S and q and for a two-dimensional airfoil may be defined as

$$C_\mu = \frac{\dot{m}V_j}{qc} = \frac{\rho_j h V_j^2}{\frac{1}{2} \rho V_\infty^2 c} = 2 \frac{\rho_j}{\rho} \frac{h}{c} \left(\frac{V_j}{V_\infty} \right)^2$$

Figure 28 shows experimental variation in the momentum coefficient for configuration 241 at 9° geometric incidence. Although theoretical C_μ is not a function of incidence (see Appendix A), when mass flow is measured experimentally the significant pressure ratio is total pressure divided by local static pressure at the slot exit, which will of course vary with q , airfoil configuration, lift coefficient and incidence.

Figures 29 and 30 show the effects of slot height variations on lift for CCW241 and CCW244. Both figures show that for a constant value of C_μ , greater lift results from a smaller slot. This is of course due to the fact that the reduced slot area is compensated for by increased jet velocity to maintain a constant C_μ . Increased V_j implies increased kinetic energy, jet turning and lift augmentation. However, these figures show that there are crossovers where reduced slot height corresponds to reduced C_L at constant C_μ . It will be noted that these values of h/c' approach the lower limit of .0005 suggested in the Design Considerations section, where internal nozzle boundary layer thickness

begins to equal the slot height. Figure 29 also indicates lines of constant pressure ratio for the two larger slot heights; these lines represent constant jet velocity. In this case, an increase in slot height produces increased lift due to the resulting higher mass flow and C_u . The final decision concerning use of reduced or increased slot height will depend on the method of air supply: a fixed pressure ratio system would suggest increase in slot height, whereas a constant C_u system might suggest reduced slot height for improved performance (although the required power, proportional to V_j^3 , would be an important consideration).

In contrast to the detrimental effects of too small a slot height, Figure 30 also confirms the problem of partial jet detachment with large slots (see Reference 11 for additional details). Under certain conditions of high pressure ratio, large slot height, and reduced trailing edge radius, the Coanda mechanism begins to break down, and the jet turning is considerably reduced, if not totally eliminated, by jet detachment from the surface. The higher C_u data points for $h = .054''$ show significant scatter and indications of jet ineffectiveness; pulsating turbulence from the vicinity of the model confirmed this. The parameter h/c' is at the upper limit suggested in the Design Considerations. Thus, both upper and lower limits on slot height are confirmed, but the associated values of C_u which should not be exceeded at those parameters have not been established for all configurations and incidences.

Reynolds Number Effects

Use of the larger chord model allowed Reynolds number variation up to 2.4×10^5 , corresponding to $q = 50$ psf. The effects on lift are given in Figure 31 for CCW245 at $\alpha_g = 0^\circ$. Again, low C_u produces relatively little C_L variation with R_e , but at higher C_u a rather noticeable increase is present. The effects of R_e alone cannot be distinguished from the effects of increasing the pressure ratio (jet velocity) in order to maintain constant C_u at increased q . It is suggested that lines of constant

$C_{\mu} M_j$, $C_{\mu} P_d/P_{\infty}$ or $C_{\mu} (1 - \frac{V_j}{V_{\infty}})$ might separate the Reynolds number and jet velocity effects.

Drag

Results of variations in section drag coefficient with blowing in Figure 32 are very similar to those of Figure 18 for the small chord airfoil: (1) nose droop produces high C_d at no blowing and low incidence, (2) application of blowing brings on rapid drag reductions at all incidences, and (3) viscous mixing on the aft lower surface or leading edge separation result in rapid drag increases with increased C_{μ} . A number of the data points found in Figure 20 have had to be eliminated from the drag plots due to movement of the momentum deficit region of the wake off the lower limits of the rake. In addition, data scatter at higher C_{μ} is attributable to more sparsely located total head probes near this lower limit of the rake. The absence of drag data for CCW242 at higher C_{μ} is due to large regions of turbulence behind the 15% chord flap perpendicular to the flow. (This large turbulent wake could produce serious problems when applied to a finite wing aircraft if the wake should fall on the horizontal tail surface.) With the above limitations in mind, a comparison of the drag data for the five configurations at $C_{l_{max}}$ points of Figure 26 is made in Figure 33. With the exception of the 90° flap case, all configurations show a rapid decrease in C_d with C_{μ} , followed by either a drag rise or a change in slope which indicates the beginning of a drag rise. In contrast, CCW242 shows constantly decreasing drag with no apparent change in slope indicative of a drag rise; this is due to the fact that $C_{l_{max}}$ for this airfoil always occurs at relatively low incidence, and to the fact that the jet can turn no further than 90° due to the existence of the flap surface. A characteristic jet flap mode with a higher degree of thrust recovery is evident.

Pitching Moment

The variation of quarter-chord (25 percent undeflected chord) pitching moment with C_{μ} at constant α_c is presented for CCW241 in Figure 34. As is characteristic of almost all high lift schemes, the

suction peak produced by the trailing edge device (be it blowing or a flap) generated additional nose-down pitching moment. There appears to be little variation with incidence (except above 12°), indicating that at constant C_μ the trailing edge suction peak is dominant over the variation in leading edge peak due to incidence. Figure 35 presents C_l vs C_{m25} along lines of constant incidence and C_μ for all five configurations. The larger nose-down moments associated with the 90° flap case are due to the near vertical component of jet thrust acting parallel to the flap surface with the high thrust recovery characteristic of jet flaps. This thrust contribution to moment is considerably reduced for all the bluff trailing edge configurations due to jet mixing. However, the extended trailing edge configuration (CCW243) does exhibit somewhat higher moments than the other bluff versions in that its jet suction peak is located near the undeflected airfoil trailing edge, roughly .15c further aft. Figure 36 points out these relative comparisons by plotting the pitching moment corresponding to $C_{l_{max}}$ at various C_μ . In addition to the above explanation, the greater nose-down moments of the 90° flap also occur because $C_{l_{max}}$ for this airfoil is always at low incidence, where the more favorable aft pressure gradients serve to create even higher jet suction peaks over the Coanda surface, and where the counter-acting leading edge suction peaks are less.

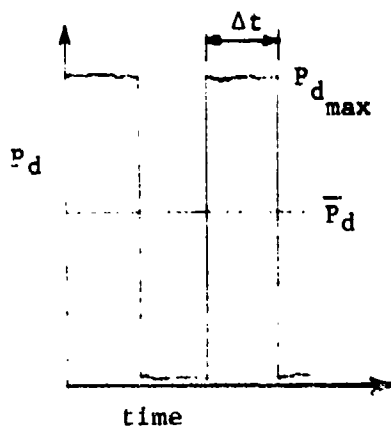
PULSED BLOWING INVESTIGATION

Investigations conducted with pulsed unsteady blowing over a blown flap (Reference 12) and on a cambered CC ellipse (Reference 13) indicated that definite additional lift augmentation above the steady-state value could be obtained by this technique. For equal values of effective momentum coefficient (time-averaged C_μ in the unsteady case), the pulsed blowing produced higher trailing edge suction peaks and lift augmentation because of the instantaneous higher values of duct pressure and jet velocity which produced greater flow entrainment and jet turning. This of course allows a desired lift coefficient to be produced at reduced mass flow rates. The results of Reference 12 indicate this reduction in required \dot{m} to be as much as 50 percent. Both investigations identified optimum pulsing frequencies, above or below which lift generation was less.

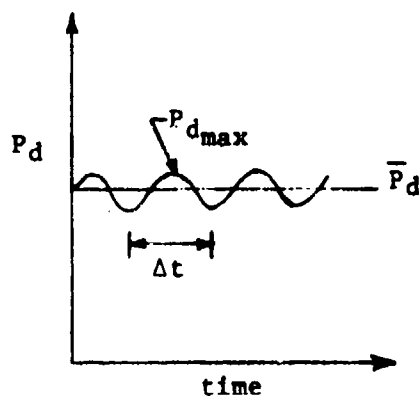
A similar investigation was conducted on configuration CCW244, which has the reduced trailing edge radius ($r/c' = .021$), to determine if similar reductions in required mass flow could be realized for a configuration of the CCW. Appendix A describes the test setup and data reduction techniques employed; the major difference from the previous tests was the insertion of a rotating butterfly valve between the venturimeter used to measure system mass flow and the plenum of the model. Figure 37 plots averaged lift and momentum coefficients as functions of pulsing rate. The lift is averaged automatically by the damping of the static pressure tubing, while mass flow is averaged by recording mean readings of the venturimeter pressures. Duct pressure and jet velocity are obtained by identifying mean values of P_d from oscillograph traces of the model plenum pressure transducer output. There is no apparent trend in lift augmentation as a function of pulsing rate from 0 to 69 cycles per second in Figure 37, with the exception that all unsteady data appears to be less effective than the steady case ($\omega = 0$ cps). It was suggested by the lack of any smooth trend with variation of ω that some error was being introduced by the venturimeter. Figure 38 plots mean mass flow recorded from this flow meter as a function of line pressure upstream of the pulsing valve. As data from Reference 12 confirms, a given mass flow at the slot should always require higher upstream line pressure than the steady case, for which the cyclic valve is producing no pressure loss. However, as Figure 38 shows, mean mass flow for the 20 and 40 cps cases is produced at lower line pressure than the steady case. It was concluded that the venturimeter was being adversely affected by the pressure fluctuations feeding back upstream from the butterfly valve, and its measurements were unreliable.

As an alternative, mean duct pressure \bar{P}_d read from the oscillograph traces was used with a previous calibration to determine slot height deflection under pressure, and the resulting slot areas and pressure ratios were substituted into the isentropic equations in Appendix A to yield mean mass flow, jet velocity and C_u . The results in Figure 39 indicate that for the cases investigated, pulsed blowing has little discernable lift augmenting effect. This may be due to two aspects of

the test setup. The pulsing device of Reference 12 produced a square wave variation of duct pressure in which the minimum was almost zero-- this produced a maximum value almost twice the mean, and thus jet turning and augmentation that were considerably higher than for the mean C_D . The pulsating valve used for the present investigation produced a sinusoidal pressure variation in which the maximum pressure was never more than 15 percent higher than the mean or comparable steady state pressure. Thus the augmentation was minimal. The comparison is sketched below.



Reference 12



Present Investigation

Secondly, the trailing edge configuration was probably not ideal for this investigation. The small radius ($r = .4375''$) and larger slot produced $h/r = 0.0617$, which under conditions of higher jet velocity could produce detrimental effects. Furthermore, as Reference 12 indicates, the vorticity produced by jet pulsing which is responsible for the additional augmentation begins to decay when the time intervals between the pulsing become greater than approximately $50 r/U_{\max}$, where U_{\max} is the maximum value in the wall jet velocity profile. Thus small radii are detrimental to unsteady augmentation under higher jet velocities or greater pressure ratios. Therefore, considering this along with the ineffective pulsing valve used, the present investigation did not verify the positive effects of pulsed blowing determined in References 12 and 13, but did suggest more appropriate model and valve configurations for any further experiments.

SPOILER INVESTIGATION

The application of CCW airfoil sections promises to lower the approach and take-off speeds of fixed wing aircraft to the point where conventional aerodynamic control devices may become ineffective. Reference 2 data shows that ailerons on a partially blown wing can be exposed to severe spanwise flow or outboard separation, and in addition can generate adverse yawing characteristics. It was surmised that spoilers, located upstream of the blown trailing edge, would be a far more effective roll control and would not produce the adverse yaw problem. The possibility of a spoiler being too effective when deflected into the boundary layer just upstream of the tangential jet led to a preliminary two-dimensional investigation. The model, a 20.6 percent thick ellipse with 3.6 percent circular arc camber and $r/c = 0.045$ had previously been installed in the 3- x 8-foot inserts, and was felt to be characteristic of the trailing edge region of a CCW profile even though it was a rotor blade section. Figure 5 depicts the model and the two spoiler configurations employed. Both were made from angle iron to provide rigidity over the 36-inch span, and were located so as to pivot about a point on the upper surface at $0.70c$. The spoiler length c_s was $0.0982c$, and deflection relative to the airfoil chord was from -9° (flush to the surface) to $+51^\circ$. The slotted version of the full spoiler was constructed by removing half the spoiler length nearest to the airfoil, so that part of the airfoil boundary layer flow could penetrate through to the jet slot. All tests were run at zero airfoil incidence at $q = 20$ psf ($Re = 0.66 \times 10^6$). Wall blowing to prevent three-dimensionality was not employed. Data are corrected for tunnel blockage and boundary constraints, but not for induced incidences.

Figure 40 presents lift as a function of blowing for various spoiler deflections and types, and for the clean airfoil ($\delta_s = -9^\circ$). The effect on C_L of deflection of the full spoiler is quite severe; supercirculation is heavily restricted and the airfoil behaves quite like a jet flap, with lift almost linearly proportional to blowing. Even with the small spoiler deflection of zero degrees (a perpendicular aft-facing step of only 3 percent chord), lift at $C_{\mu} = 0.16$ is reduced to 28 percent of the clean

airfoil value. The slotted spoiler shows some improvement: lift returns to the more conventional form where $C_L = f(\sqrt{C_D})$ and supercirculation is partly restored. Figure 41 plots lift loss ($\Delta C_L = C_L - C_{L_{clean}}$) as a function of spoiler deflection and C_D . The full spoiler possesses the undesirable trait that lift loss is not linearly proportional to spoiler deflection; the majority of reduction occurs between -9° and 0° . The slotted spoiler is more linear and should have more desirable control characteristics.

Figure 42 shows that at an increased blowing rate, the separated flow behind the full spoiler at $\delta_s = 0^\circ$ can be made to reattach due to increased flow entrainment at higher C_D . The effect of Reynolds number is seen to be minimal for this case, at least below the reattachment point, but there appears to be some Reynolds number effect on the clean airfoil.

The increase in drag due to spoiler deflection is evident in Figure 43; a smaller increase in drag occurs when using the slotted spoiler. Similar trends in pitching moment are seen in Figure 44; nose-down values are greatly reduced by spoiler deflection. Both of these trends may provide effective control when applied to fixed wing operation, although the non-linearity with δ_s may present a control system design problem. Furthermore, it appears that the slotted spoiler at relatively low deflection should provide a more satisfactory control system for the CCW. Reduced lateral span of the spoiler might reduce the roll sensitivity to deflection, but this parameter and deflection schedules will have to be determined relative to a specific three-dimensional configuration.

CONCLUSIONS

A series of subsonic two-dimensional investigations conducted on a number of configurations of Circulation Control Wing airfoil profiles has confirmed the ability of thin sections employing the concept to generate high lift at relatively low values of momentum coefficient and incidence. A data base has been established for use in predicting the aerodynamic characteristics of aircraft with CC trailing edges, and the effects of variation of a number of aerodynamic and geometric parameters

on airfoil performance have been identified. The experimental data obtained from the four investigations yielded the following conclusions:

NACA 66-210/CCW Airfoil (tested over a range of α , C_{μ} , δ_{LE} , and R_e)

- A 0.15c leading edge droop of 43.6° and $C_{\mu} = 0.24$ produced a section $C_L = 5.5$ and satisfactory airfoil operation at higher positive incidence (uncharacteristic of CC rotor blade sections). Reduced droop angle resulted in leading edge separation, reduced jet turning, strong breaks in the C_L vs C_{μ} curves, rapid drag rise at onset of separation, and failure of the section to operate effectively at positive incidence. Similar results were observed for Krüger leading edge flaps.
- Effects of Reynolds number on lift were minimal with no blowing, but produced positive lift increments with increased R_e at constant C_{μ} .
- For attached leading edge flow, increased C_{μ} initially reduced drag but eventually caused a rapid drag increase as lower surface viscous mixing occurred. Separated flow at the leading edge caused immediate drag increase.
- Pitching moment rapidly became more negative with blowing, and took on the largest negative values at reduced incidence and greatest jet effectiveness.

NACA 64A-212/CCW Airfoil (tested over a range of α , C_{μ} , δ_{LE} , h , R_e and trailing edge configuration)

- The 2-D section representing the reduced chord T-2C/CCW airfoil yielded $C_L = 5.95$ at $C_{\mu} = 0.20$ and $\alpha_c = +9^\circ$; this was extrapolated to $C_L = 6.30$ for the extended trailing edge configuration at the same blowing and slightly lower incidence.
- The greatest net lift was generated by the 90° flap configuration due to its full flap chord and high effective camber, but it displayed a number of disadvantages subtracting from its suitability. These include very large nose-down pitching moment, large turbulent wake, low or negative stall angles and negative lift curve slope at most positive incidences.

- A reduction of 50% in the trailing edge radius of the shortened chord airfoil produced comparable or better lift performance due to very high jet effectiveness. Its performance was slightly reduced compared to the larger radius at higher incidence due to its slightly further aft slot location in terms of effective chord.
- Drag, pitching moment, and Reynolds number trends were similar to those of the 66-210/CCW airfoil, with the exception of the 90° flap discussed above.
- Slot height increase can have differing effects on lift augmentation, depending on the mode of operation of the blowing system. Increased h yielded reduced C_L for constant values of C_u due to reduced jet kinetic energy, but increased C_L resulted if the pressure ratio was retained constant and h increased. Suggested upper and lower limits on slot height were confirmed, beyond which adverse effects on lift augmentation occurred.

Pulsed Blowing Investigation (variation in C_u and ω)

- Results showed that no benefits were gained from unsteady blowing as performed. This was due to the poor response pattern of the valve and a small trailing edge radius on the airfoil.
- A valve capable of a square wave variation of P_d with time (resulting in much higher $P_{d_{max}}$ for a given mean duct pressure) and a larger trailing edge radius appear necessary to realize any lift augmentation due to pulsed blowing.

Spoiler Investigations (variation in C_u , δ_s and spoiler type)

- The full spoiler showed very large reductions in C_L , C_D and nose-down pitching moment as compared to the clean airfoil. All reductions appeared to be non-linear with spoiler deflection.
- The slotted spoiler showed reductions in lift, drag, and pitching moment not quite as large as those for the full spoiler, and the variations appeared to be much more linear with deflection.

RECOMMENDATIONS

The following recommendations are suggested by the present investigations and by the listed conclusions:

- Whereas leading edge droop appeared to control leading edge separation, it was detrimental at lower incidence and appeared to still allow some undesirable boundary layer development at high incidence and lift. A more effective leading edge device, such as a slat or leading edge tangential blowing, should be substituted for droop in a future experiment.
- The significant performance variations with trailing edge configuration suggest that other geometries might prove more optimum. The deviation from circular into cycloidal or other geometrically similar shapes is suggested. A parametric study of trailing edge variation needs to be undertaken, and the development of an analytic method able to predict the viscous characteristics of this type of airfoil is strongly suggested.
- To further investigate the possible advantages of pulsed blowing, an additional 2-D investigation is recommended with a larger trailing edge radius and an alternate pulsing mechanism which produces larger $P_{d_{max}}$ relative to the mean duct pressure.
- Additional spoiler investigations are suggested where small deflections in the range of -9 to 0 degrees for the full spoiler, and -9 to 25.5 degrees for the slotted spoiler are evaluated for possible linearity in those ranges. Also, a spoiler on a 3-D configuration should be investigated in which variations in spanwise length and lateral location of the spoiler are conducted.

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APPENDIX A

MODELS, EXPERIMENTAL APPARATUS, AND TECHNIQUE

MODELS

Both CCW modifications of conventional airfoil sections were based on the geometric parameters of Tables I and II and are shown in Figures 3 and 4. Coordinates of the airfoils ahead of the slot are identical to the original airfoils with the exception of deflected leading edge devices. Leading edge droop for both airfoils involved rotation of the nose about a lower surface hinge point at 15 percent of the original chord, and filling the resulting gap with a circular arc with center at the hinge point. Slot height was adjustable by means of compression and jack screws; the slot was contoured to be the minimum area of a smoothly converging nozzle. Nominal slot height is the value measured with feeler gage stock with zero plenum pressure. Slot expansion with pressure was measured for each configuration and found to be linear for the 66-210/CCW airfoil, but of no specific trend for the 64A-212/CCW airfoil since the plenum geometry was not always identical for all configurations. On the 66-210/CCW section, the trailing edge was fixed in the fully rotated position of Figure 1 and only the slot height and droop were variable. For the 64A-212/CCW configuration, the trailing edge configurations were interchangeable as shown in Figure 4, and droop and slot height were variable. The CC rotor airfoil used in the spoiler test (Figure 5) was built by Lockheed-California Company under contract for application to a research rotary wing aircraft; for the present tests, only the deflection of the added spoilers was variable. All models had a chordwise distribution of static pressure taps at or near the midspan, and one to three rows of spanwise static taps to measure two-dimensionality from wall to wall. Plenum total pressure and temperature were recorded by a total pressure probe and thermocouple located in the plenum near midspan.

TEST APPARATUS AND TECHNIQUE

The small chord model 66-210/CCW airfoil was installed in the DTNSRDC 15- x 20-inch subsonic model tunnel, spanning the short dimension of the test section and attached to circular wall mounts which rotated to vary incidence. All pressure data from the airfoil and wake rake was recorded automatically by a 144-port scannivalve system, punched on paper tape, and reduced by XDS-930 digital computer. Mass flow into the model was measured by orifice plate or venturimeter in the supply line. Test technique was identical to that employed in previous tests of elliptic rotor blade airfoils (Reference 1) and presented in detail in Reference 7. One exception was that the strong three-dimensional induced effects produced by interference between wall boundary layer and jet adverse pressure gradient were controlled by tangential blowing from the tunnel vertical sidewalls at stations ahead of the nose and on the upper surface ahead of the jet suction peak. Blowing rates from these jets were set to those values which best restored two-dimensionality to the spanwise pressure taps as displayed on manometer boards.

Both the 64A-212/CCW and the elliptic airfoil were installed on rotatable endplates in the walls of the 3- x 8-foot 2-D inserts installed in the DTNSRDC 8- x 10-foot subsonic South Tunnel. Figure 6, 7, and 8 show this installation, and Reference 14 describes in detail the development, calibration and operation of this facility. Data recording, mass flow measurement, and test technique were similar to the small tunnel investigations, with the exception that only one set of wall blowing slots was used to control two-dimensionality due to limited facility air supply. It was found later that these were not totally effective, and it was necessary to correct the data for induced effects, as discussed below. For the spoiler tests, no wall blowing was employed at all, since only data trends were of interest there.

DATA REDUCTION AND CORRECTIONS

As mentioned previously, all force and moment data was from integration of model static pressures or deficits in wake momentum distributions. All coefficients have been nondimensionalized by the original

chord which connects undeflected leading and trailing edges (8 inches for 66-210, 24 inches for 64A-212, and 10.6 inches for the cambered ellipse). Incidence is referenced to this chord, and Reynolds number is based on it as well. This allows direct comparison of all airfoil results. It should be noted however, that the pressure distributions for the 66-210/CCW airfoil are plotted in terms of x/c' to stretch out the longitudinal coordinates. Normal and axial force coefficients from pressure integration (subscript "p") were modified by the jet thrust component and then combined to yield the lift coefficient:

$$C_{L_j} = C_{n_p} + C_{\mu} \sin \delta_j \quad \text{where } C_{n_p} = \int C_p \frac{dx}{c}$$

$$C_{A_j} = C_{a_p} - C_{\mu} \cos \delta_j \quad \text{where } C_{a_p} = \int C_p \frac{dy}{c}$$

$$C_L = C_n \cos \alpha_c - C_a \sin \alpha_c$$

where δ_j is the angle between the chord and line of jet thrust, and α_c is the corrected incidence. The drag integration employs the methods of Betz and Jones (Reference 9) to determine the drag coefficient $C_{d_{rake}}$, which must then be modified (References 5, 7 and 10) to account for the additional jet momentum in the control volume:

$$C_d = C_{d_{rake}} - \frac{\dot{m}V_{\infty}}{qc} = C_{d_{rake}} - C_{\mu} \frac{V_{\infty}}{V_j}$$

The pitching moment coefficient $C_{m_{25}}$ is determined from integration of the normal and axial components of static pressure and the jet thrust reaction about the quarter-chord point. The freestream dynamic pressure is corrected for solid blockage as follows:

$$q = q_u (1+2\epsilon)$$

$$\text{where } \epsilon = 0.822 \lambda_2 (t/h_t)^2$$

and λ_2 is an airfoil shape factor from Reference 15.

The above coefficients are referenced to this corrected value of dynamic pressure, and corrections for tunnel wall constraint (induced camber) are then applied (where subscript "u" is the uncorrected value as determined above):

$$C_l = C_{l_u} - \frac{\pi^2}{48} \left(\frac{c'}{h_t} \right)^2 C_{l_u}$$

$$C_{m_{25}} = C_{m_{25u}} + \frac{\pi^2}{192} \left(\frac{c'}{h_t} \right)^2 C_{l_u}$$

$$\alpha_c = \alpha_g + \frac{57.3\pi}{96} \left(\frac{c'}{h_t} \right)^2 (C_{l_u} + 4C_{m_{25u}})$$

The momentum coefficient was calculated as

$$C_\mu = \frac{\dot{m}V_j}{qS} = \frac{\dot{m}V_j}{qc} \quad (\text{if } \dot{m} \text{ is per unit span})$$

where the total mass flux (\dot{m}) was recorded experimentally from the installed flowmeter, and the jet velocity was calculated assuming an isentropic expansion from plenum total conditions to freestream static condition:

$$V_j^2 = 2RT_d \left(\frac{\gamma}{\gamma-1} \right) \left[1 - \left(\frac{P_\infty}{P_d} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

For the pulsed blowing cases where it was necessary to calculate the isentropic mass flows, these were determined as follows:

$$\text{choked flow: } \dot{m} = A_j P_d \sqrt{\frac{\gamma}{RT_d}} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

$$\text{unchoked flow: } \dot{m} = A_j P_d \left\{ \frac{2\gamma}{(\gamma-1)RT_d} \left[\left(\frac{P_m}{P_d} \right)^{2/\gamma} - \left(\frac{P_m}{P_d} \right)^{\frac{\gamma+1}{\gamma}} \right] \right\}^{1/2}$$

For the 64A-212/CCW airfoils, one additional set of data corrections was applied. In this case, the tangential tunnel wall blowing did not prove totally effective in eliminating the three-dimensionality and induced effects discussed in the text, and it was evident that the airfoil was operating at an effective incidence less than α_c . As discussed in References 5, 7, and 10, this effective incidence could be determined by matching potential flow pressure distributions with the experimental distributions at the same effective C_l over a range of incidence, and determining that incidence at which the theoretical and experimental leading edge stagnation points coincided. This would be the true effective incidence of the experimental data. With increasing C_l , this incidence becomes considerably less than α_c . Incidence correction curves similar to Figure 24 were calculated in this manner for each configuration of the 64A-212/CCW airfoil, and the lift curves of Figure 23 were corrected accordingly.

PULSED BLOWING APPARATUS

For this investigation, a housing containing a rotating flat disc driven by a variable frequency motor was installed in the air supply line roughly 8 feet downstream of the venturimeter. When this butterfly valve disc was perpendicular to the flow, the entire cross sectional area of the supply line was closed off. However, for frequencies of rotation between 20 and 69 cycles per second, the area was closed off for such a small portion of the period that the pressure downstream in the model plenum never varied more than 15 percent from the mean plenum pressure. As discussed in the text, the sinusoidal plenum pressure variation was

recorded by oscillograph traces and the mean was used to calculate jet velocity. Upstream and differential pressure across the venturimeter were sensed by transducers whose output was displayed on TIC readout units, where the mean was recorded by hand. When these venturimeter readings proved questionable, the isentropic mass flow was calculated using the previous equations and the calibrated variation of slot height with duct pressure as shown below.

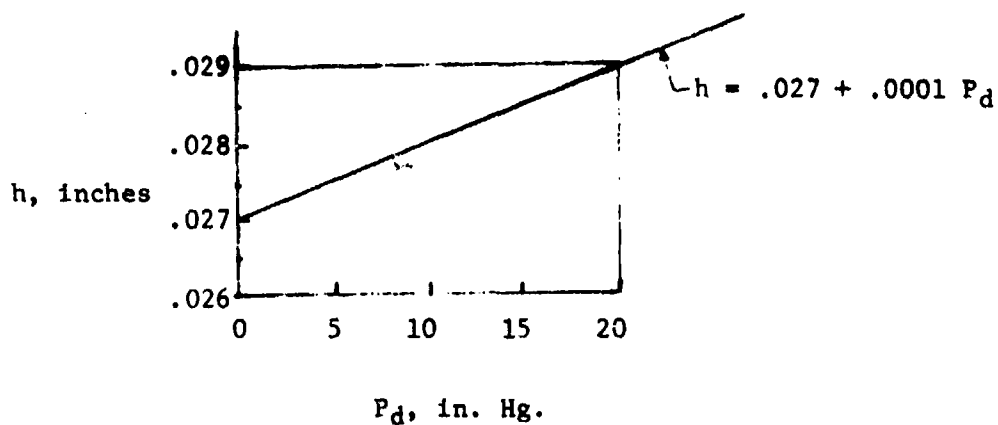


TABLE - I GEOMETRIC PROPERTIES OF NACA 66-210/CCW
AIRFOIL SECTIONS

Parameters common to all four configurations:

$c' = 7.083''$	$c = 8.000''$
$\delta_f = 180^\circ$	
$r = 0.276''$	
$h = 0.009''$	
$r/c' = 0.03897$	$r/c = 0.0345$
$h/r = 0.0326$	
$h/c' = 0.00127$	$h/c = .00113$
$x_{slot} = 6.819''$	
$x_{slot}/c' = 0.9627$	$x_{slot}/c = 0.8524$
$t = 0.813''$	
$t/c' = 0.1148$	$t/c = 0.0102$
$r_{LE} = 0.0530''$	
$r_{LE}/c' = 0.00748$	$r_{LE}/c = 0.00662$
$x_{droop} = 1.200''$	
$x_{droop}/c' = .1694$	$x_{droop}/c = .1500$

Leading Edge Deflection:

Configuration	δ_{LE} , deg	c_{droop}/c	c_{droop}/c'
CCW			
800	0	.8854	1.00000
815	15.3	.8879	1.00282
829	29.0	.8853	0.99989
844	43.6	.8711	0.98385

(c_{droop} is chord from drooped leading edge to rotated trailing edge,
but is not used in coefficient calculation)

TABLE II - GEOMETRIC PROPERTIES OF NACA 64A-212/CCM AIRFOIL SECTIONS
 $c = 24.00"$, $x_{slot} = 20.40"$ ($= 24.00"$ for CCM 243), $t/c = 0.120$, $t_{LE}/c = .00994$

Configuration, CCM-	δ_{LE} , deg	δ_f , deg	c', inches	r, inches	h, inches	r/c'	h/r	h/c'	$\frac{x_{slot}}{c}$	t/c'	r/c	h/c	$\frac{x_{slot}}{c}$	q, psf
241 (Rotated flap)	30	180	21.272	0.875	0.027	.04113	.03086	.00127	.9590	.1354	.03646	.00113	.8500	10, 20, 30, 40, 50
	↓	↓	↓	↓	0.020	↓	.02286	.00094	↓	↓	↓	.00083	↓	30
	↓	↓	↓	↓	0.014	↓	.01600	.00000	↓	↓	↓	.00058	↓	30
	↓	↓	↓	↓	0.007	↓	.00800	.00000	↓	↓	↓	.00029	↓	30
242 (90° Flap)	30	90	21.272	0.875	0.027	.04113	.03086	.00127	.9590	.1354	.03646	.00113	.8500	30
243 (Extended T.E.)	30	180	24.875	0.875	0.027	.03318	.03086	.00109	.9648	.1158	.03646	.00113	1.0000	30
244 (Reduced T.E.)	30	180	20.835	0.4375	0.027	.02100	.06171	.00130	.9791	.1382	.01823	.00113	.8500	30
	↓	↓	↓	↓	0.014	↓	.03200	.00067	↓	↓	↓	.00058	↓	↓
	↓	↓	↓	↓	0.054	↓	.12343	.00259	↓	↓	↓	.00225	↓	↓
	↓	↓	↓	↓										
245 ($\delta_{LE} = 0$)	0	180	21.272	0.875	0.027	.04113	.03086	.00127	.9590	.1354	.03646	.00113	.8500	10, 20, 30, 40, 50

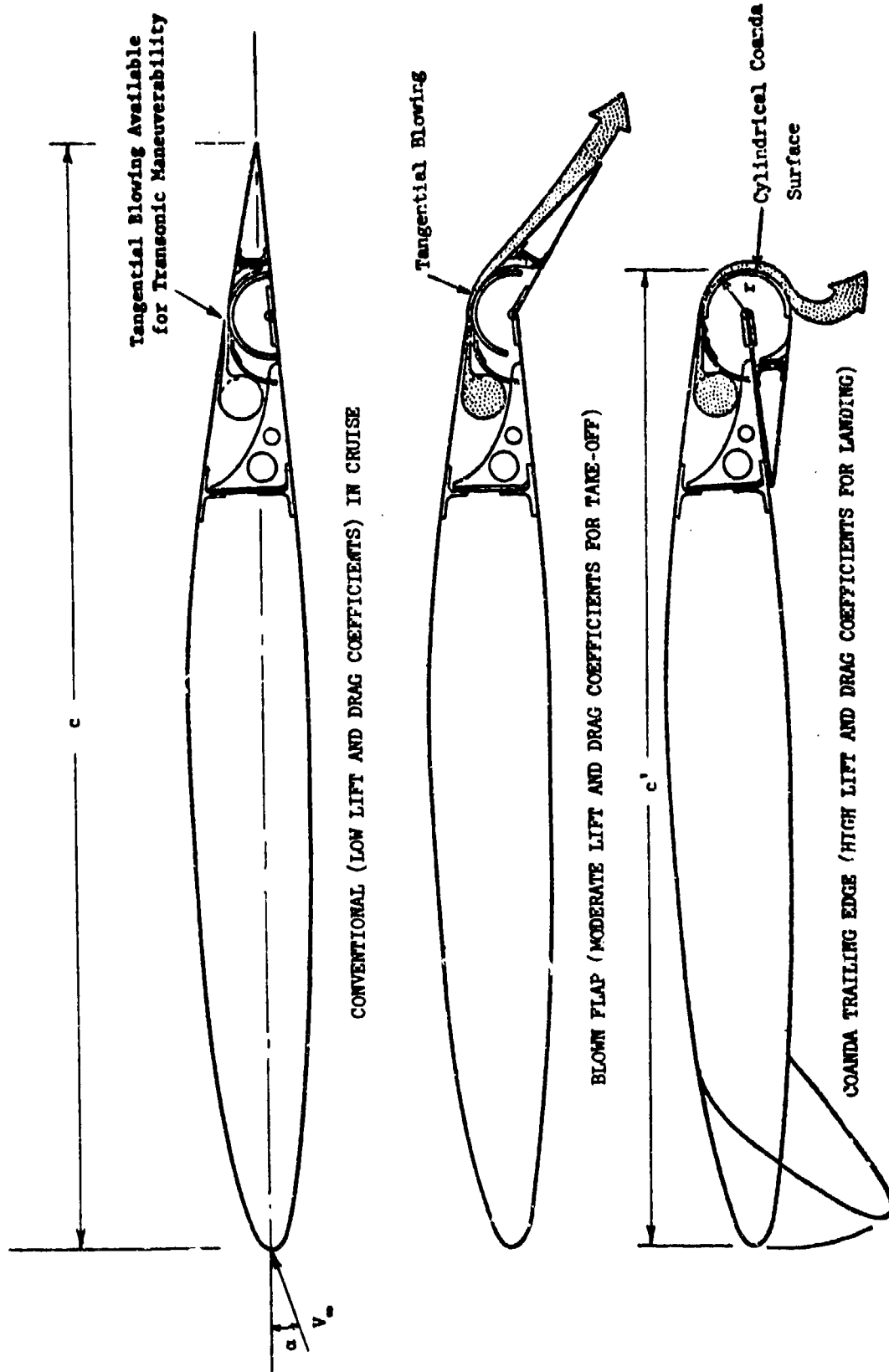
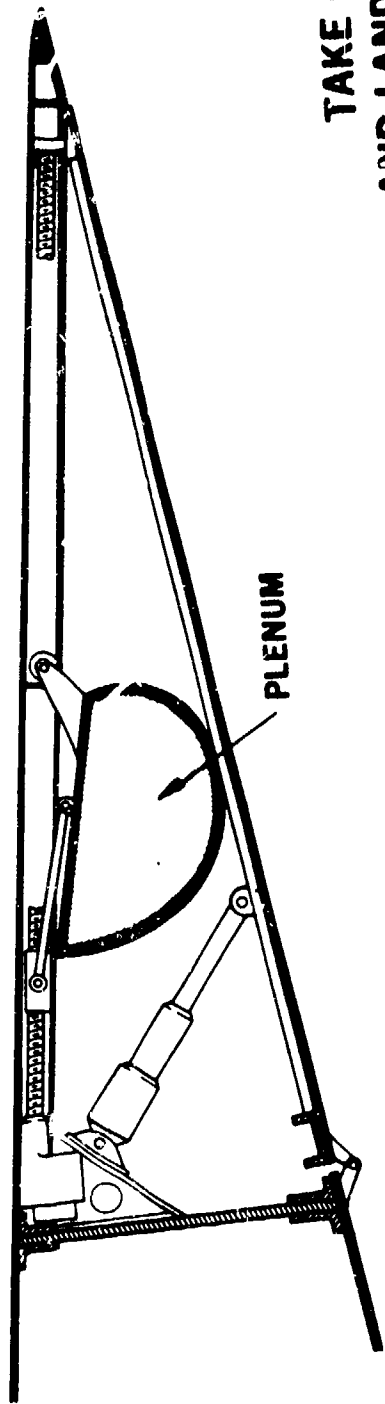


Figure 1 Circulation Control Wing Modes of Operation, Rotating Short Chord Flap Configuration

CRUISE



**TAKE OFF
AND LANDING**

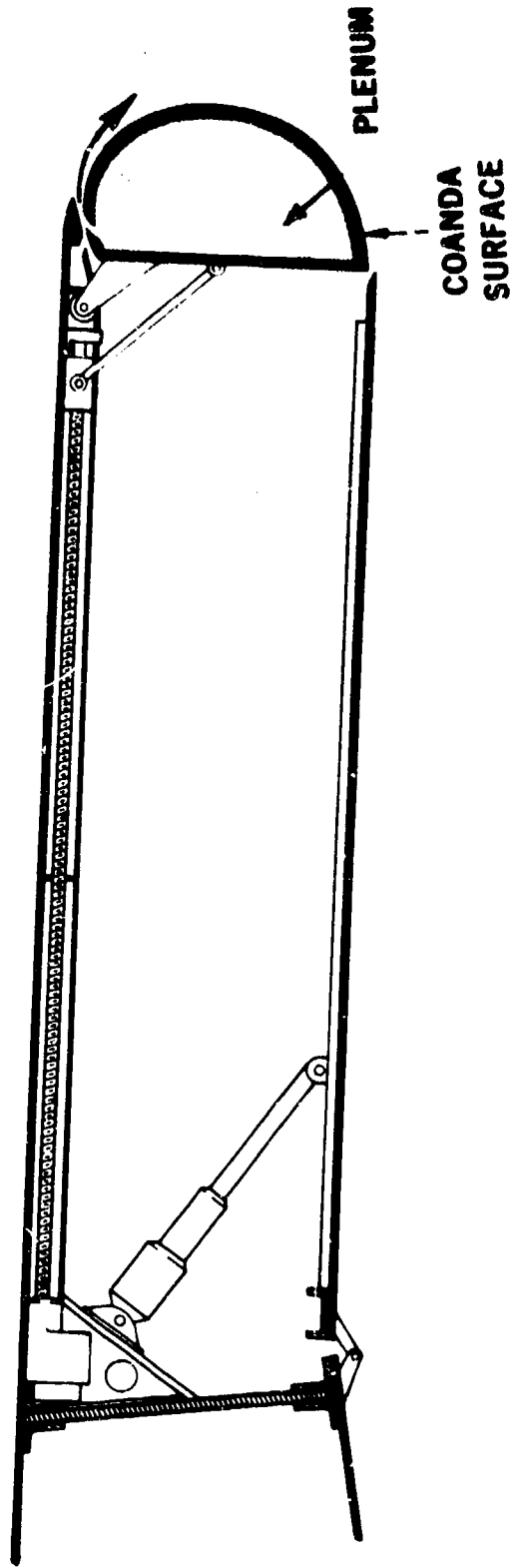


Figure 2 - Extended Trailing Edge Configuration

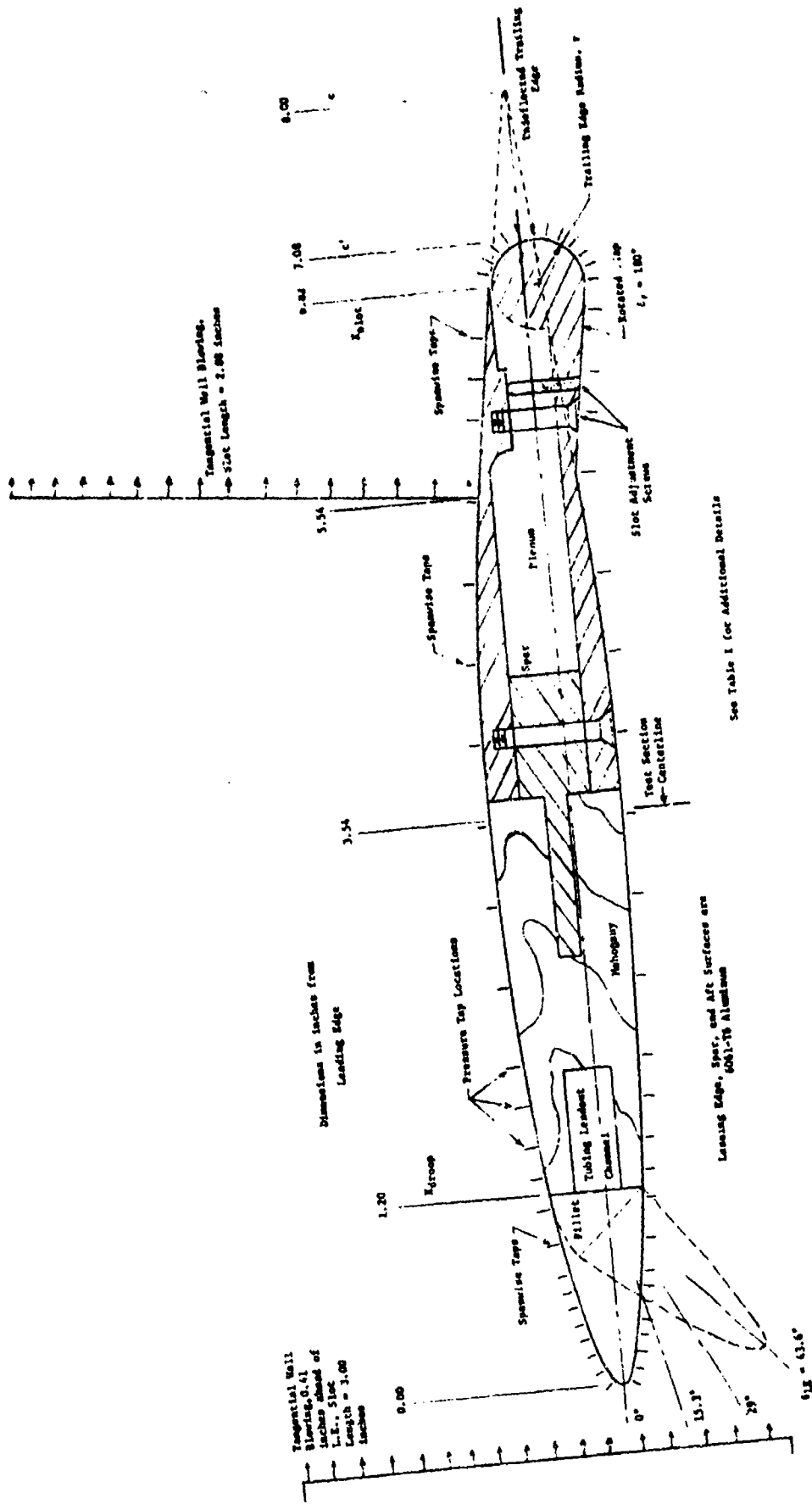


Figure 3 - Model Geometry, NACA 66-210/CCW Airfoil

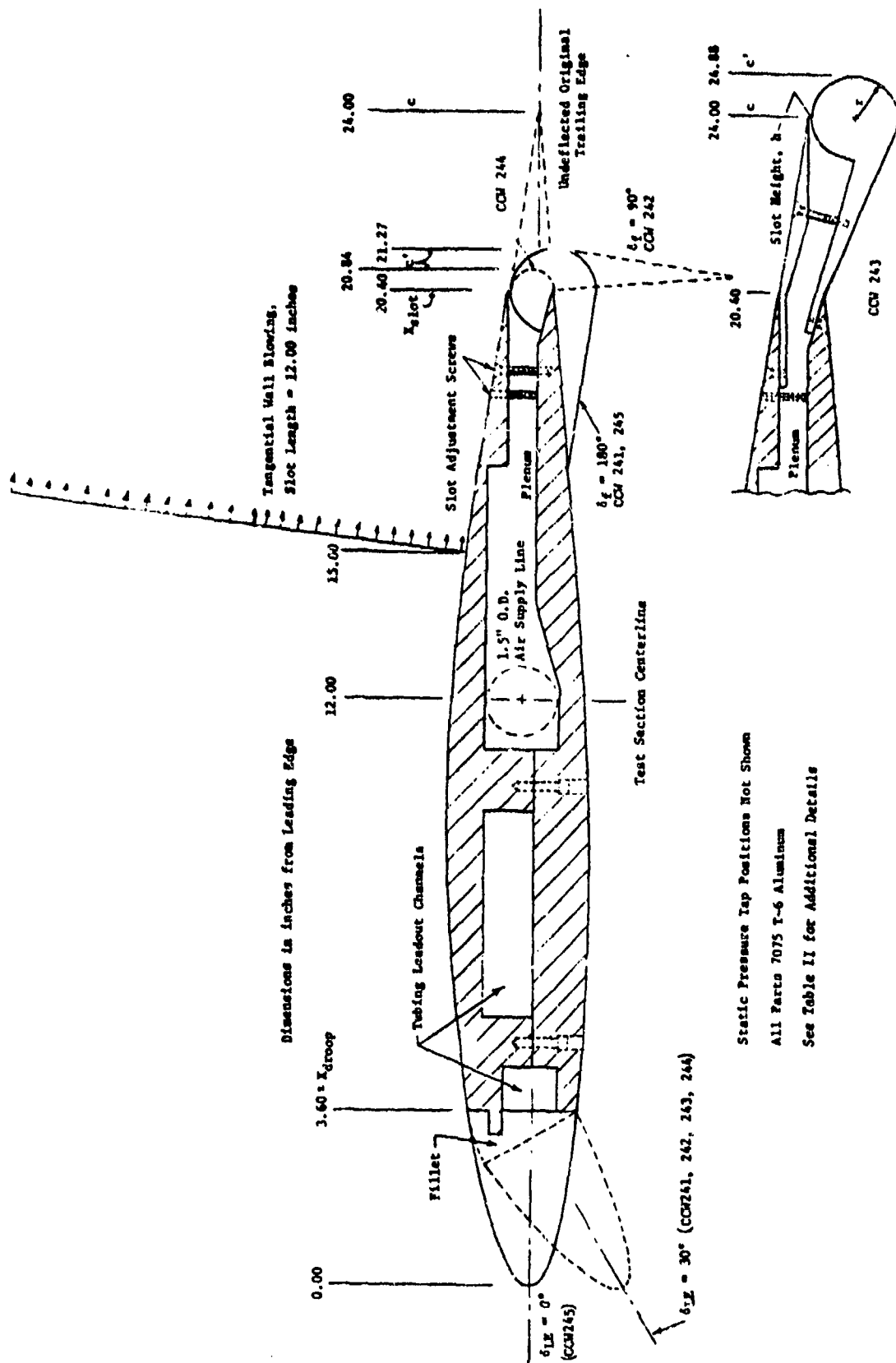


Figure 4 - Model Geometry, NACA 64A-212/CCW Airfoil

$c = 10.18$
 $\tau = .458$
 $h = .005$
 $t/c = .206$
 $\delta/c = .036$
 $\tau/c = .045$
 $h/c = .00049$
 $h/\tau = .0109$
 $X_T = 7.123$
 $X_{T/c} = .700$

$X_{slot} = 9.90$
 $X_{slot/c} = .9725$
 $C_s = 1.00$
 $C_{s/c} = .0982$

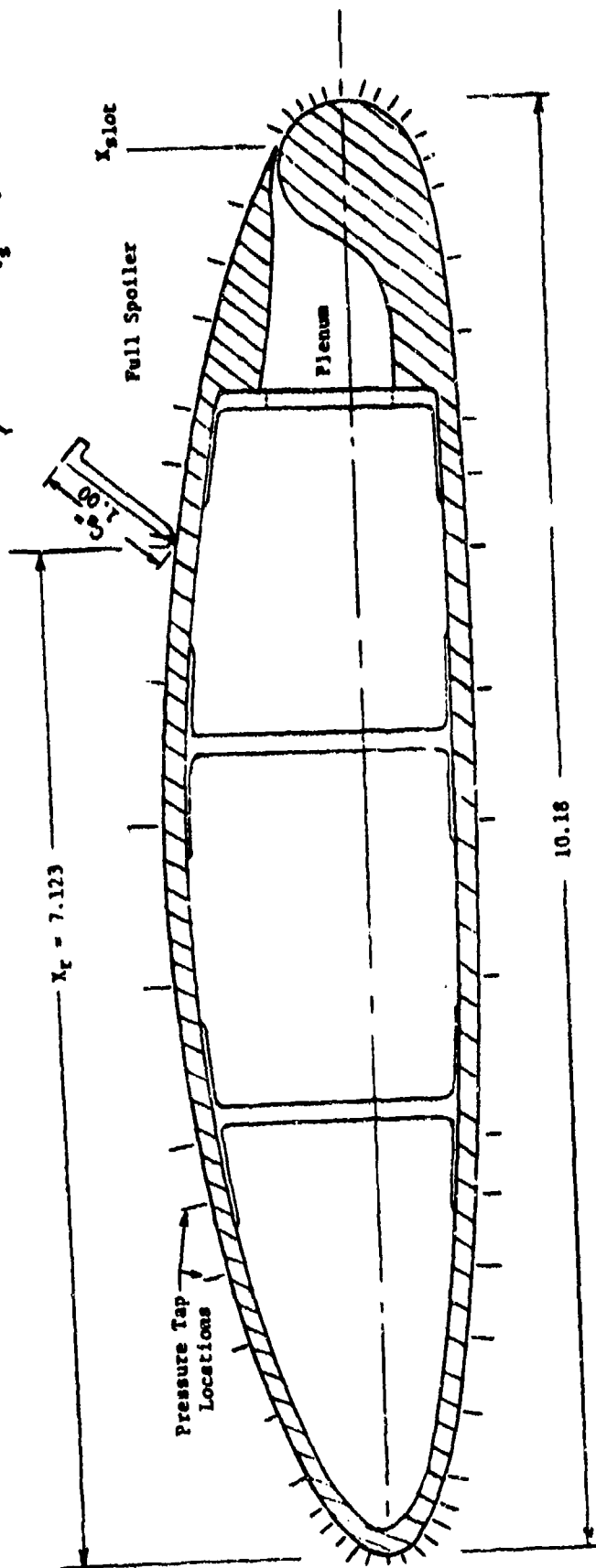
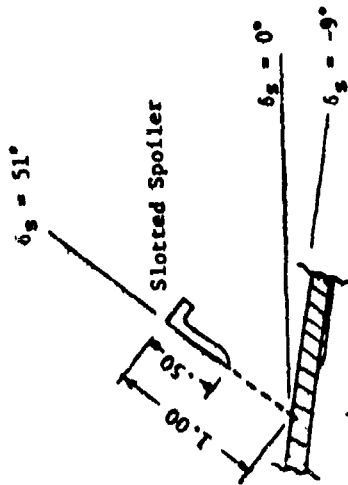


Figure 5 - 2-D Elliptic CC Airfoil with Spoilers Installed
 (Basic Airfoil Constructed by Lockheed-California Co.)



Figure 6 - 2-D Inserts and MACA 64A-212/CCW Model Installed
in 8 x 10-Ft South Subsonic Tunnel



Figure 7 - Configuration CCM 243 Installed on Insect Turntables with
Tangential Wall Blowing

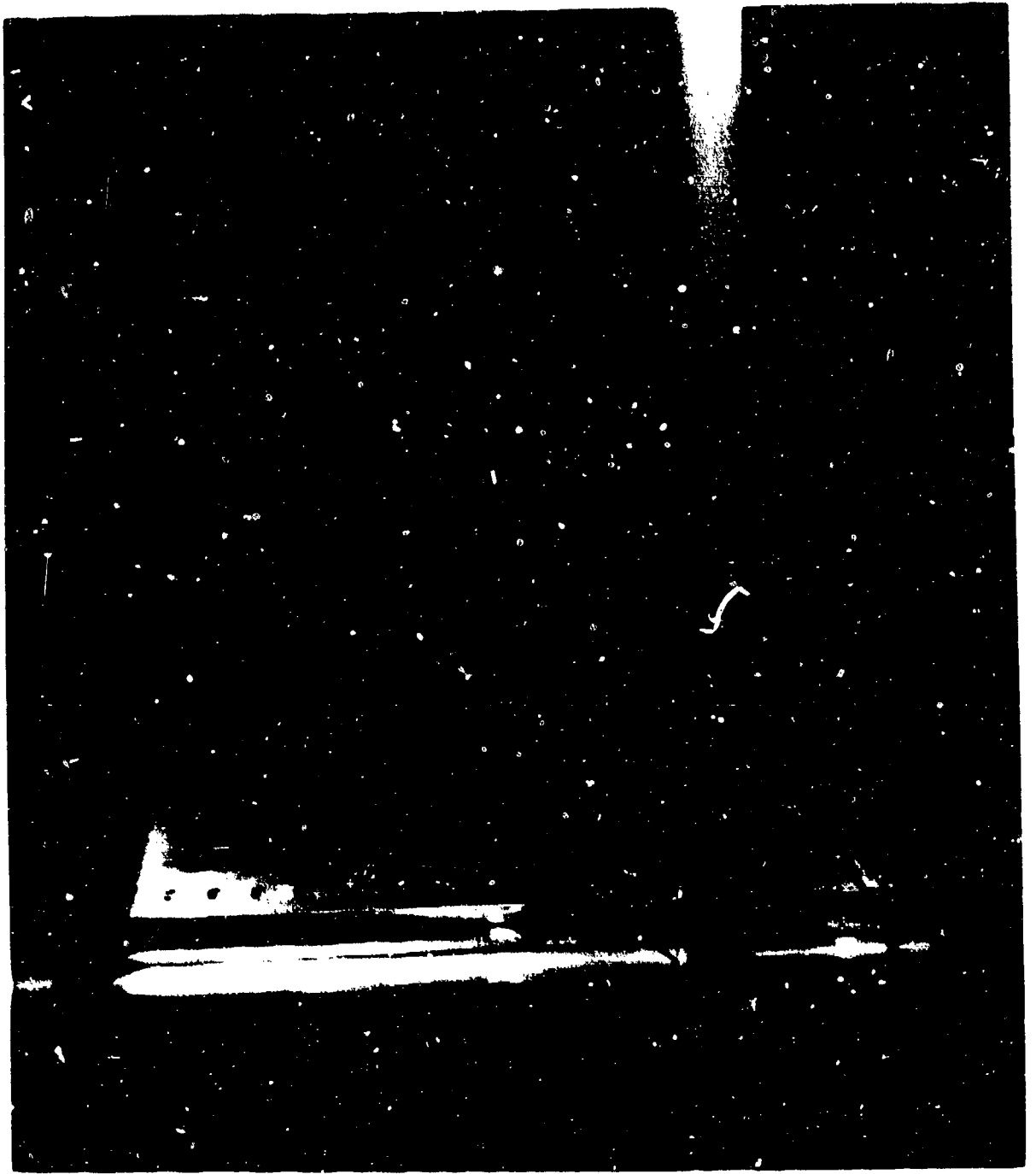


Figure 8 - Aft View Showing Wake Rake, Model, and Tangential Wall Blowing

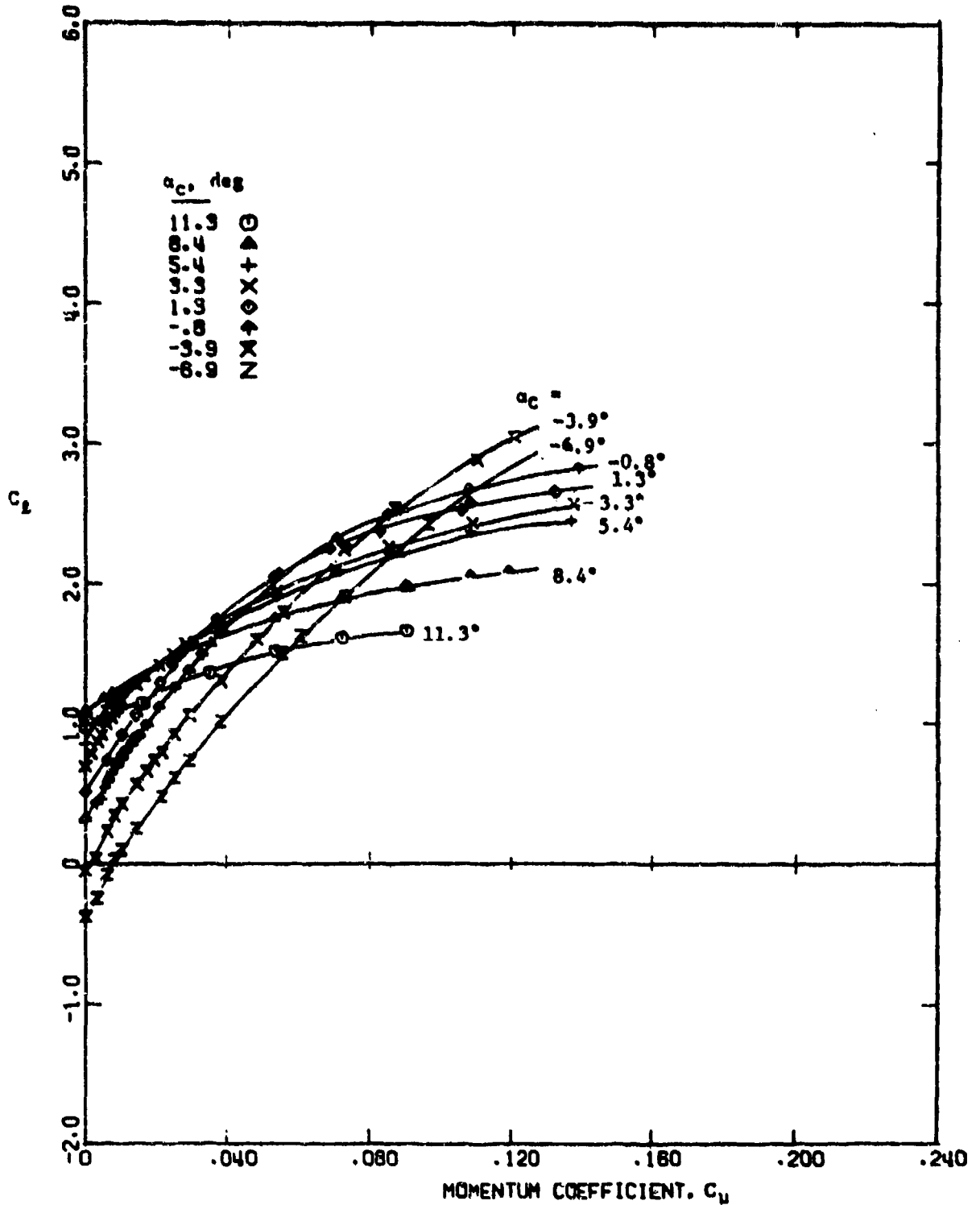


Figure 9 - Lift as a Function of Blowing for the NACA 66-210/CCW
 Airfoils, $q = 30$ psf, $R_e \approx 0.64 \times 10^6$, $h = 0.009''$
 (a) CCW 800, $\delta_{LE} = 0^\circ$

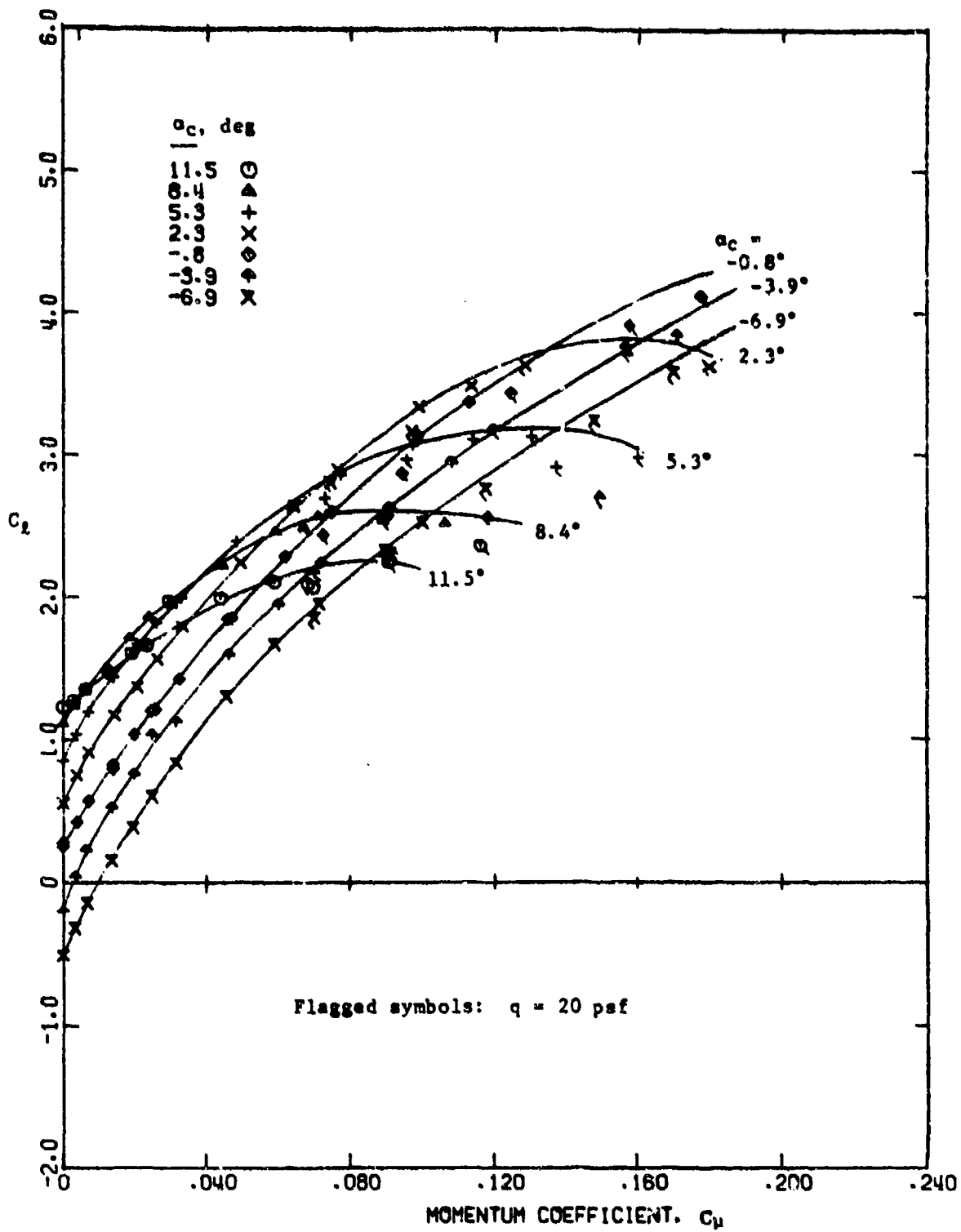


Figure 9 - (Continued)

(b) CCW α_{15} , $\delta_{LE} = 15.3^\circ$

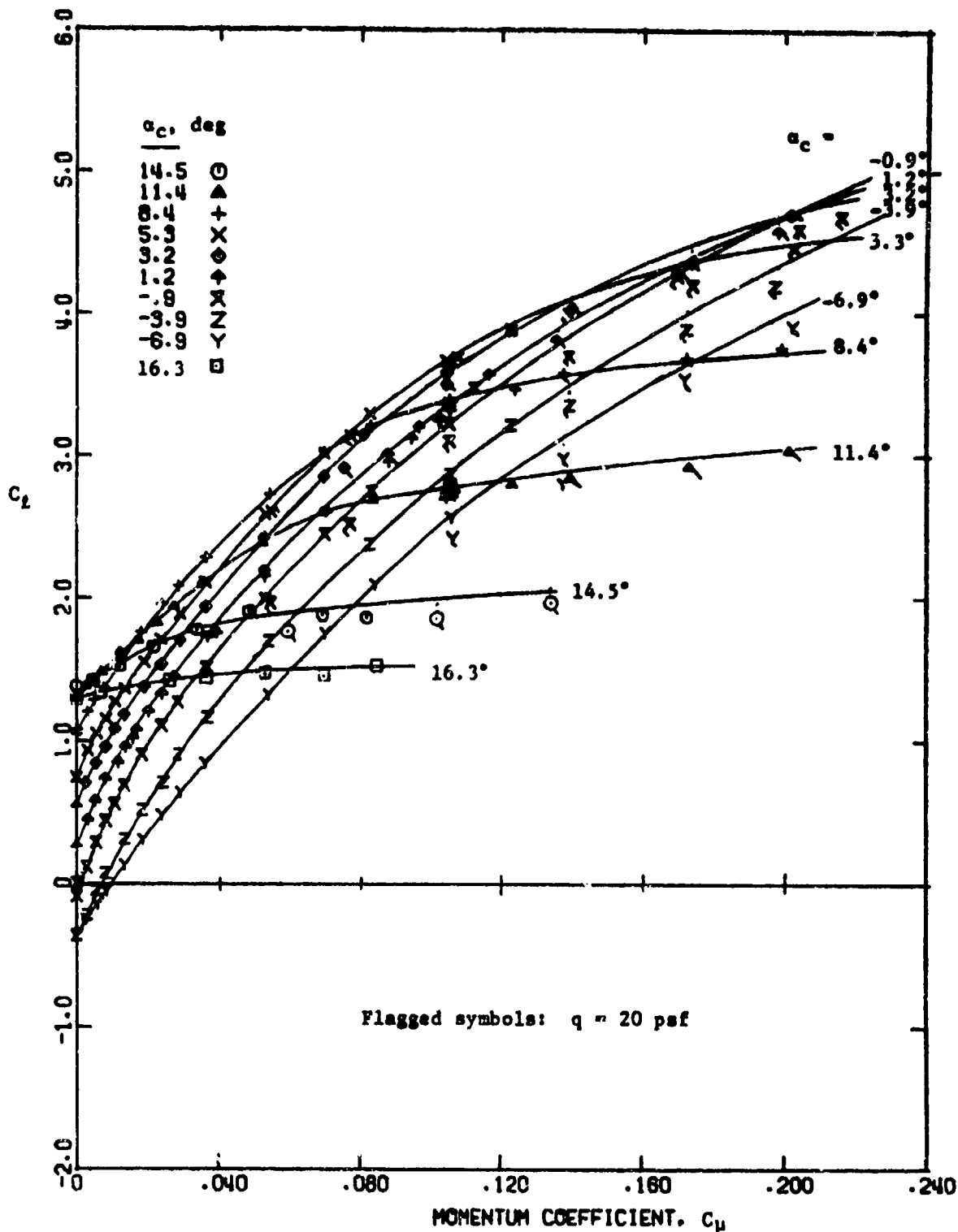


Figure 9 - (Continued)

(c) CCW 829, $\delta_{LE} = 29^\circ$

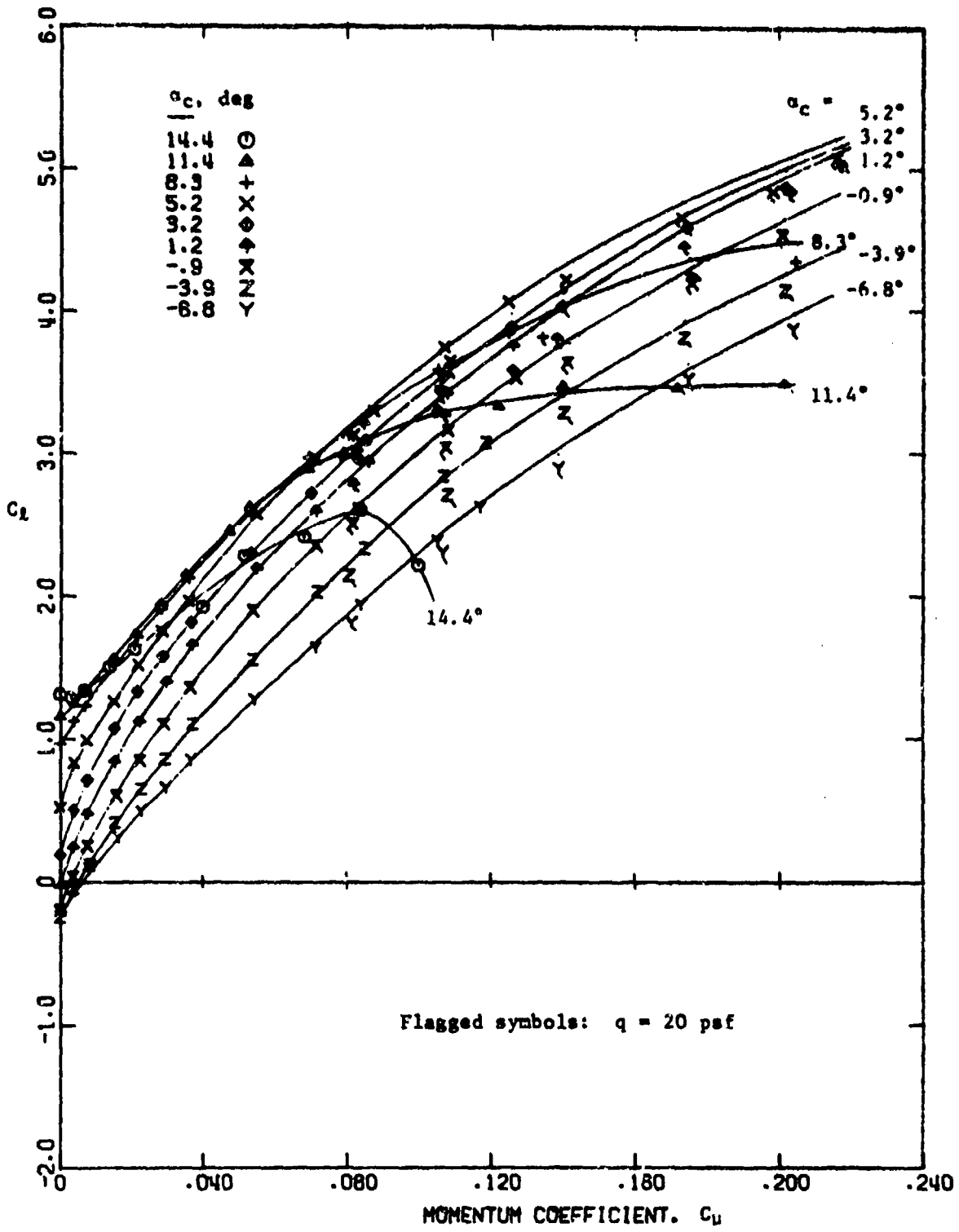


Figure 9 - (Concluded)
 (d) CCW 844, $\delta_{LE} = 43.6^\circ$

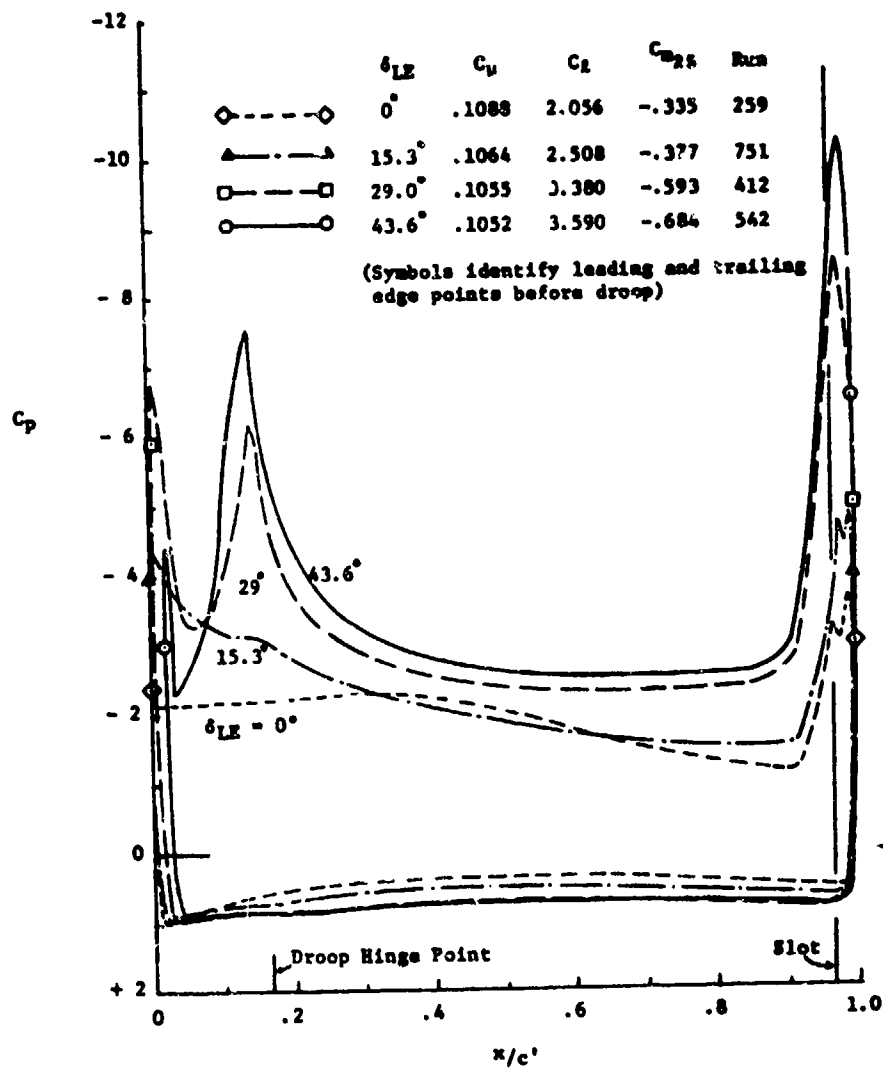
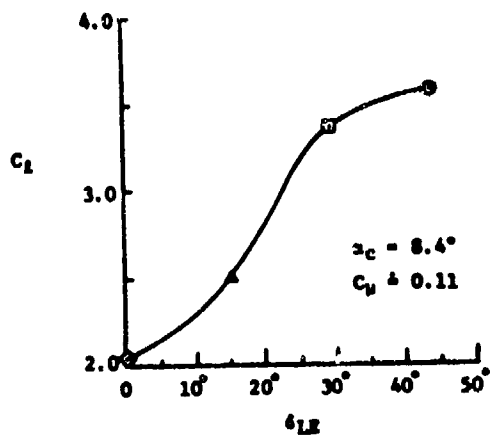


Figure 10 - Effect of Droop on Preventing Leading Edge Separation,
 NACA 66-210/CCW Airfoil, $\alpha_c = 8.4^\circ$, $C_\mu \approx 0.11$,
 Experimental Pressure Distributions

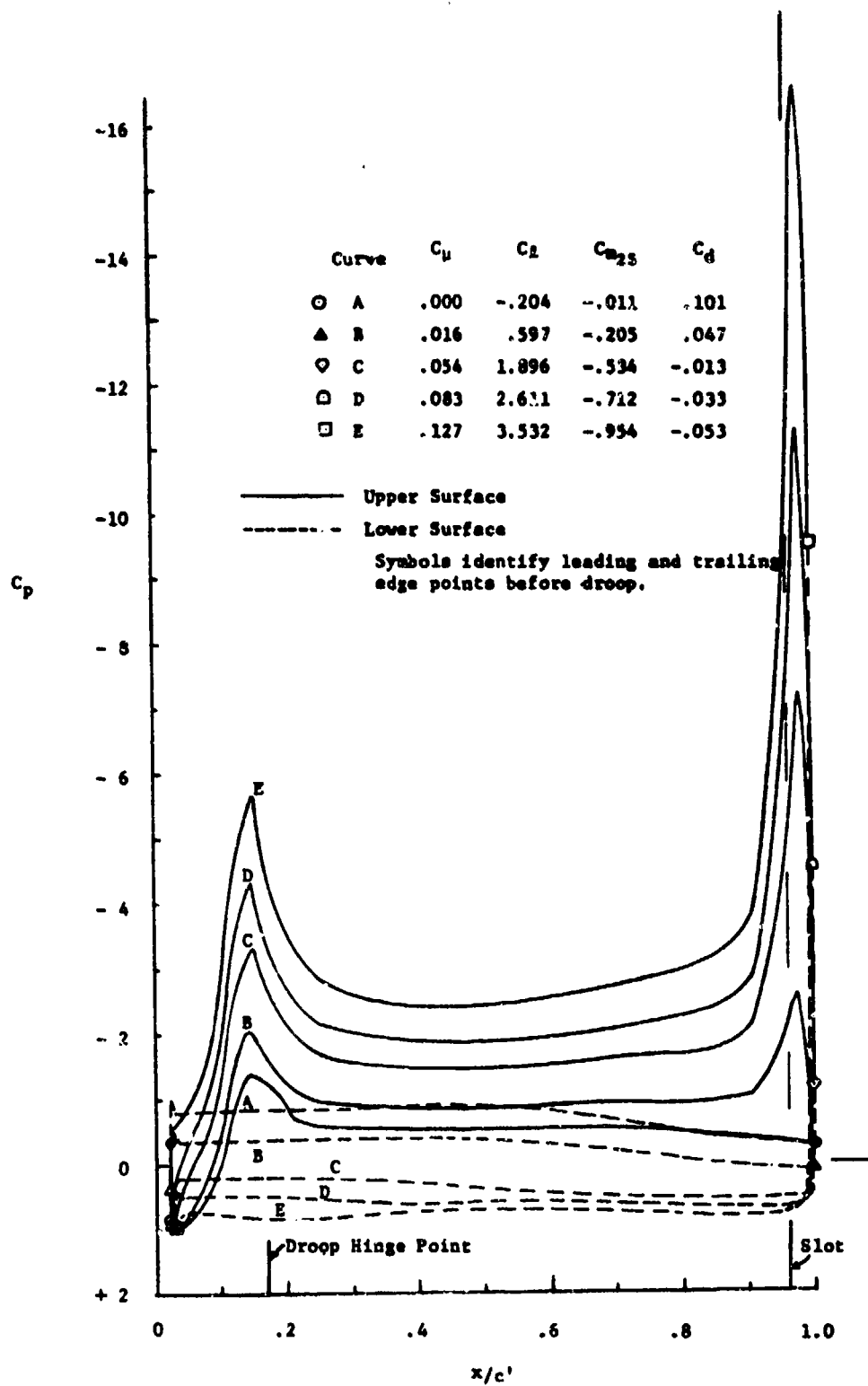


Figure 11 - Effect of Blowing on Experimental Pressure Distributions for NACA 66-210/CCW Airfoil, $\delta_{LE} = 43.6^\circ$, $\alpha_c = -0.86^\circ$

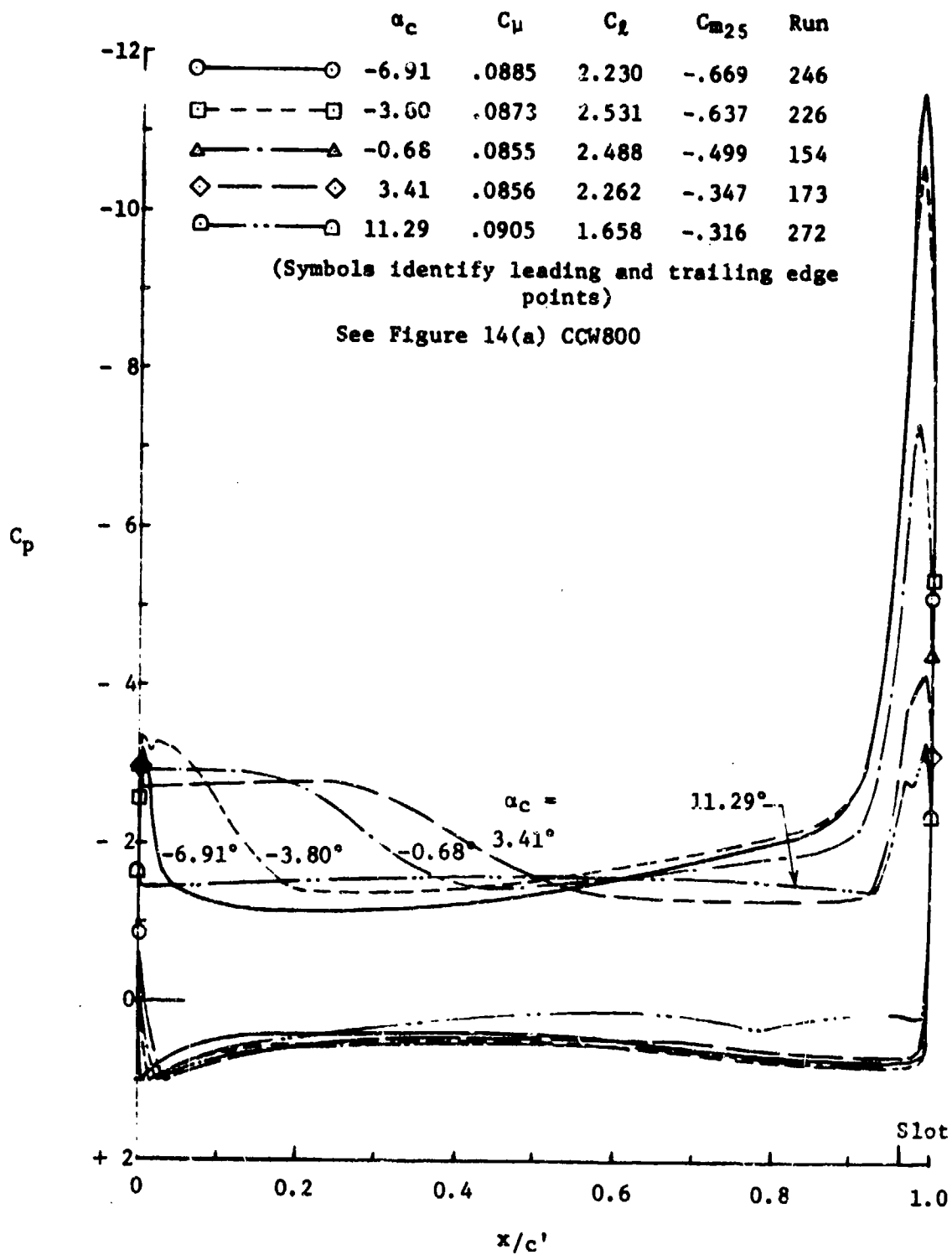


Figure 12 - Effect of Incidence on NACA 66-210/CCW with No Leading Edge Droop at $C_u \approx .088$, Experimental Pressure Distributions

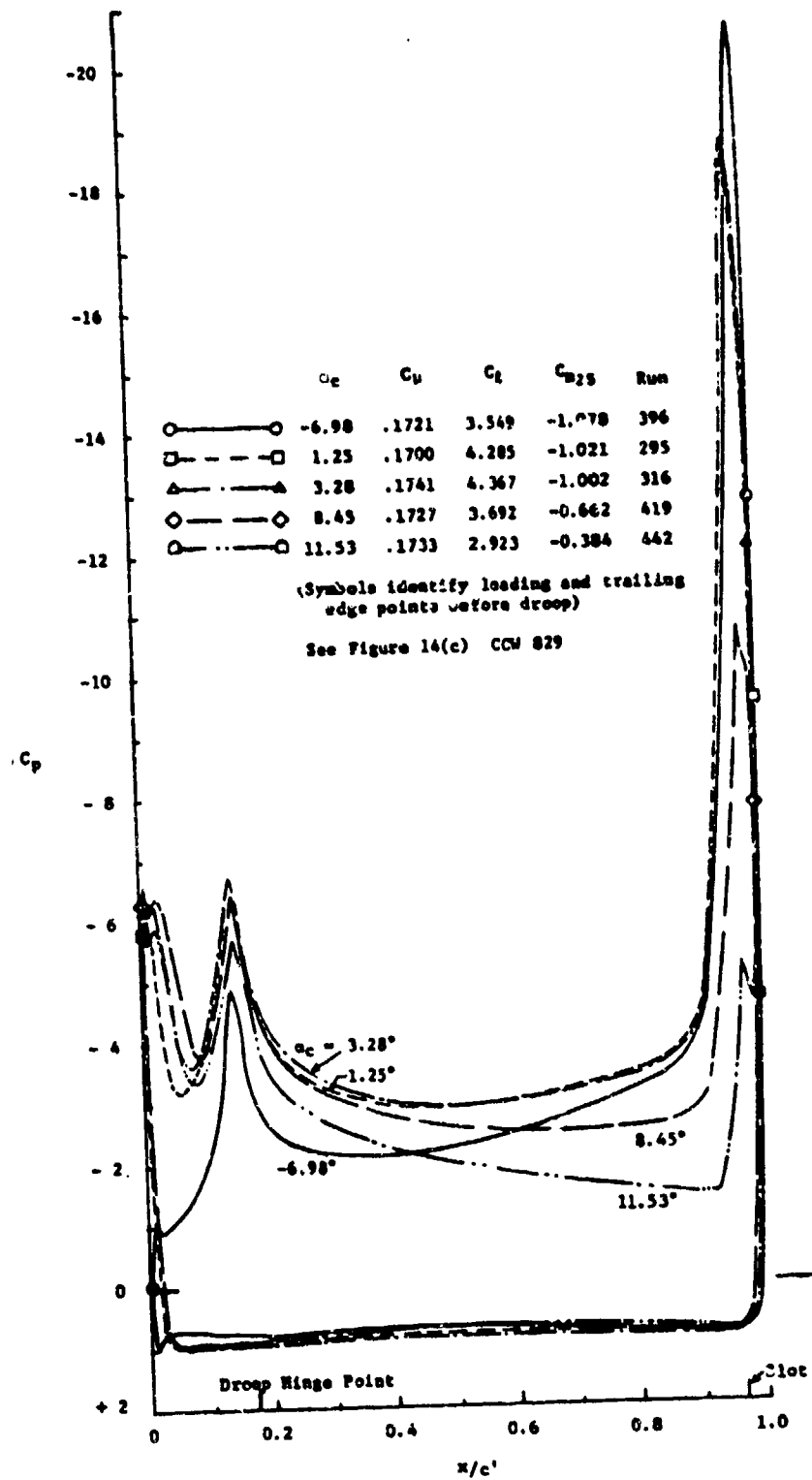


Figure 13 - Effect of Incidence on NACA 66-210/CCW Airfoil with 29° Leading Edge Droop at $C_u \approx 0.173$, Experimental Pressure Distributions

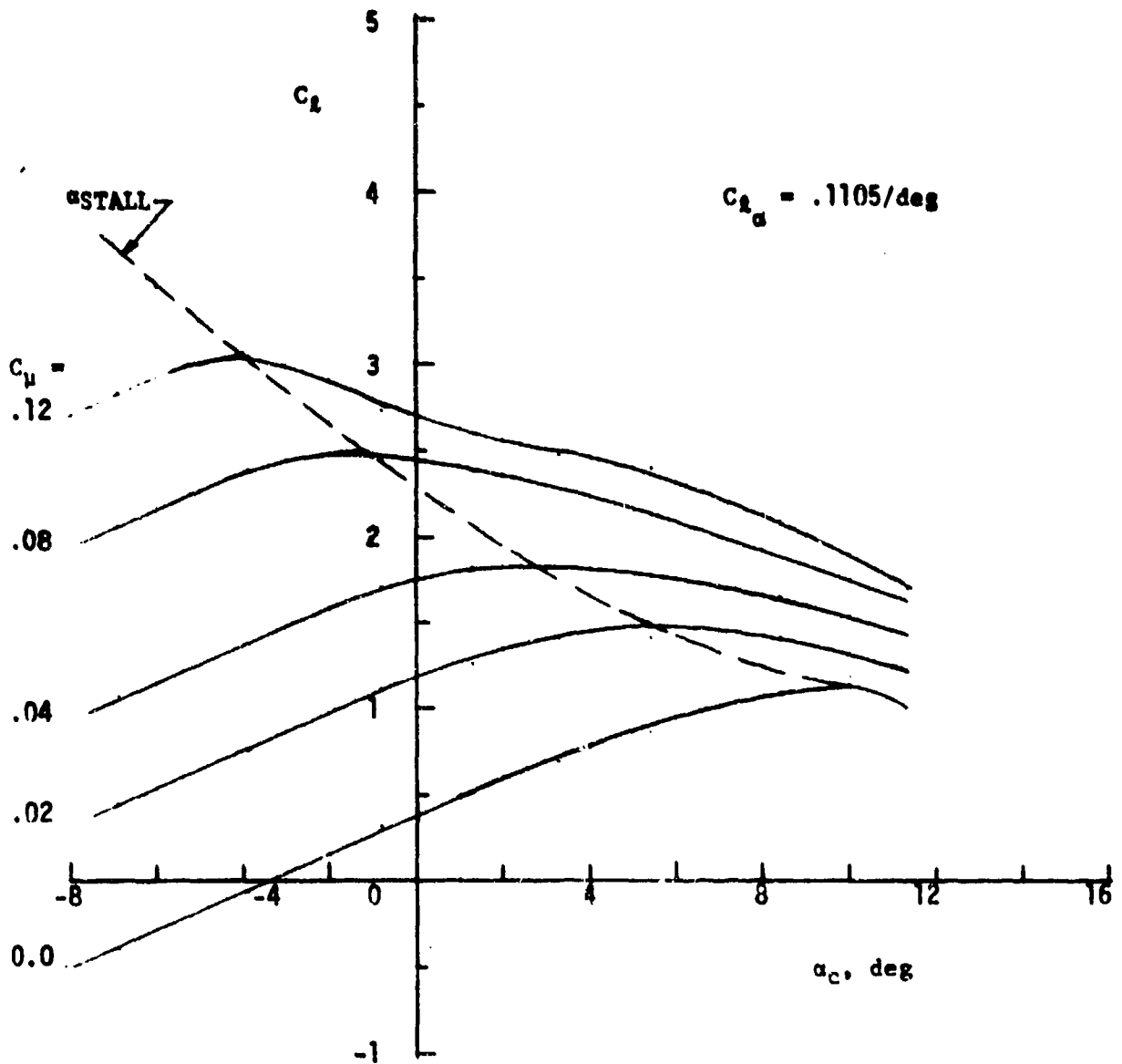


Figure 14 - Lift Curves at Constant Momentum Coefficient for
 66-210/CCW Airfoils, $q = 30$ psf, $Re \approx 0.64 \times 10^6$,
 $h = .009''$

(a) CCW 800, $\delta_{LE} = 0^\circ$

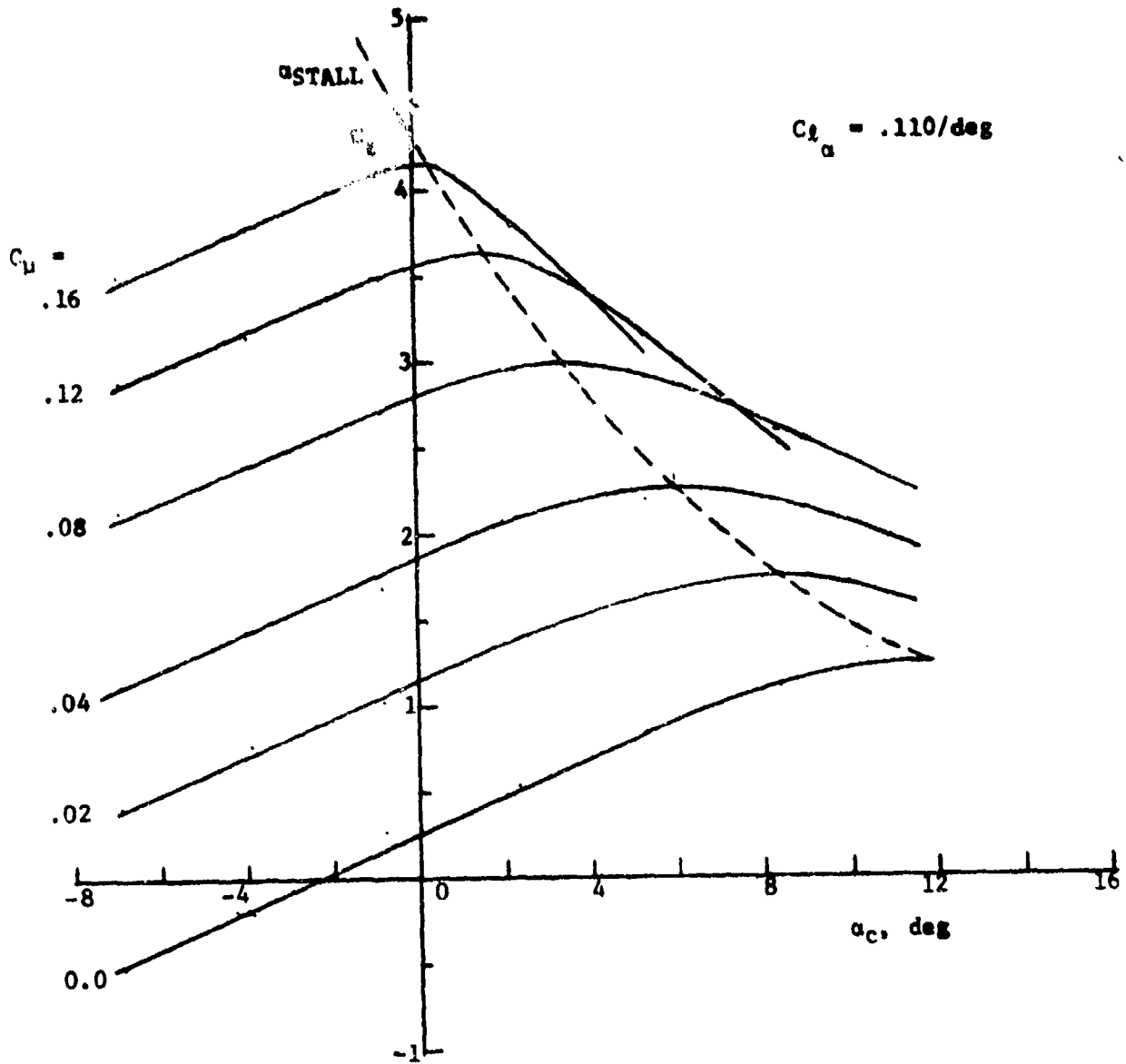


Figure 14 - Continued
 (b) CCW 815, $\delta_{LE} = 15.3^\circ$

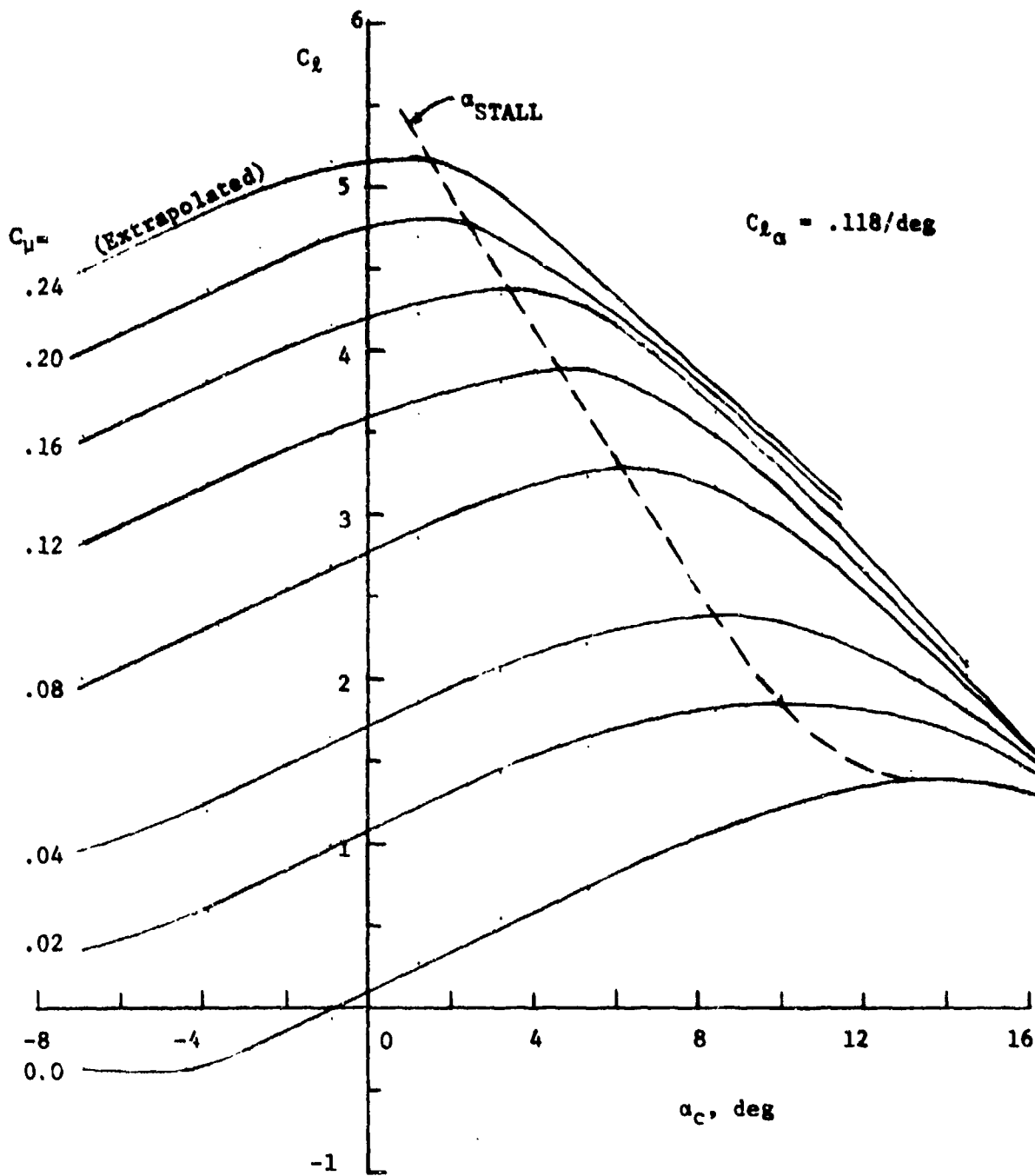


Figure 14 - Continued
(c) CCW 829, $\delta_{LE} = 29^\circ$

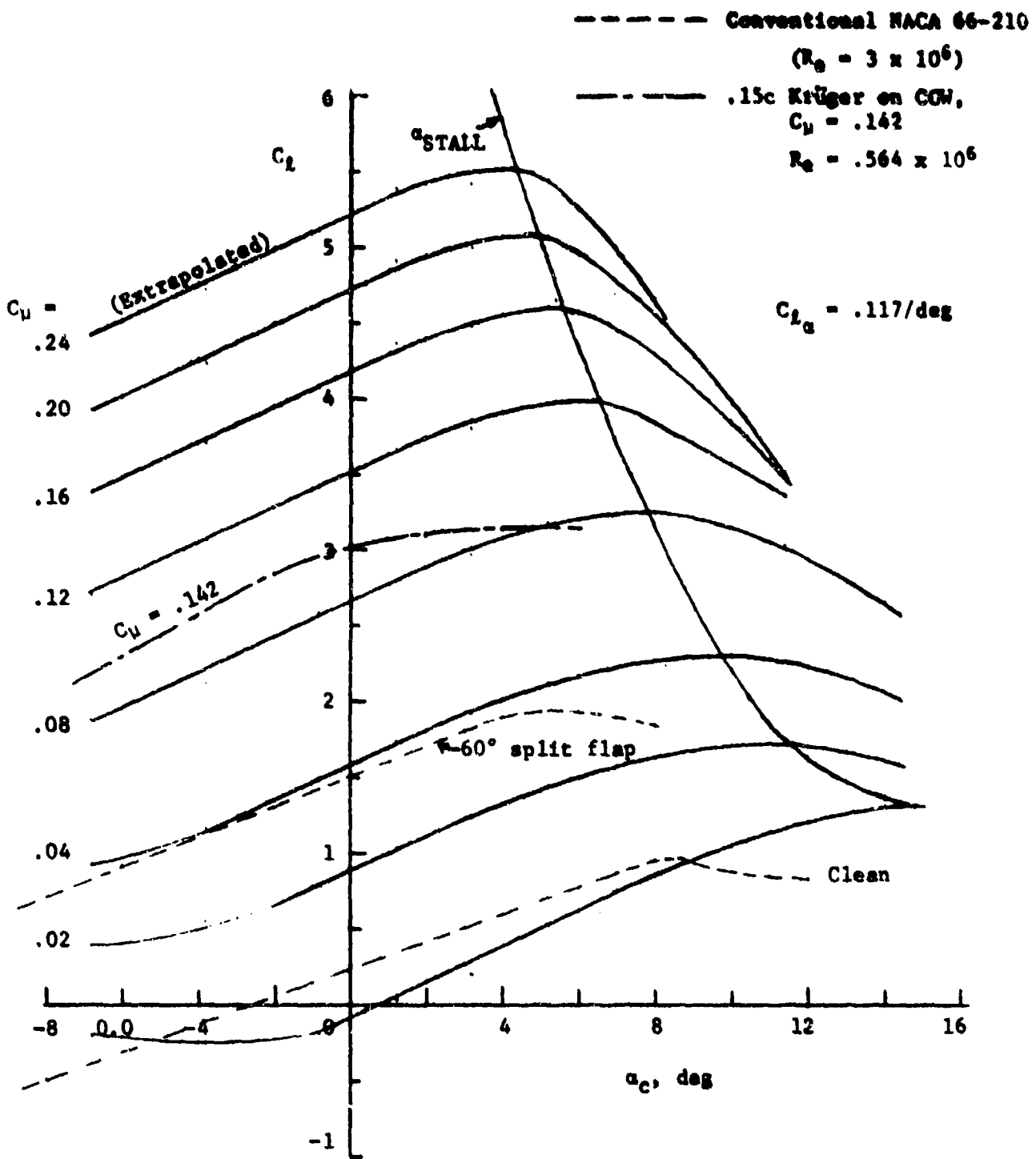


Figure 14 - Concluded
 (d) CCW 844, $\delta_{LE} = 43.6^\circ$

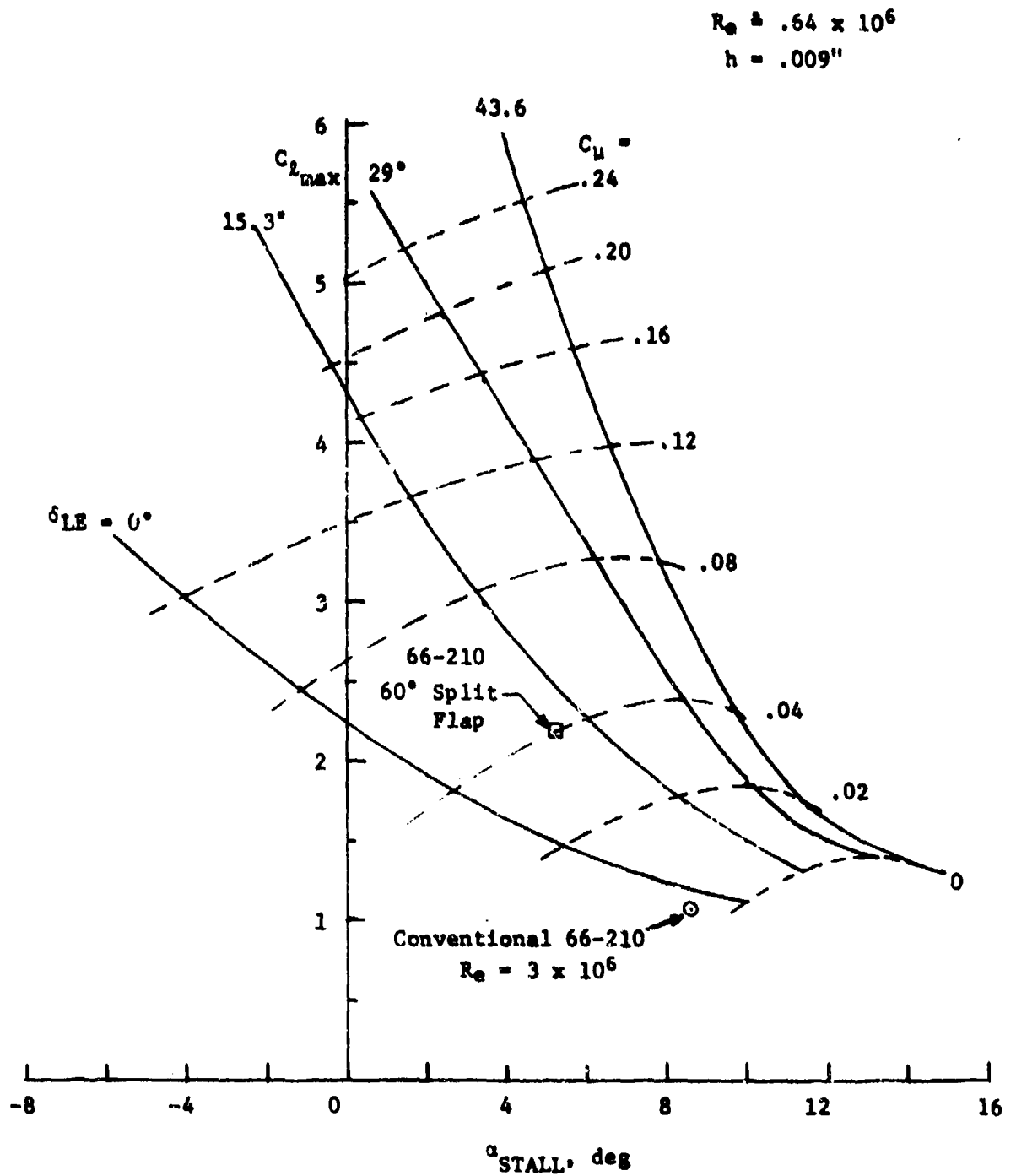


Figure 15 - $C_{L_{max}}$ and α_{STALL} as Functions of Momentum Coefficient and Nose Droop Angle for 66-210/CCW Airfoils

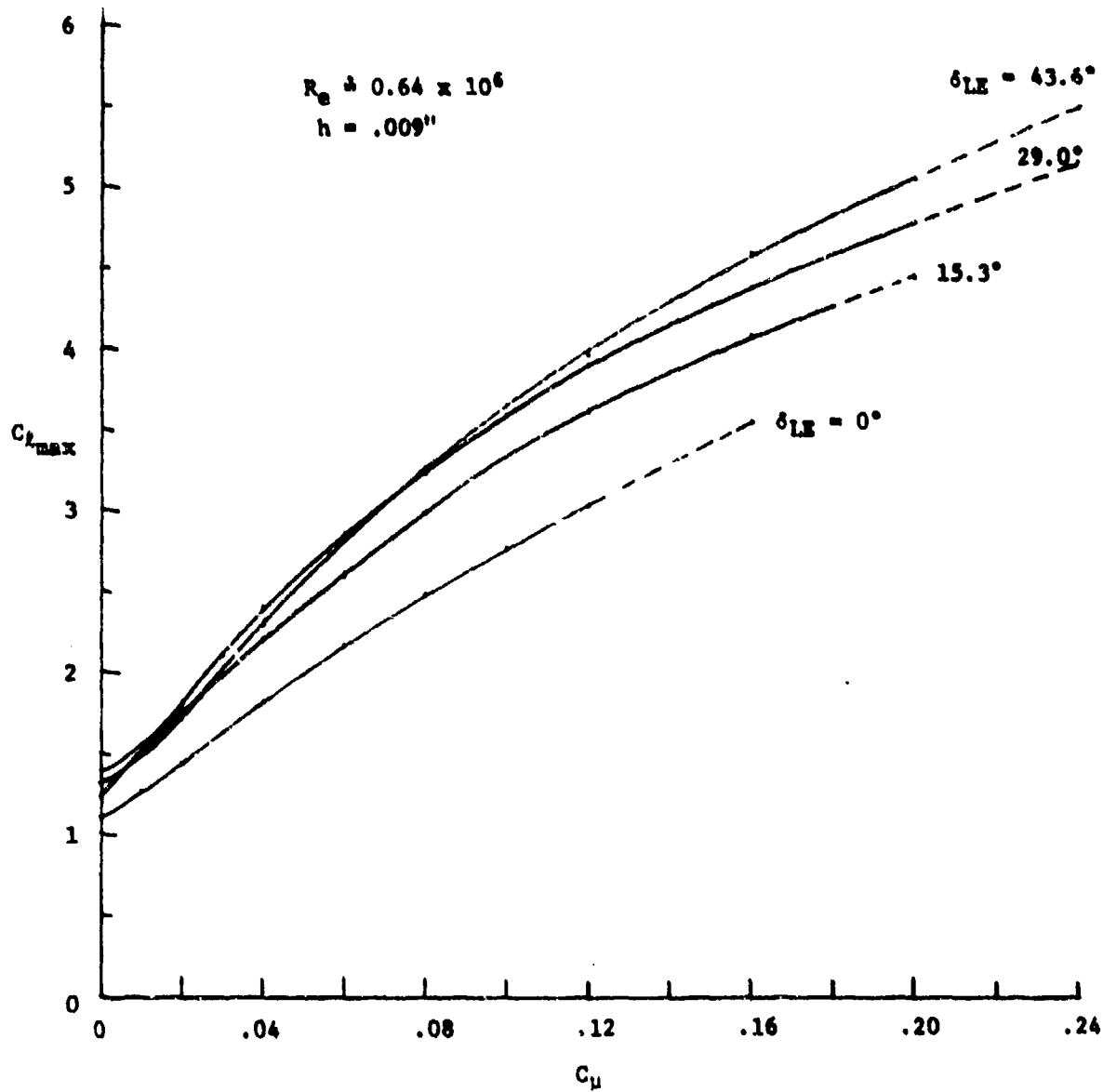


Figure 1C - $C_{l_{max}}$ as a Function of Droop and Momentum Coefficient, NACA 66-210/CCW Airfoils

C_L

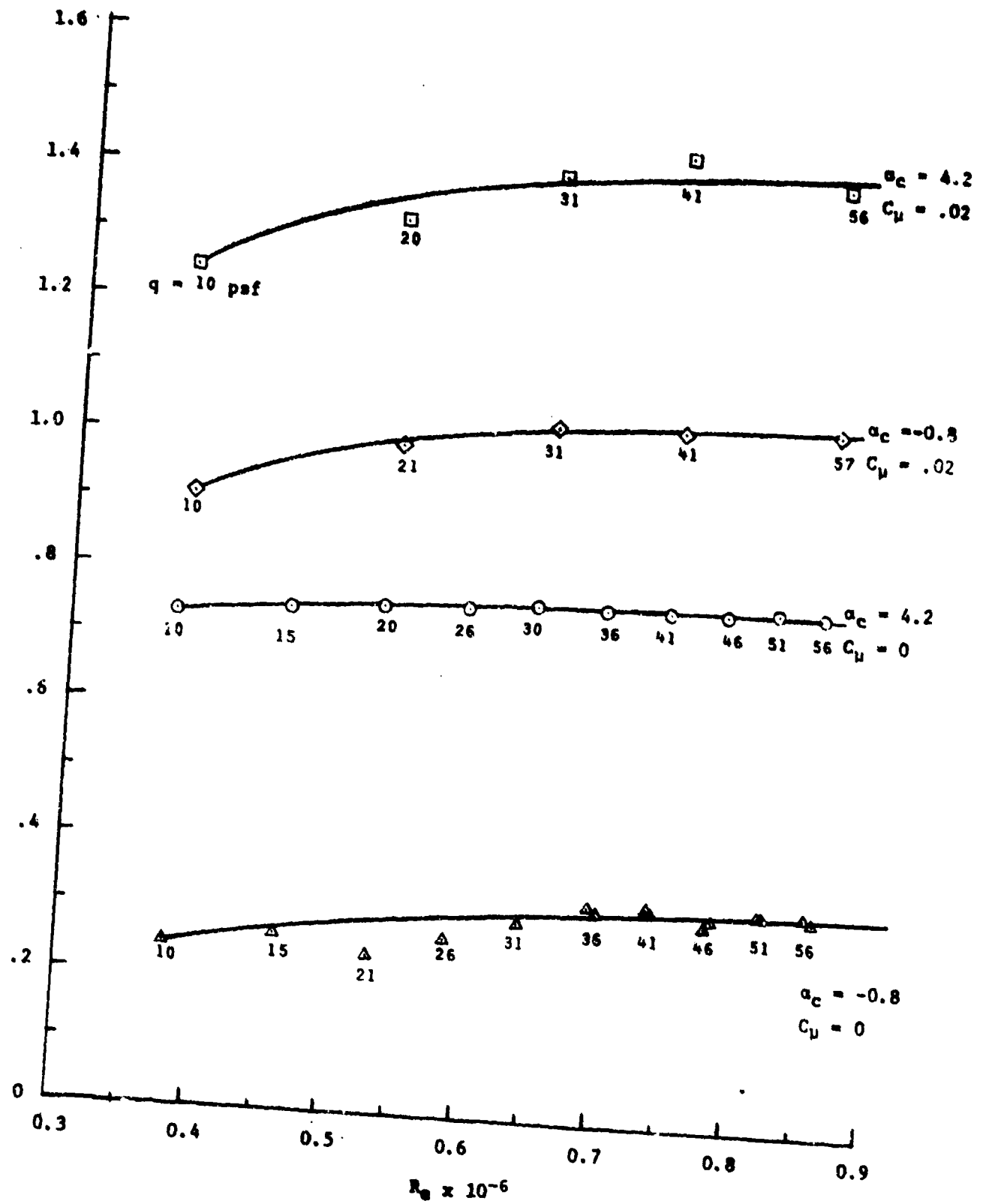


Figure 17 - Effects of Reynolds Number on Lift Coefficient for NACA 66-210/CCW Airfoil, CCW 800, $\delta_{LE} = 0^\circ$, $h = .009''$

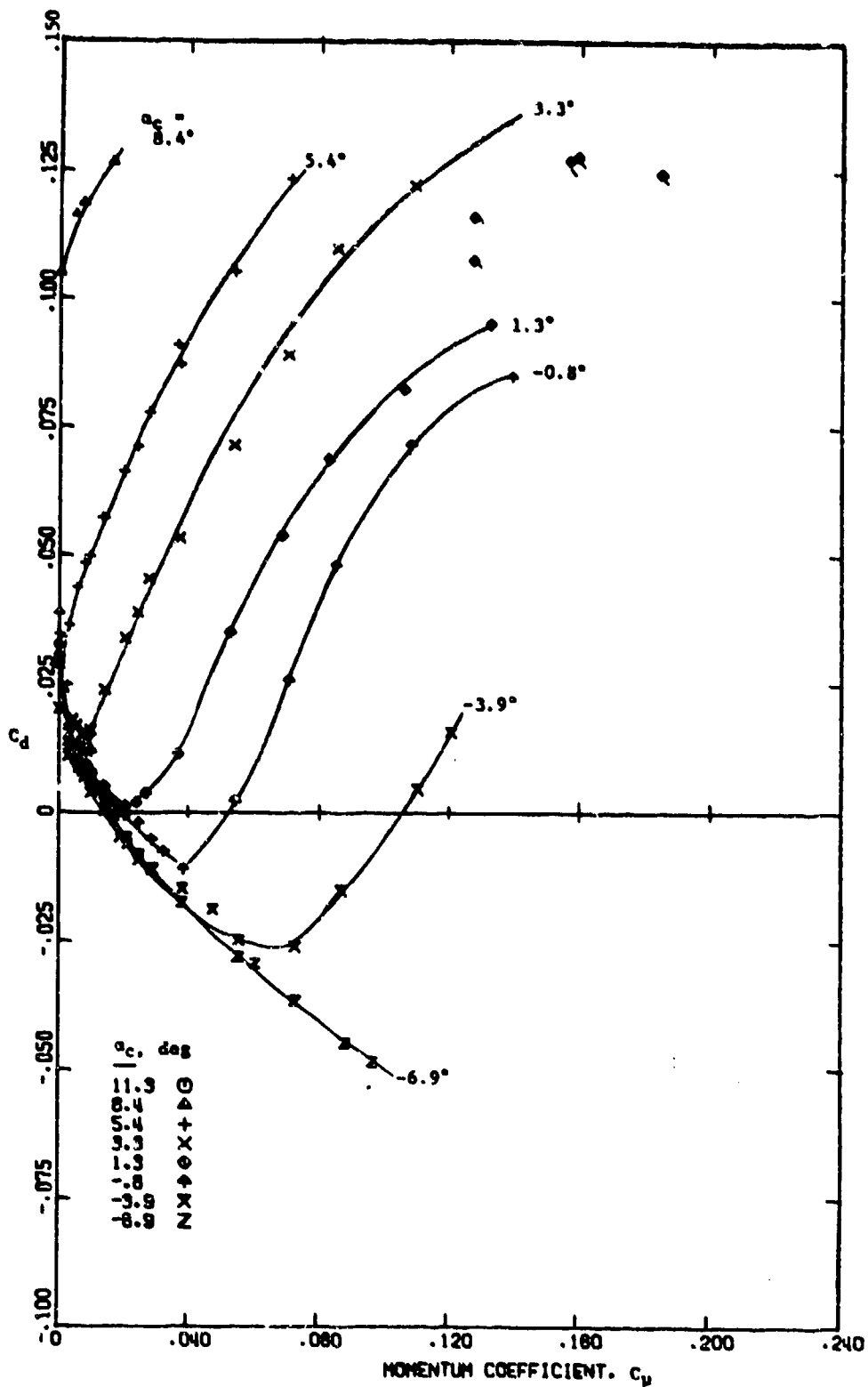


Figure 18 - Drag as a Function of Blowing for the NACA 66-210/CCW Airfoils, $q = 30$ psf, $R_e = 0.64 \times 10^6$, $h = 0.009''$
 (a) CCW 800, $\delta_{LE} = 0^\circ$

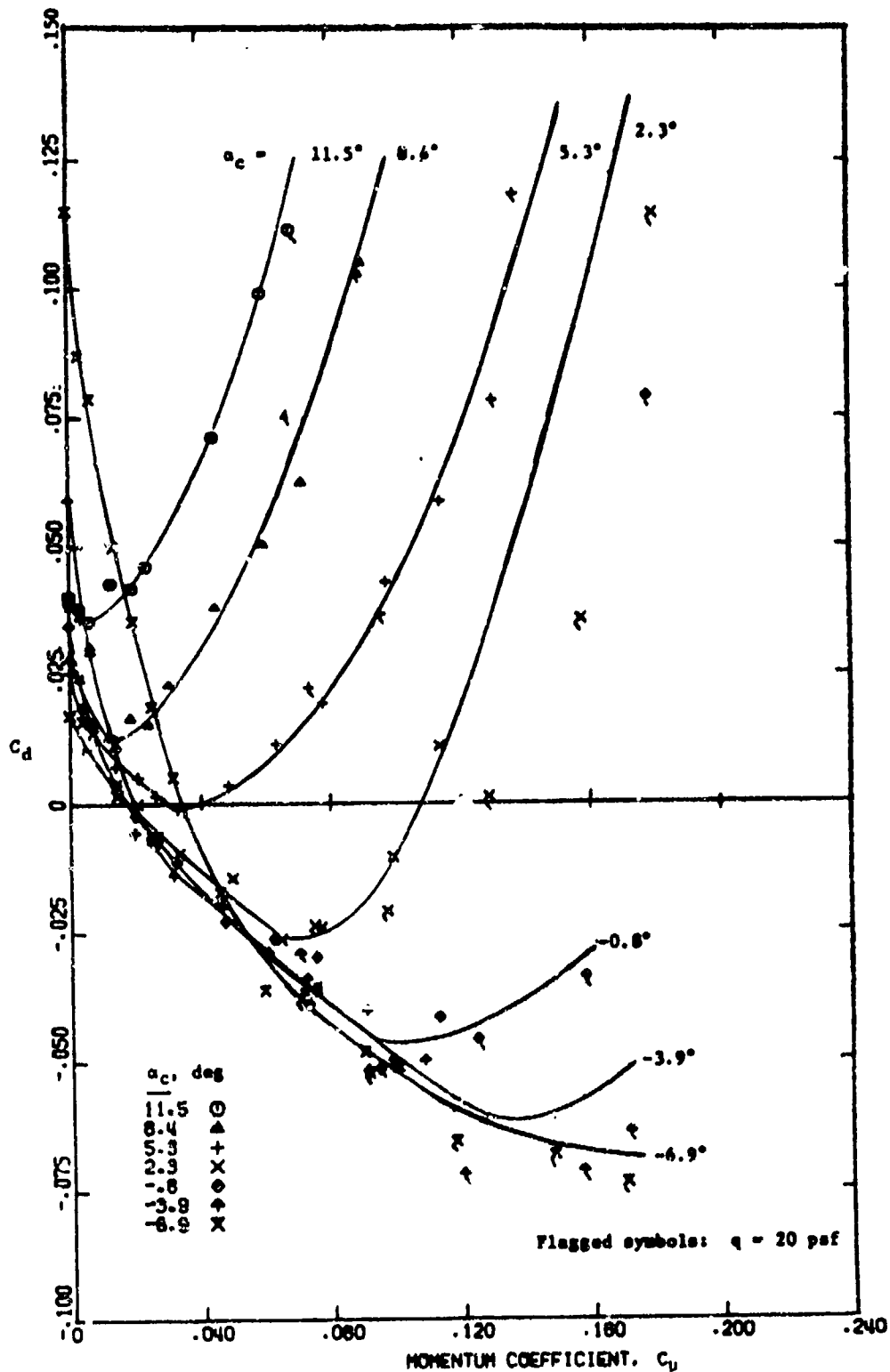


Figure 18 - (Continued)

(b) CCW 815, $\delta_{LE} = 15.3^\circ$

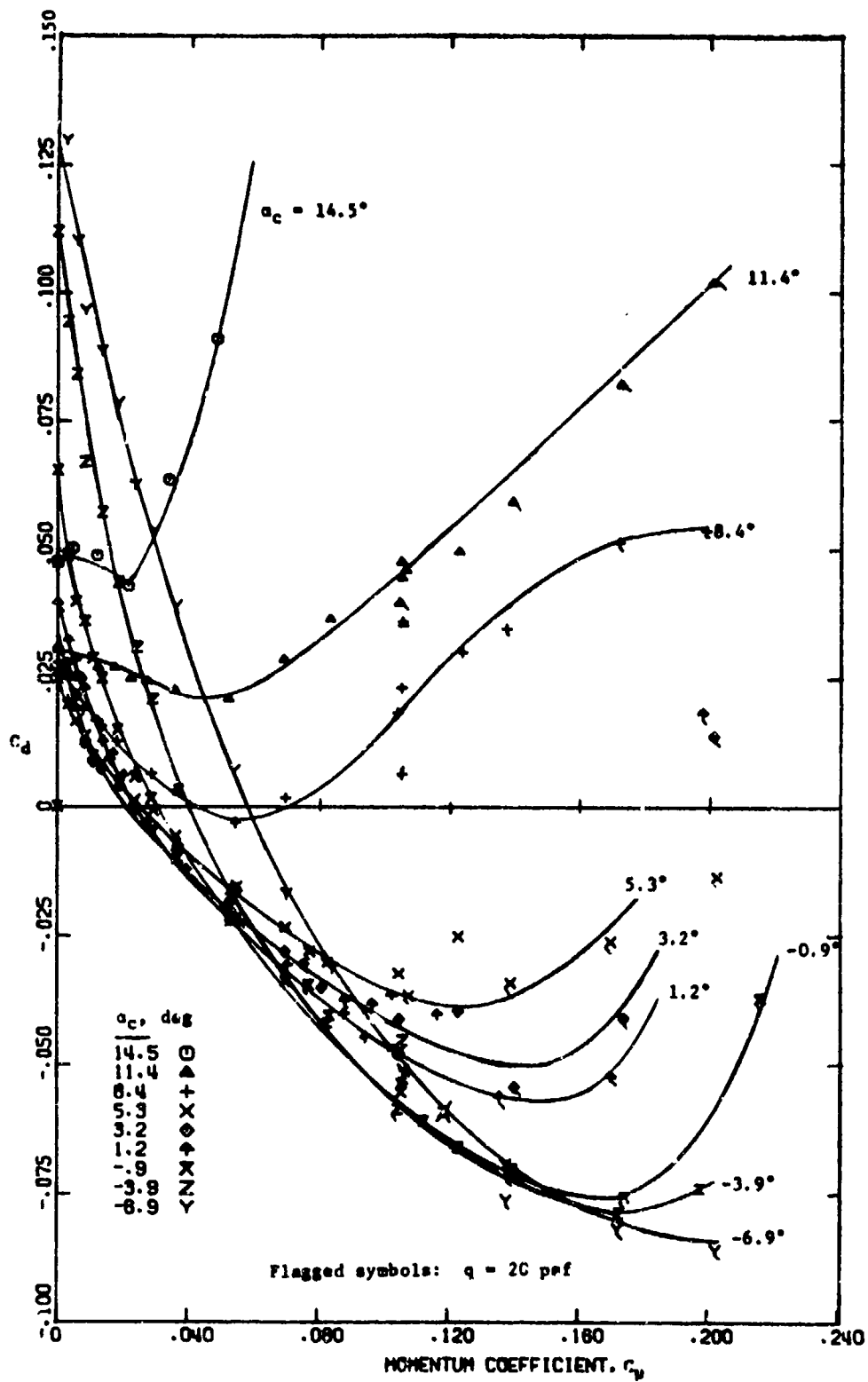


Figure 18 - (Continued)

(c) CCW 829, $\delta_{LE} = 29^\circ$

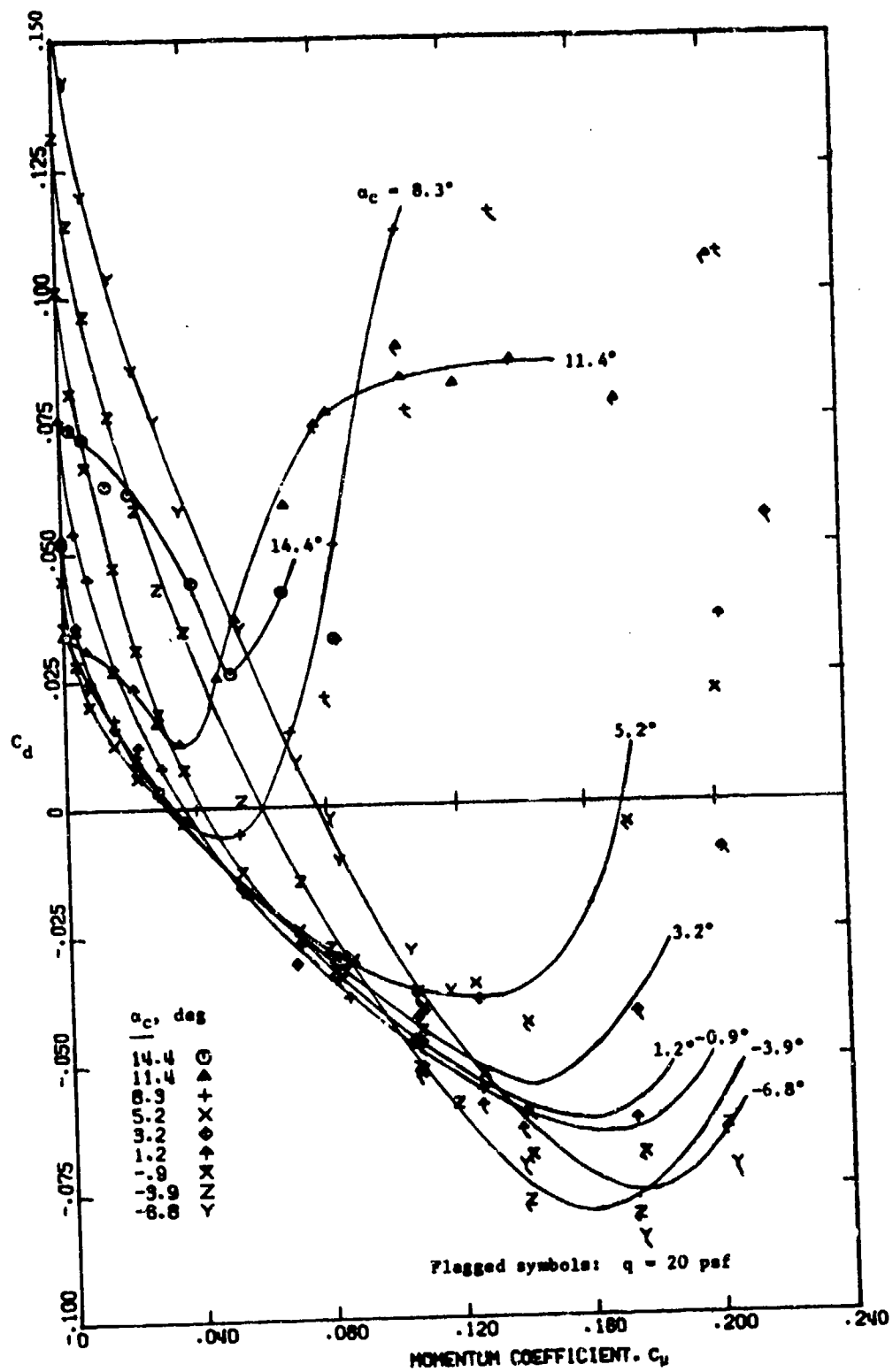


Figure 18 - (Concluded)

(d) CCW 844, $\delta_{LE} = 43.6^\circ$

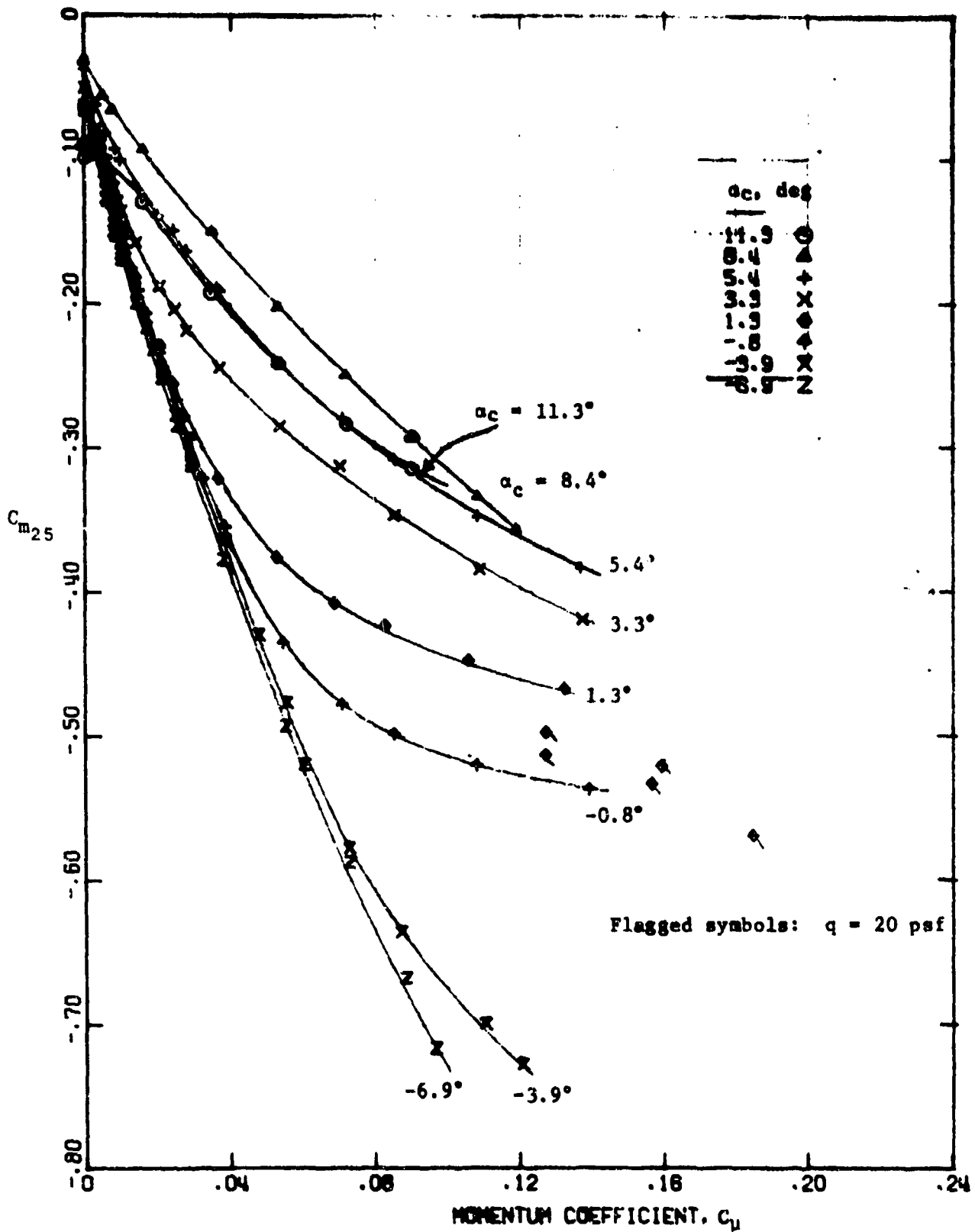


Figure 19 - Pitching Moment as a Function of Blowing for the NACA 66-210/CCW Airfoils, $q = 30$ psf, $R_e = 0.64 \times 10^6$, $h = 0.009''$

(a) CCW 800, $\delta_{LE} = 0^\circ$

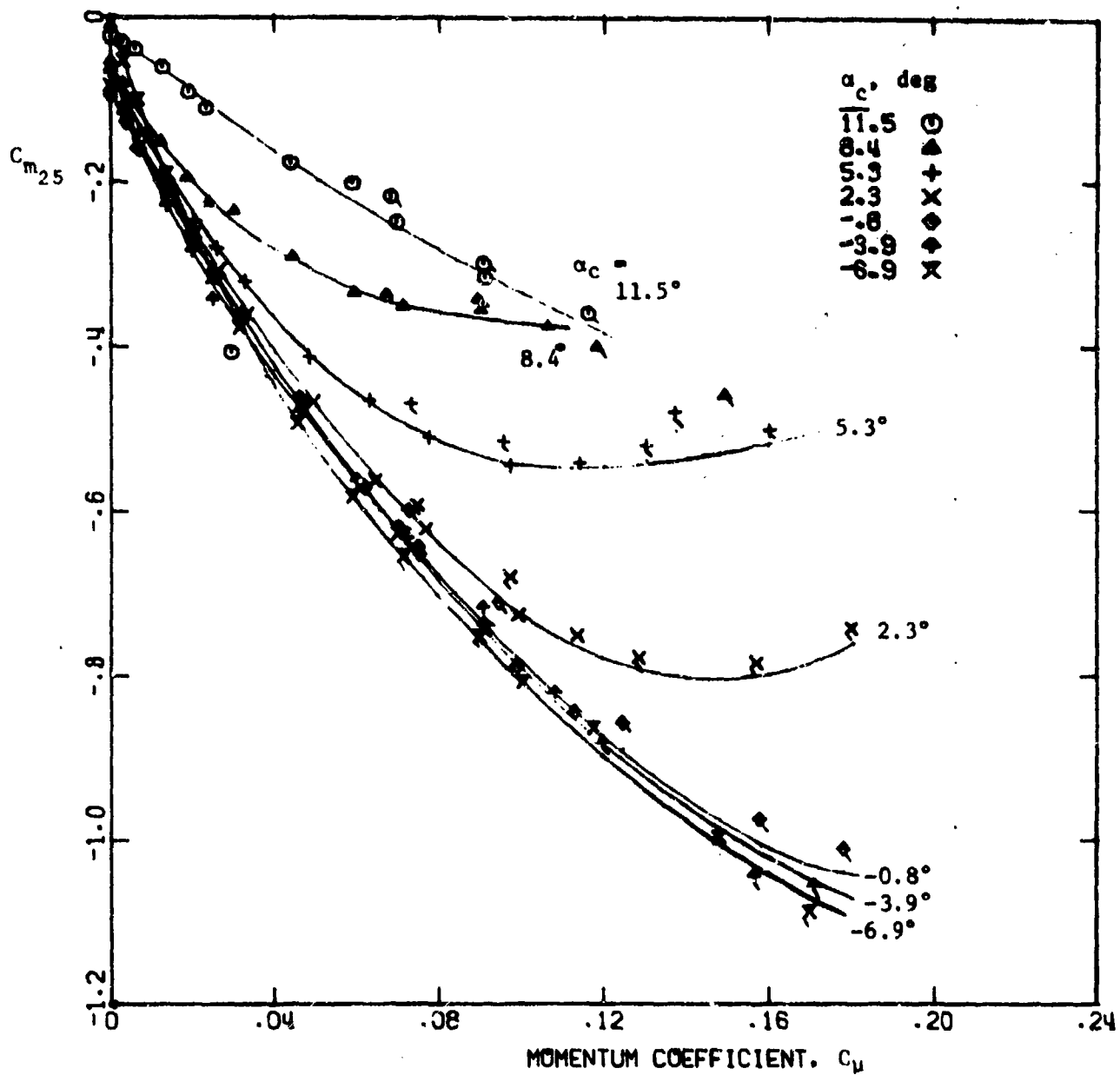


Figure 19 - (Continued)

(b) CCW 815, $\delta_{LE} = 15.3^\circ$

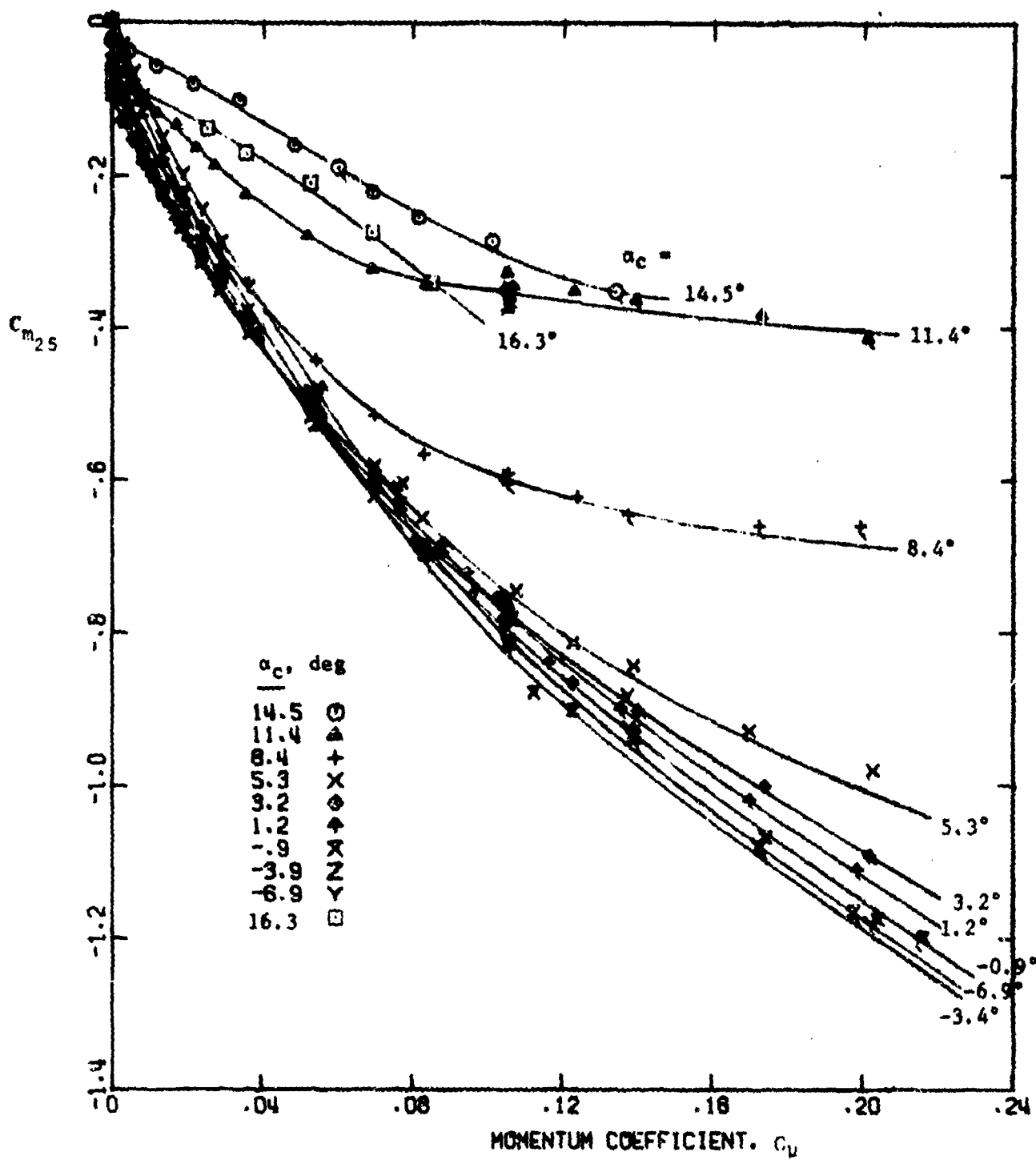


Figure 19 - (Continued)

(c) CCW 829, $\delta_{LE} = 29^\circ$

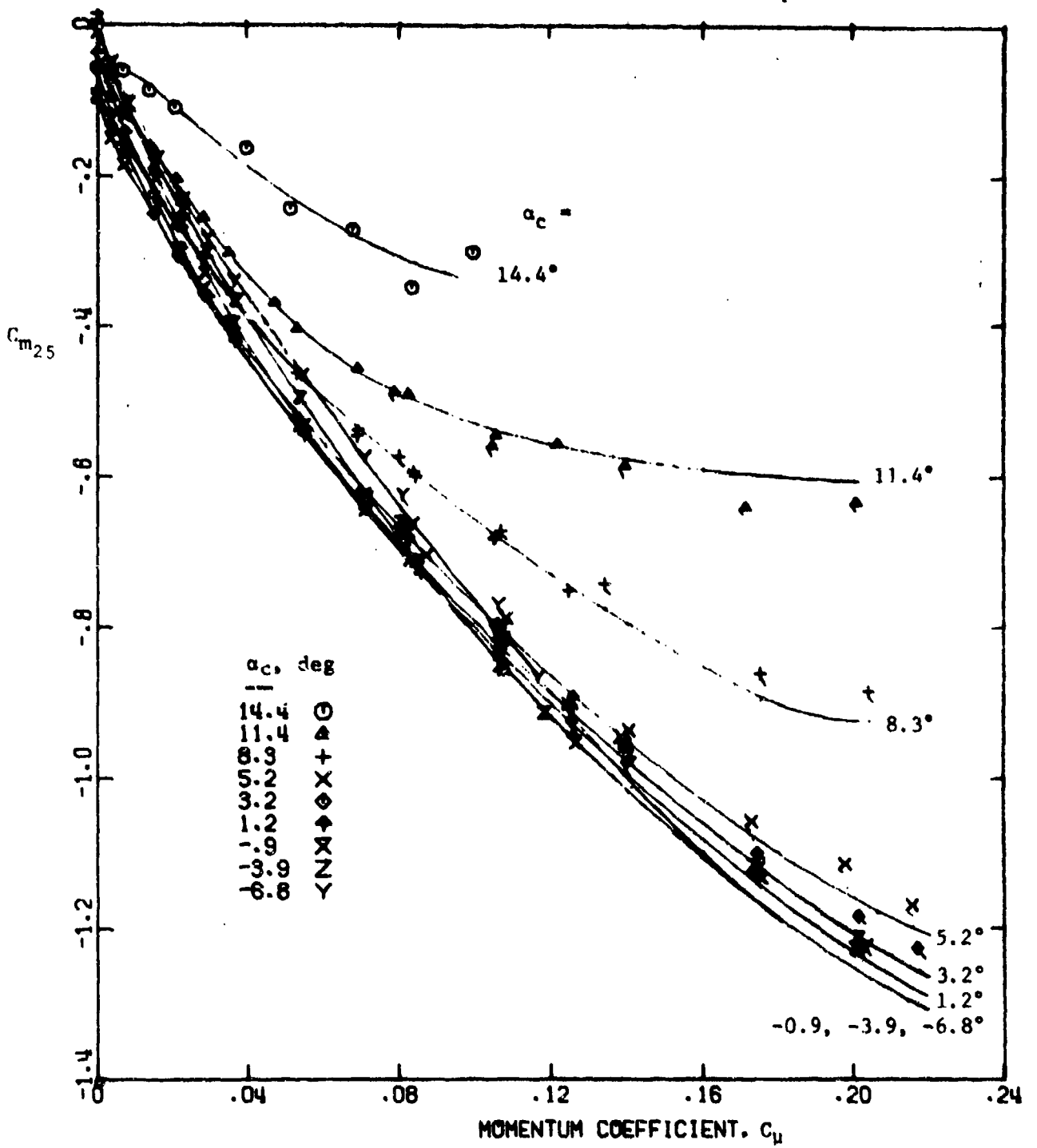


Figure 19 - (Concluded)

(d) CCW 844, $\delta_{LE} = 43.6^\circ$

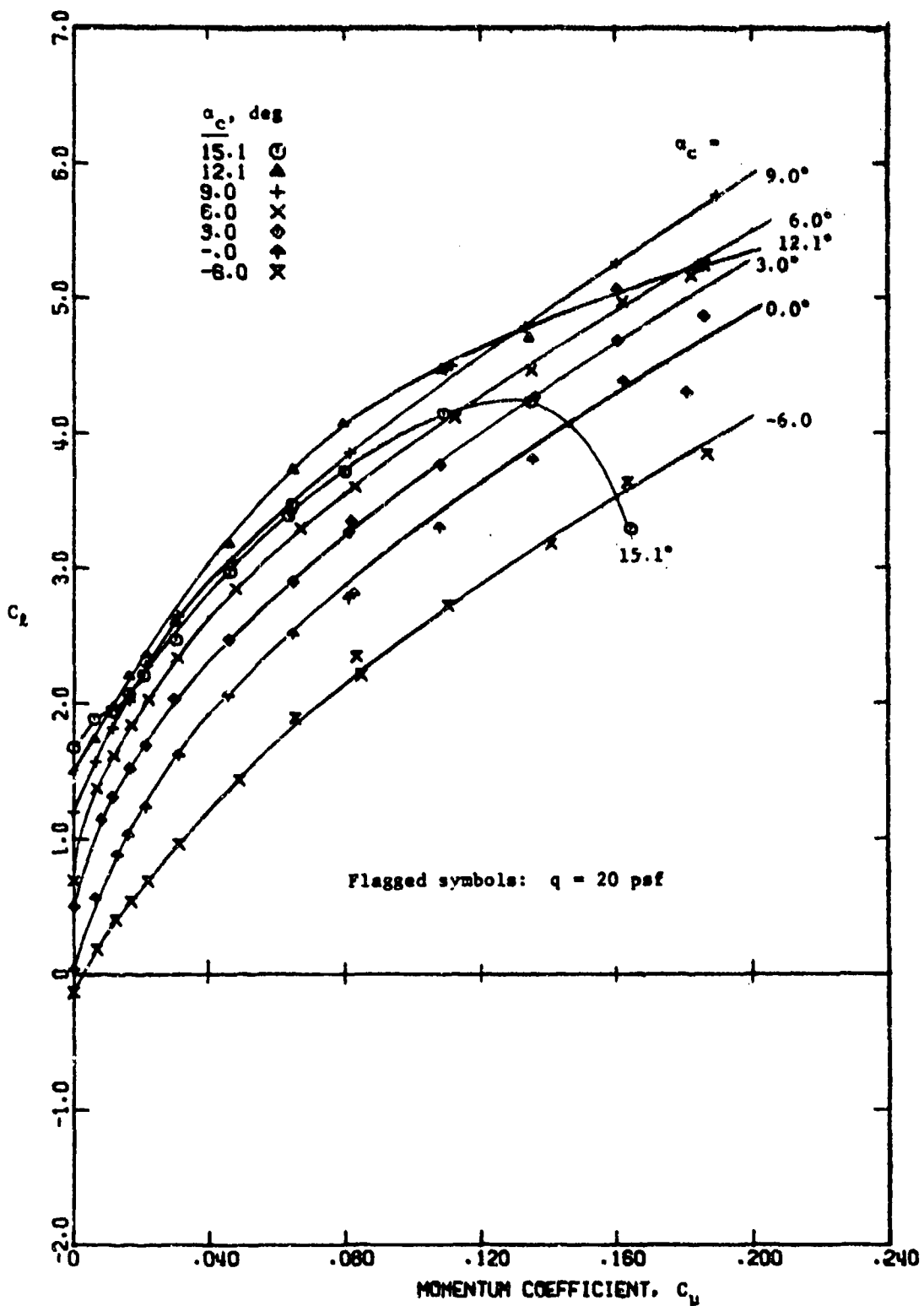


Figure 20 - Lift as a Function of Blowing for NACA 64A-212/CCW Airfoils,
 $q = 30$ psf, $R_e \approx 1.98 \times 10^6$, $h = 0.027''$
 (a) CCW 241, $\zeta_f = 180^\circ$, $\delta_{LE} = 30^\circ$

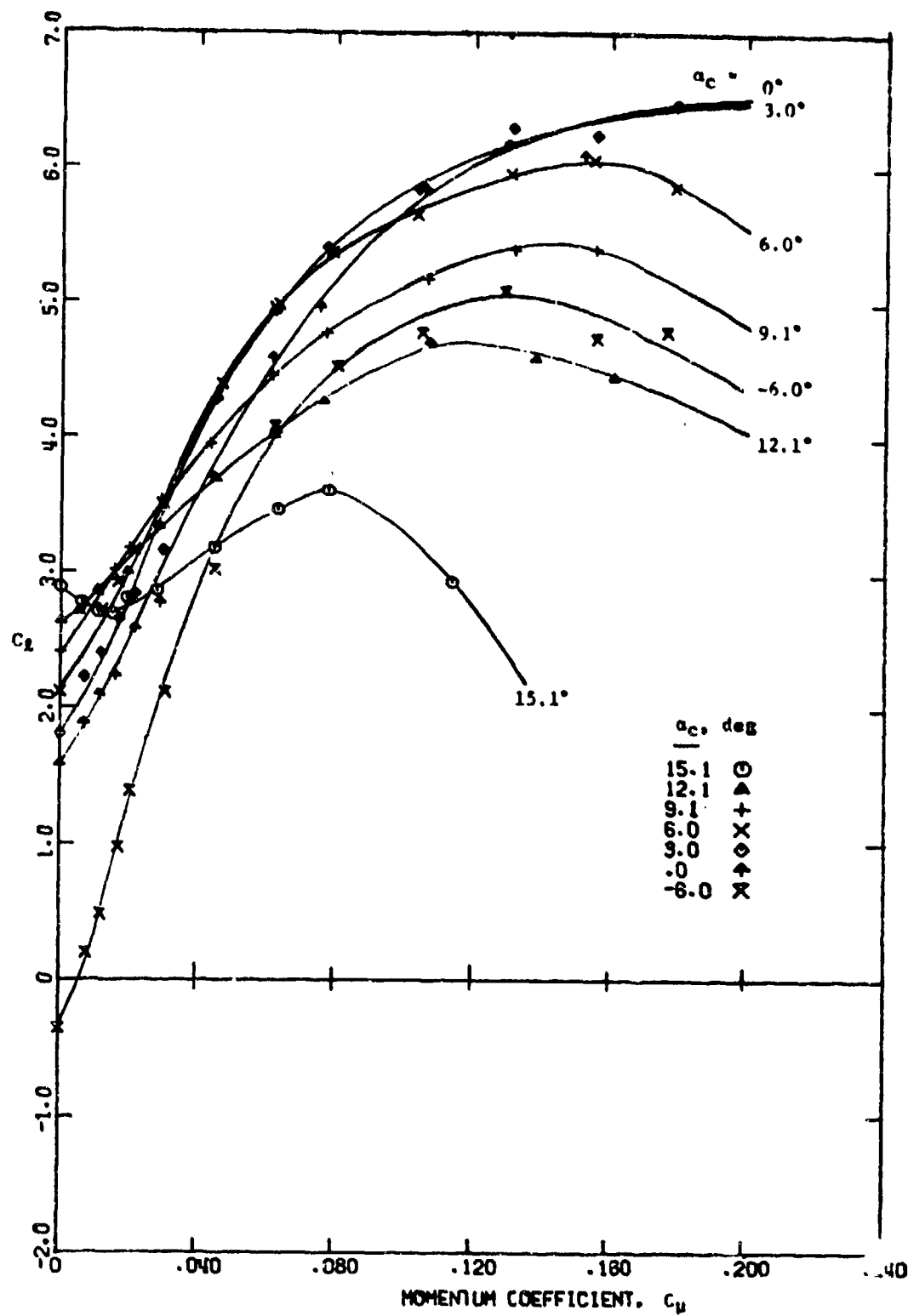


Figure 20 - (Continued)

(b) CCW 242, $\delta_f = 90^\circ$, $\delta_{LE} = 30^\circ$

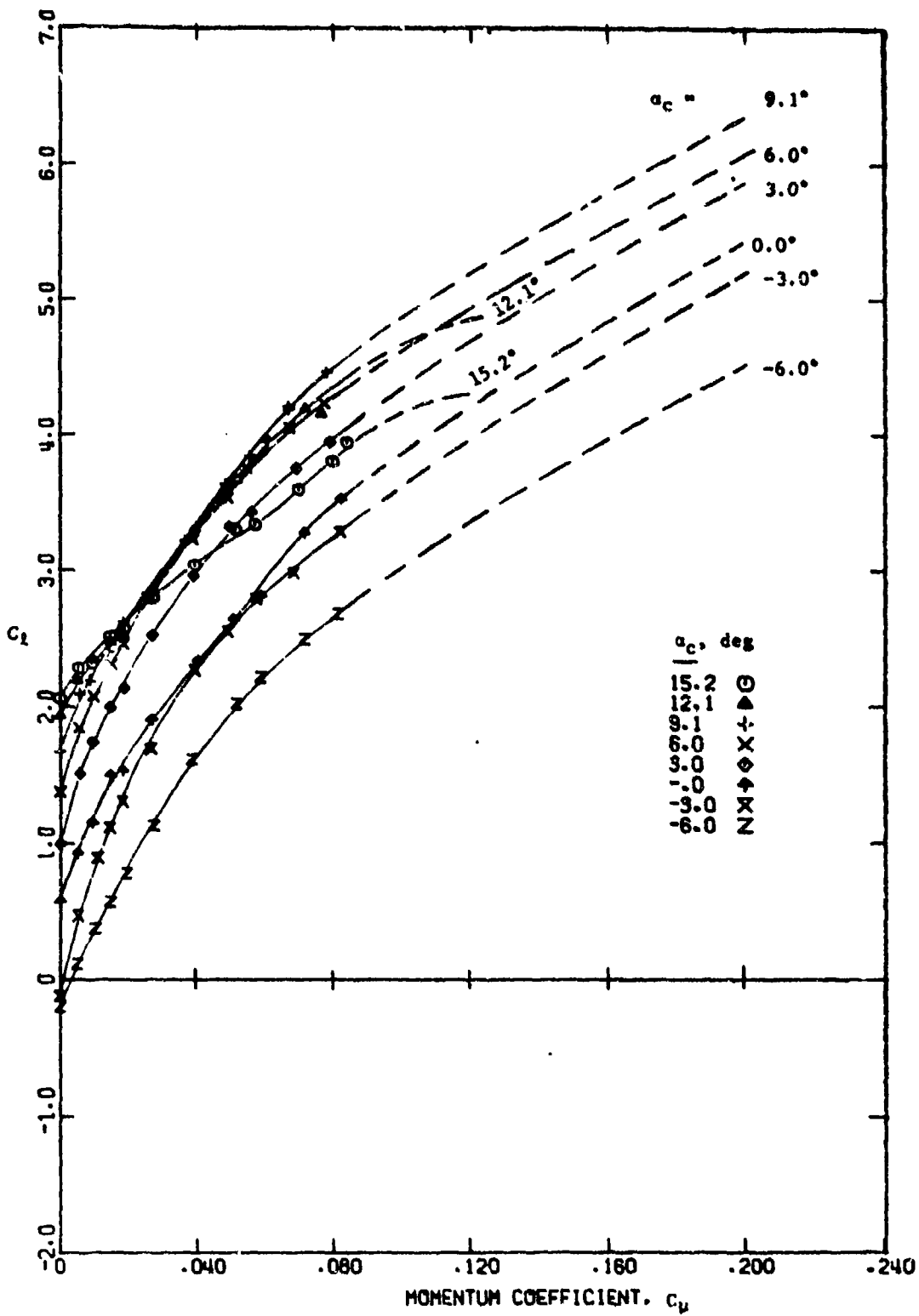


Figure 20 - (Continued)

(c) CCW 243, Extended T.E., $\delta_{LE} = 30^\circ$

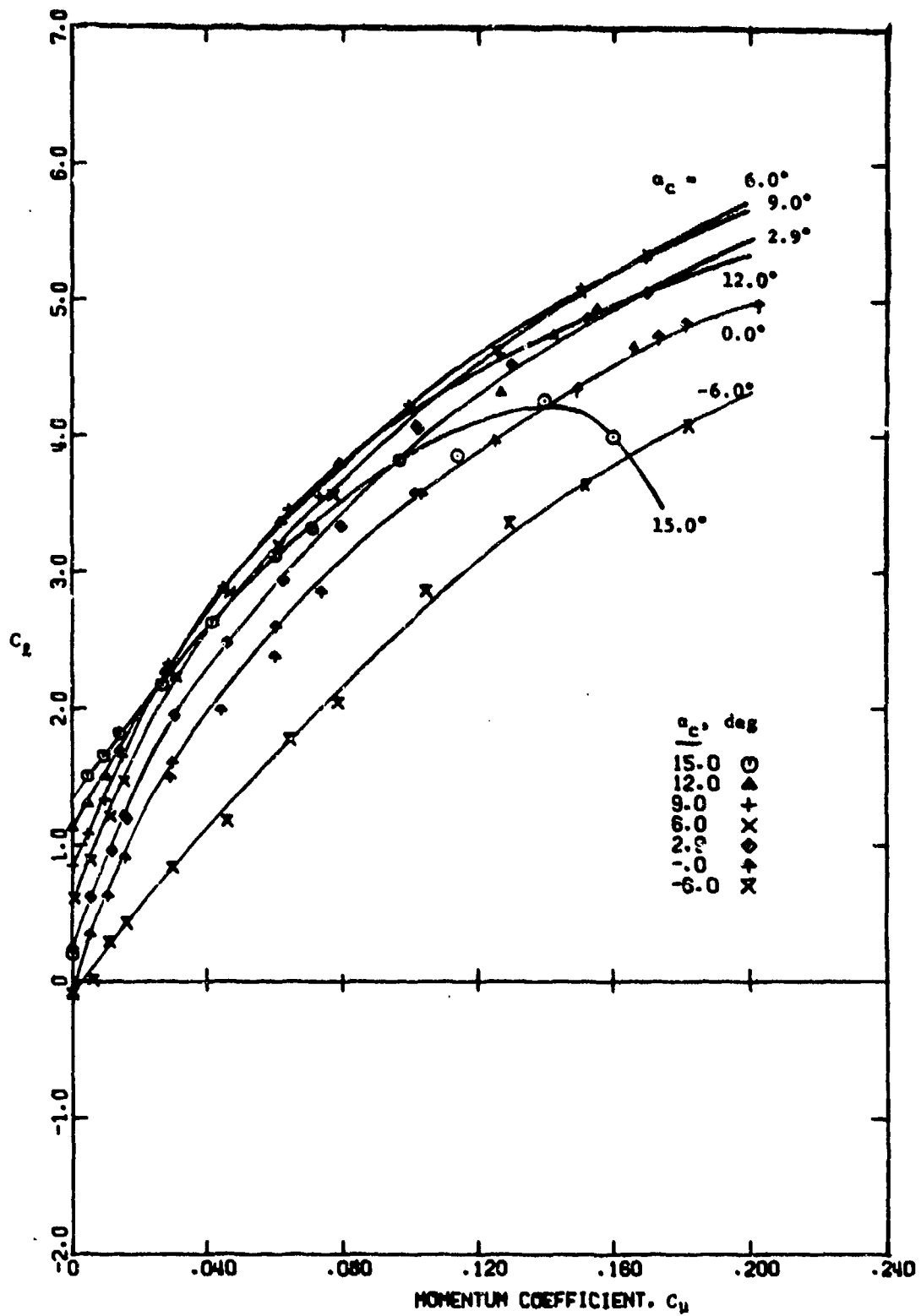


Figure 20 - (Continued)

(d) CCW 244, Reduced T.E., $\delta_{LE} = 30^\circ$

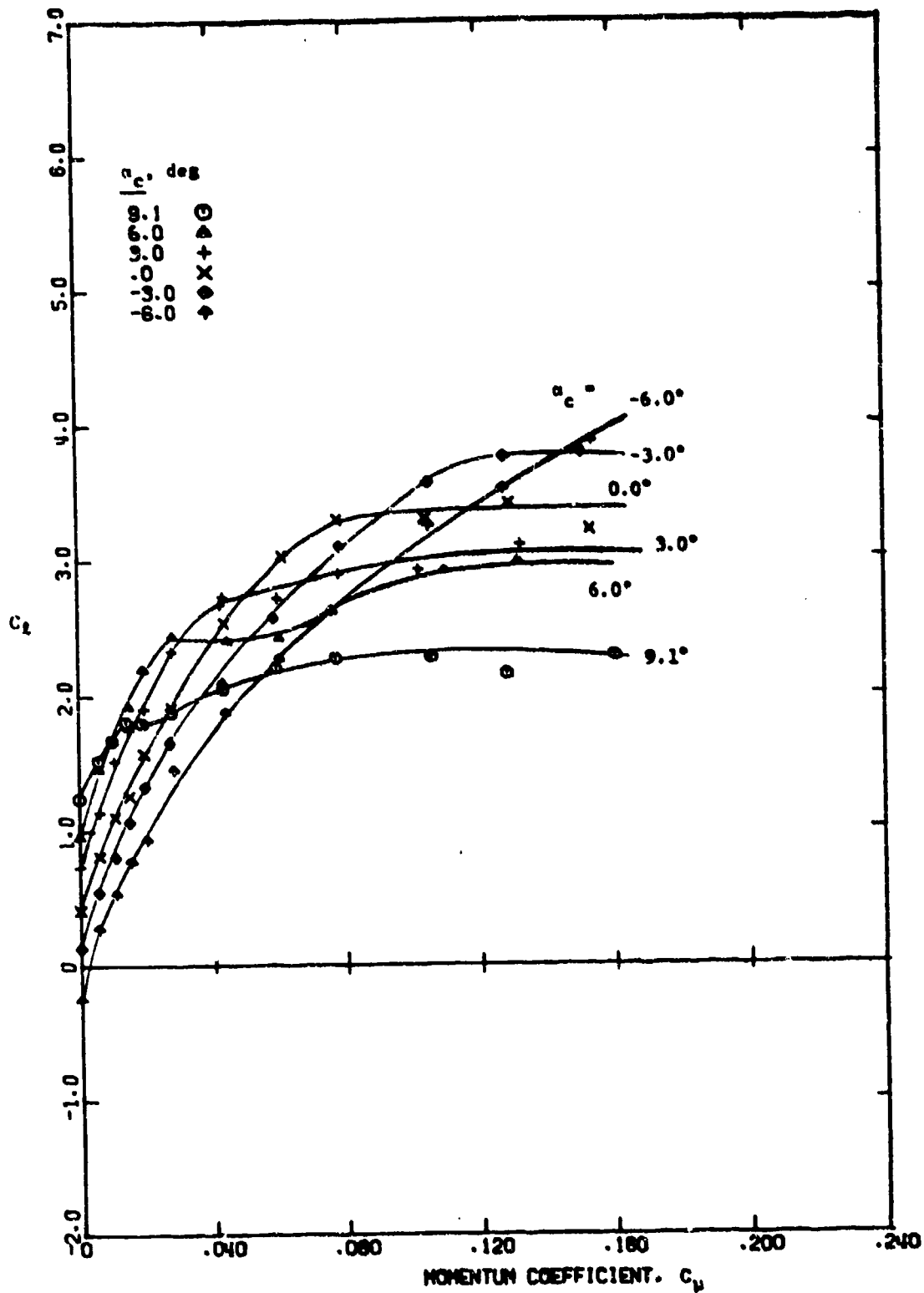


Figure 20 - (Concluded)

(e) CCW 245, $\delta_f = 180^\circ$, $\delta_{LE} = 0^\circ$

	<u>CCW 241</u>	<u>CCW 829</u>
$Re \times 10^{-6}$	1.98	0.64
δ_{LE}	30°	29°
c'	21.27"	7.08"
r	.875	.276
h	.027"	.009"
h/c'	.00127	.00127
r/c'	.0412	.0390
t/c'	.1355	.1148
x/c') slot	.960	.963
h/r	.0309	.0326

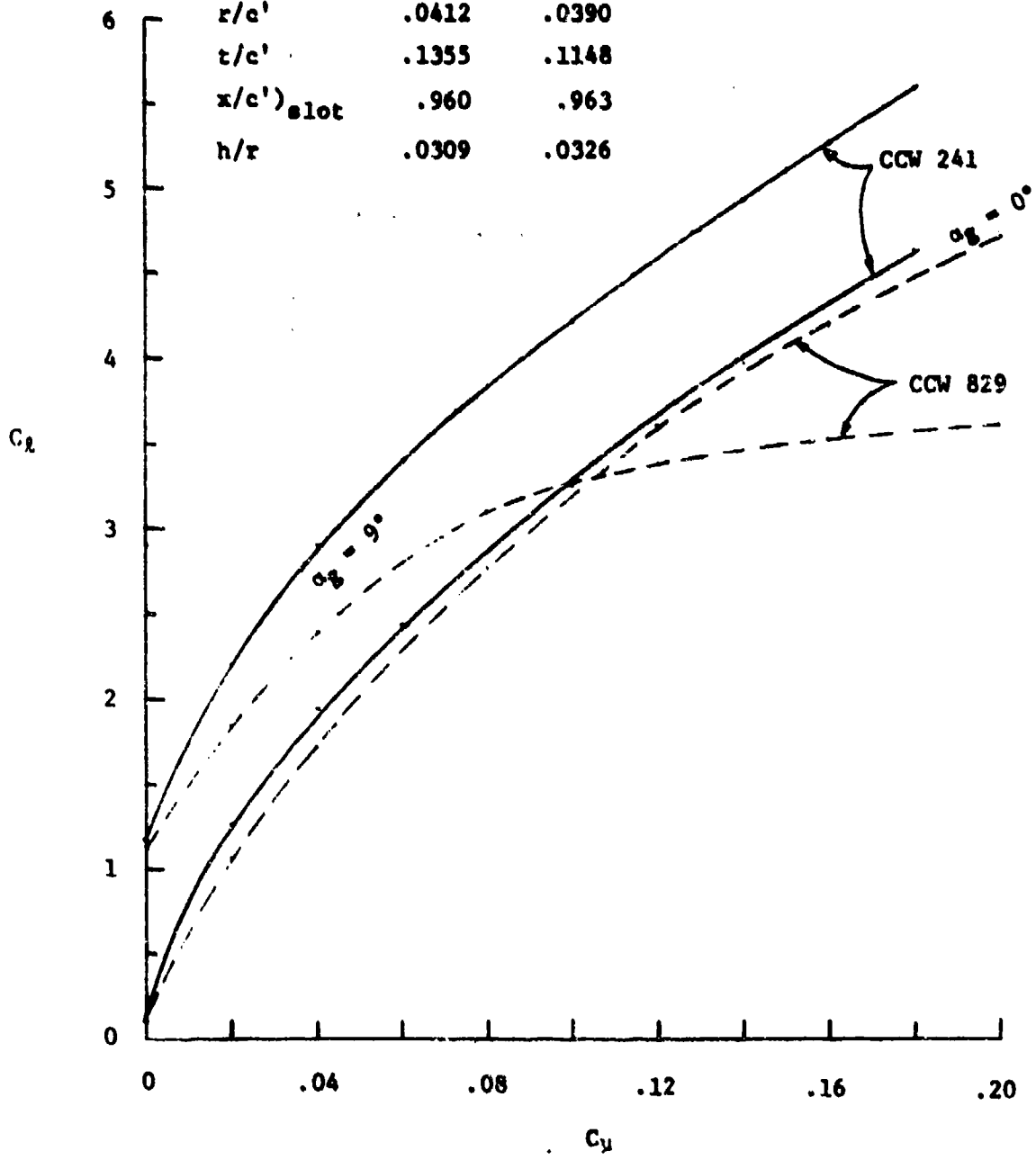


Figure 21 - Small and Large Chord CCW Airfoil Comparison

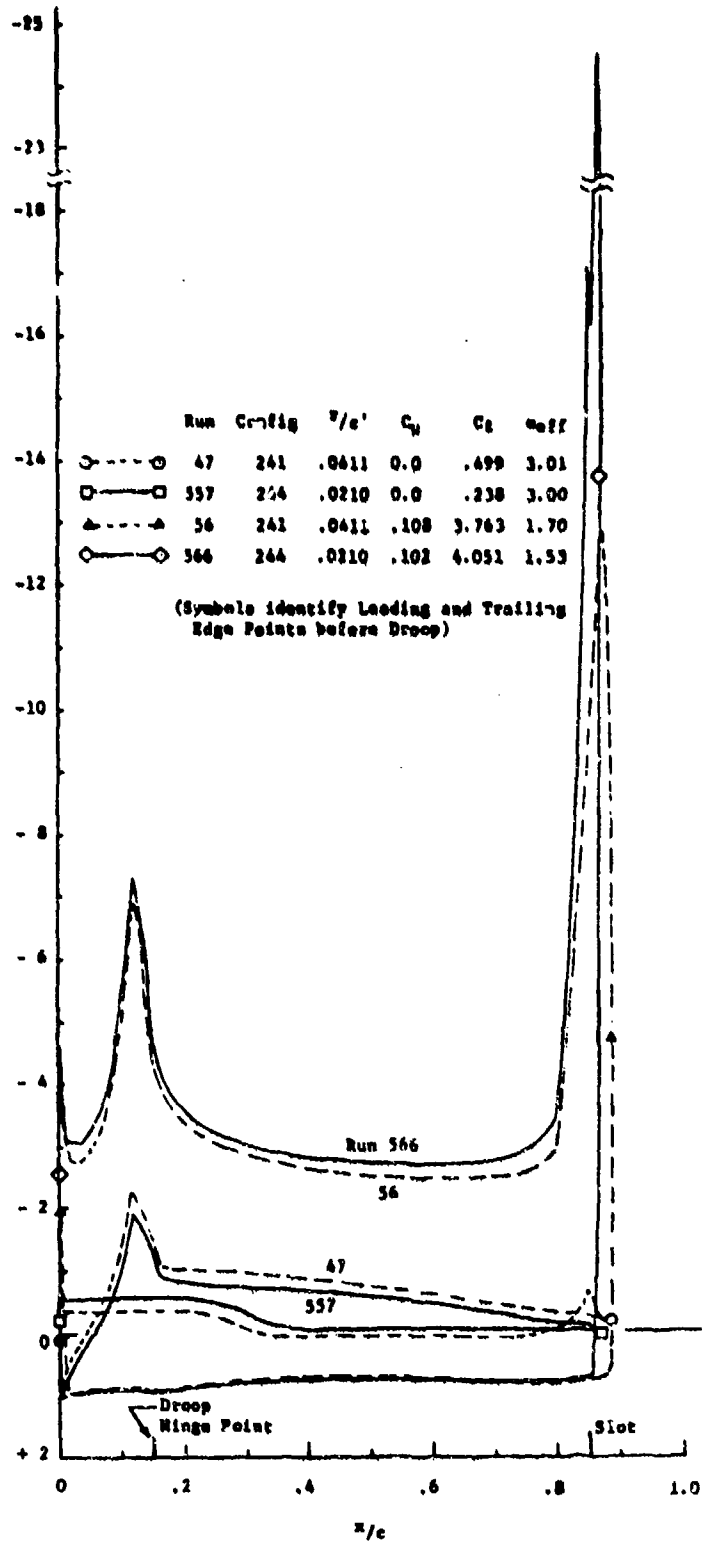


Figure 22 - Effects of Reduced Trailing Edge Radius - Comparison Between Configuration CCW 241 and CCW 244 Experimental Pressure Distributions

(a) $\alpha_c \approx 3^\circ$

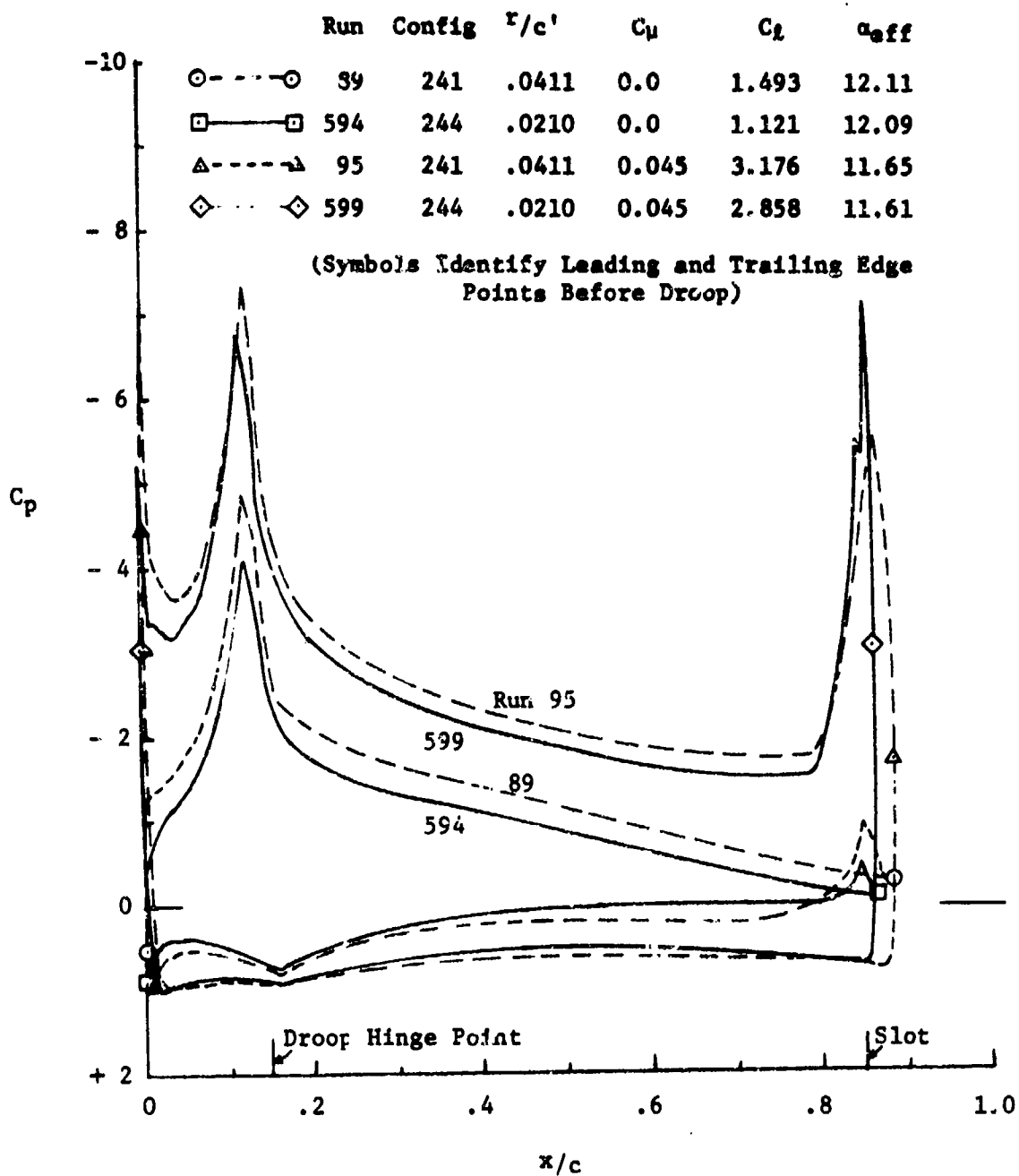


Figure 22 - Continued
 (b) $\alpha_c \sim 12^\circ$

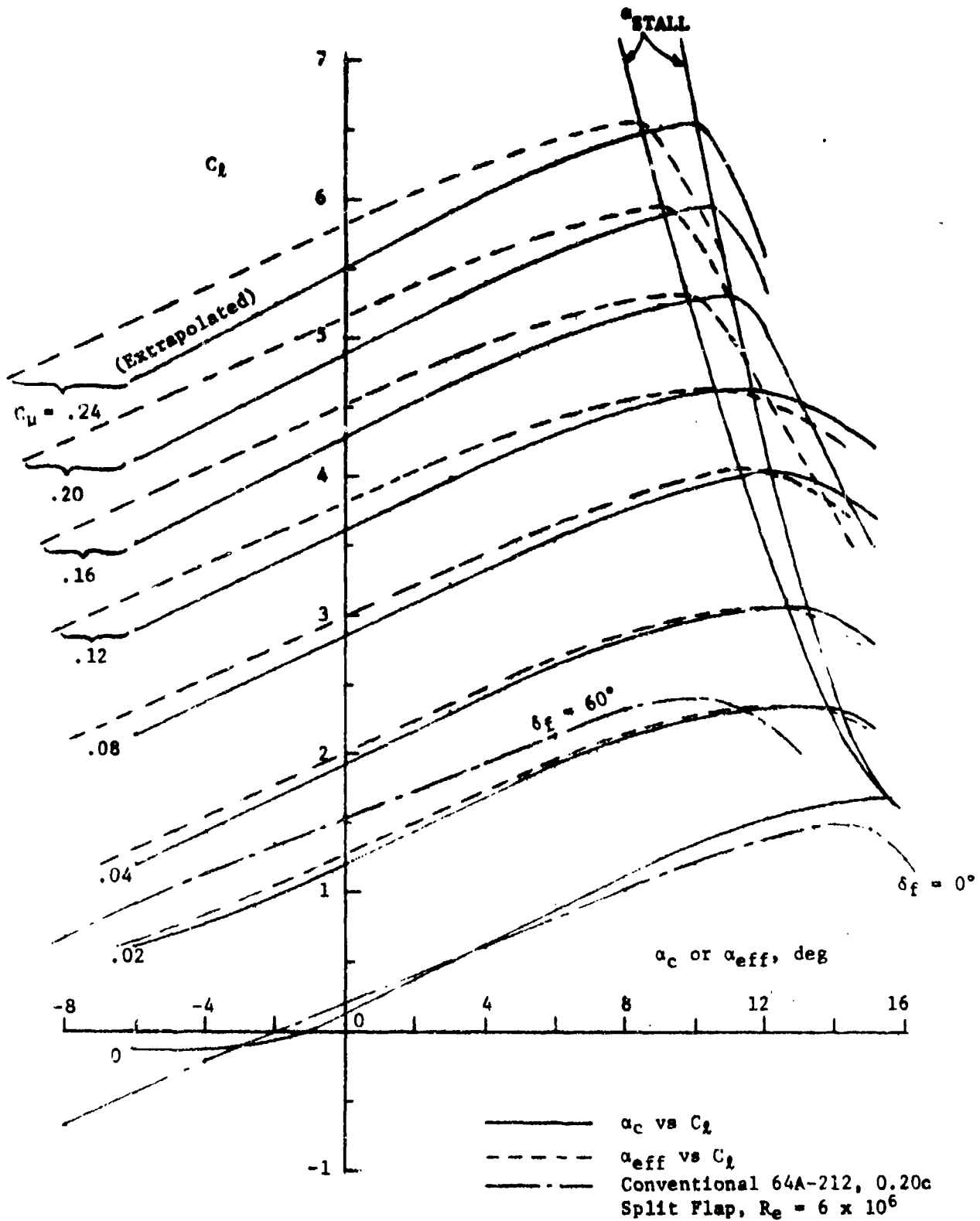


Figure 23 - Lift Curves at Constant Momentum Coefficient for 64A-212/CCW Airfoils
 $q = 30 \text{ psf}$, $R_e = 1.98 \times 10^6$, $h = .027''$
 (a) CCW 241, $\delta_f = 180^\circ$, $\delta_{LE} = 30^\circ$

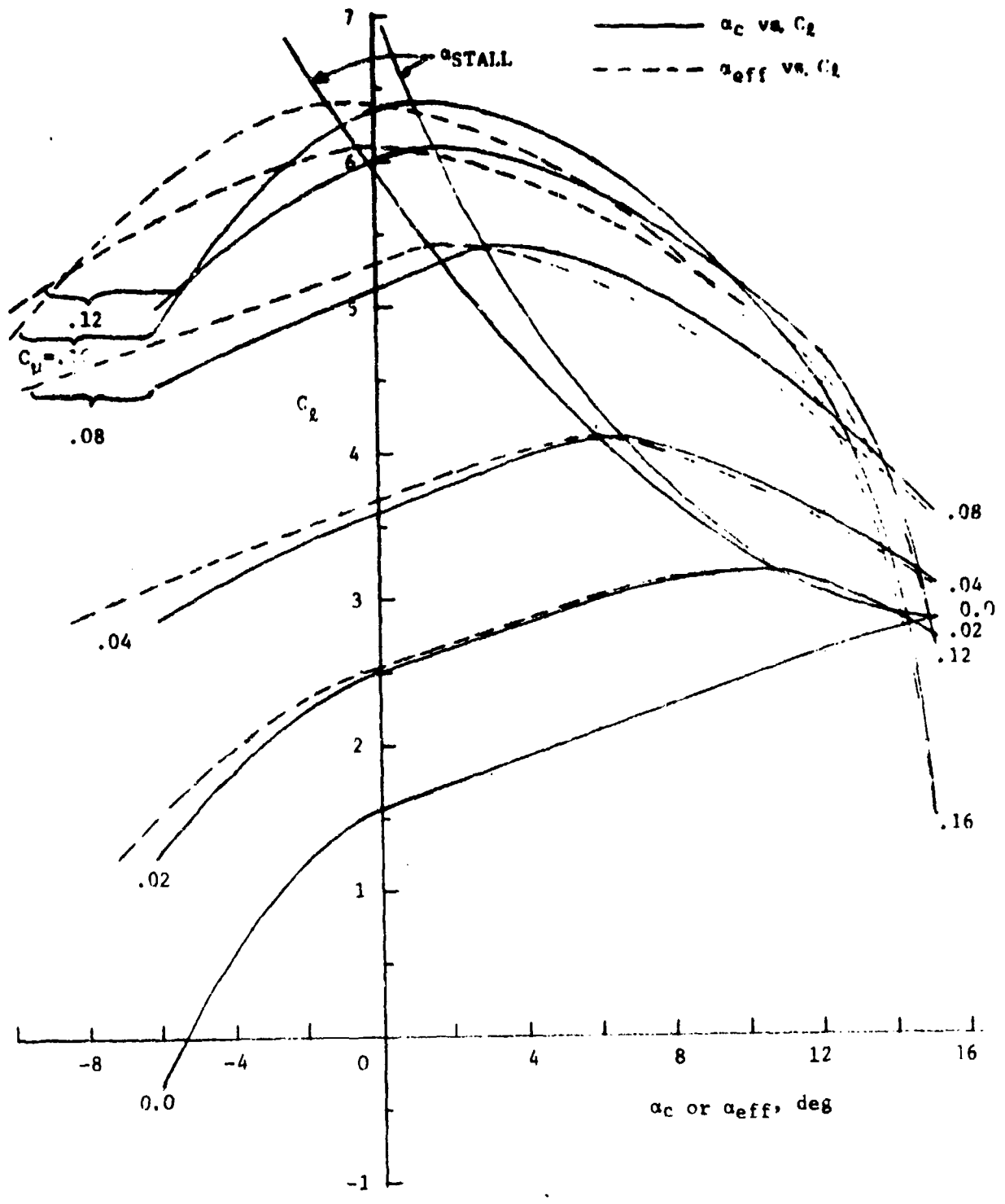


Figure 23 - Continued
 (b) CCW 242, $\delta_E = 90^\circ$, $\delta_{\gamma,E} = 30^\circ$

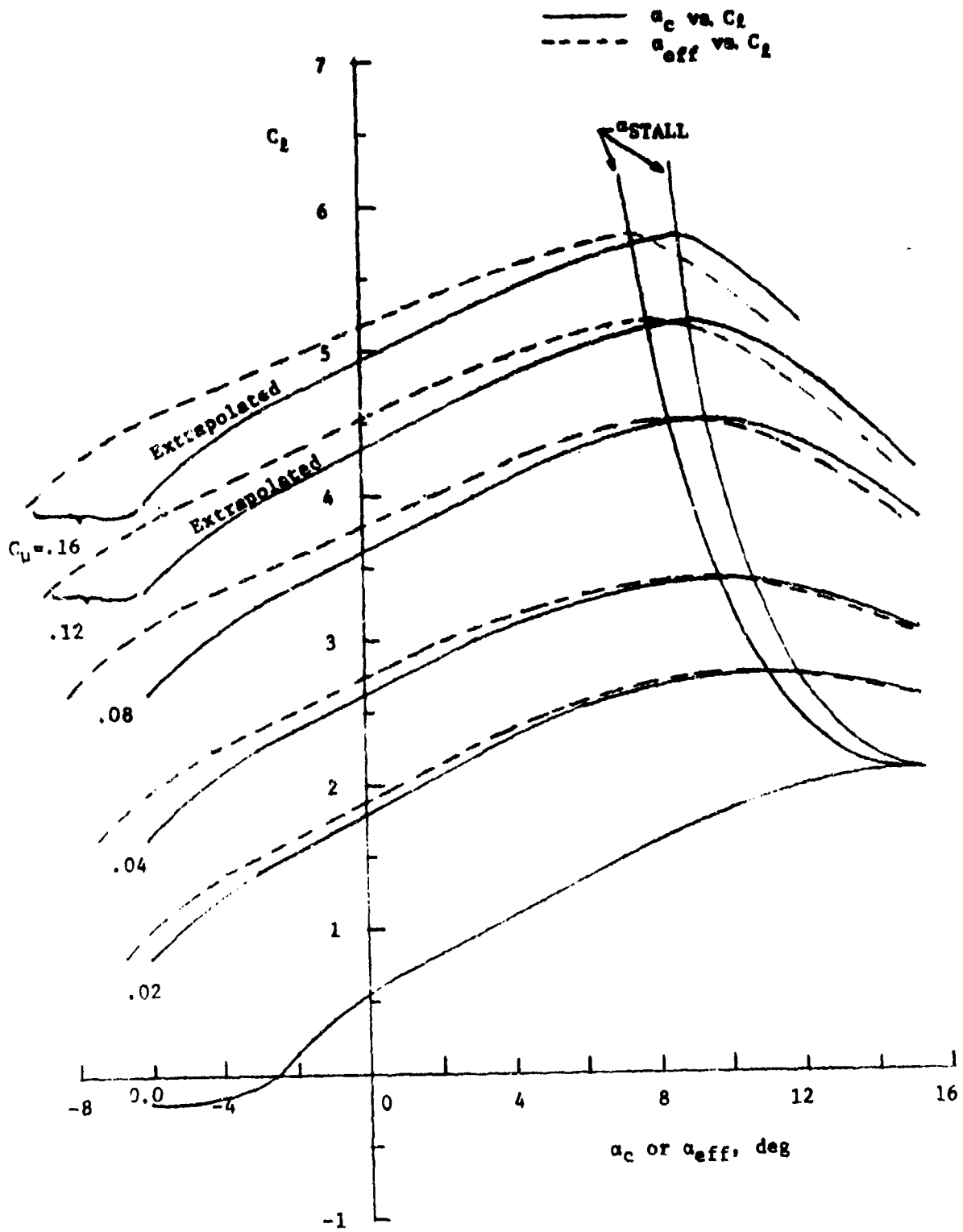


Figure 23 - Continued
 (c) CCW 243, Extended T.E., $\delta_{1E} = 30^\circ$

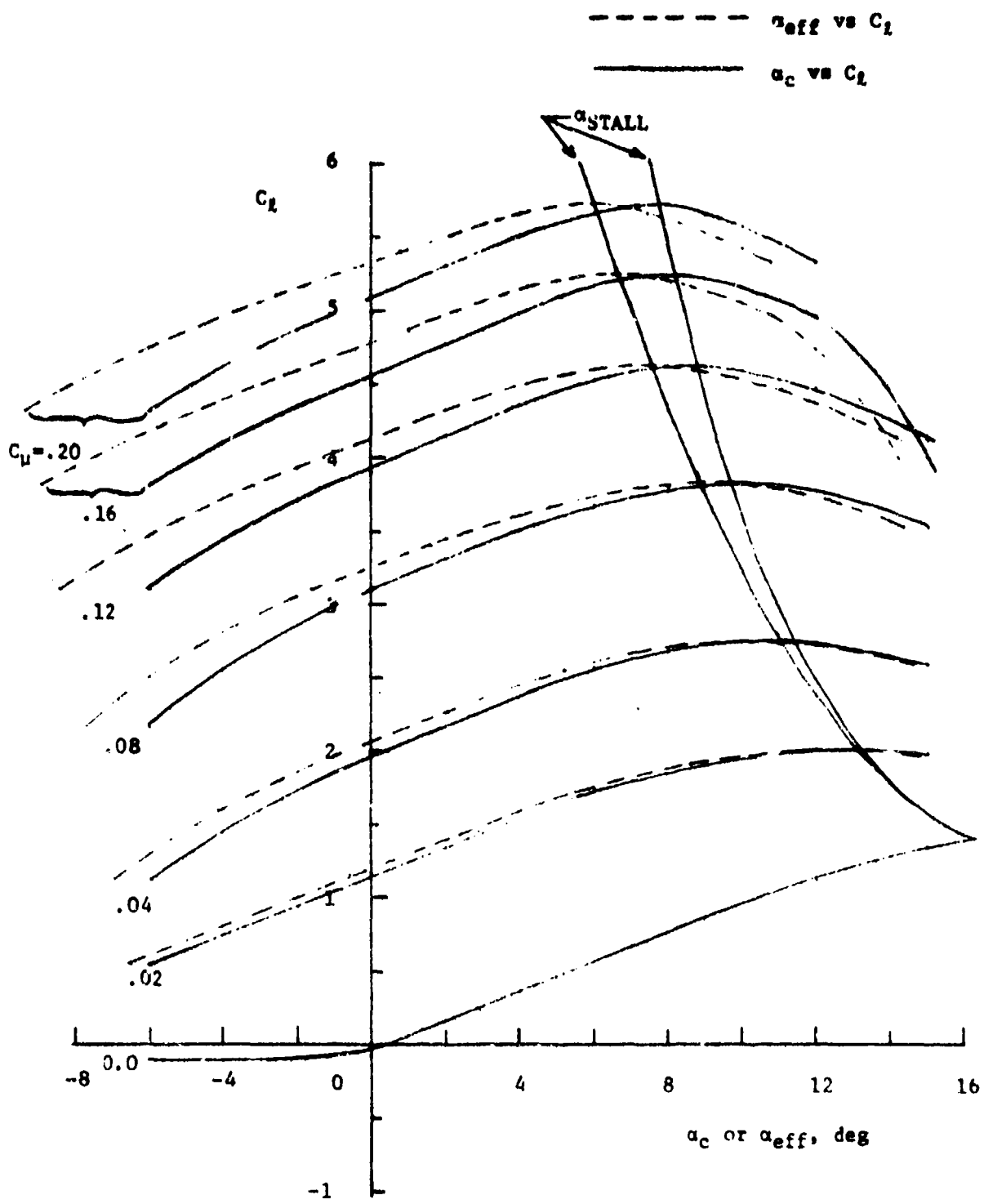


Figure 23 - Continued
 (d) CCW 244, Reduced T.E., $\delta_{LE} = 30^\circ$

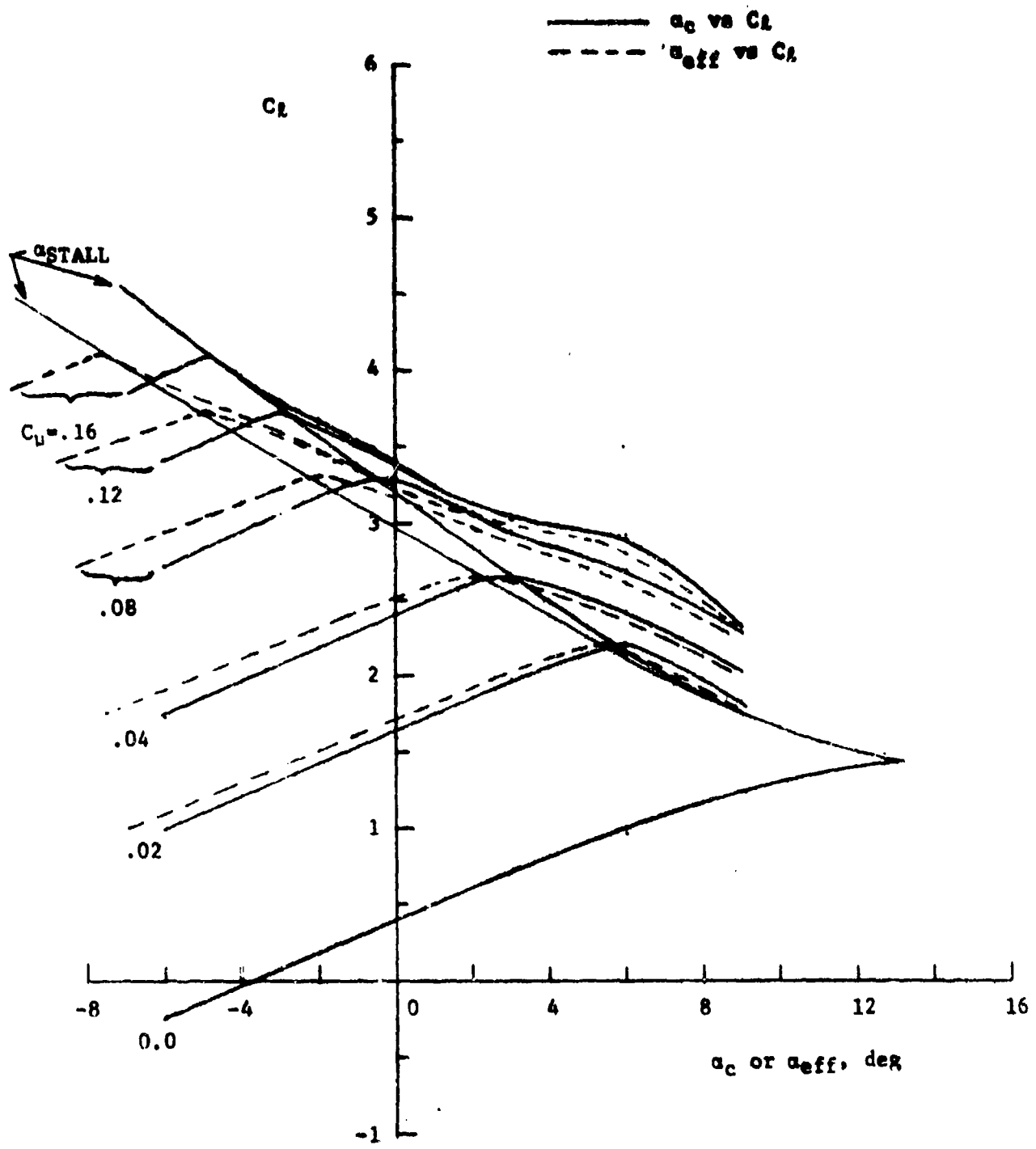


Figure 23 - Concluded
 (e) CCW 245, $\delta_f = 180^\circ$, $\epsilon_{LE} = 0^\circ$

Limits of Test Data, $C_{y1} = 0.20$

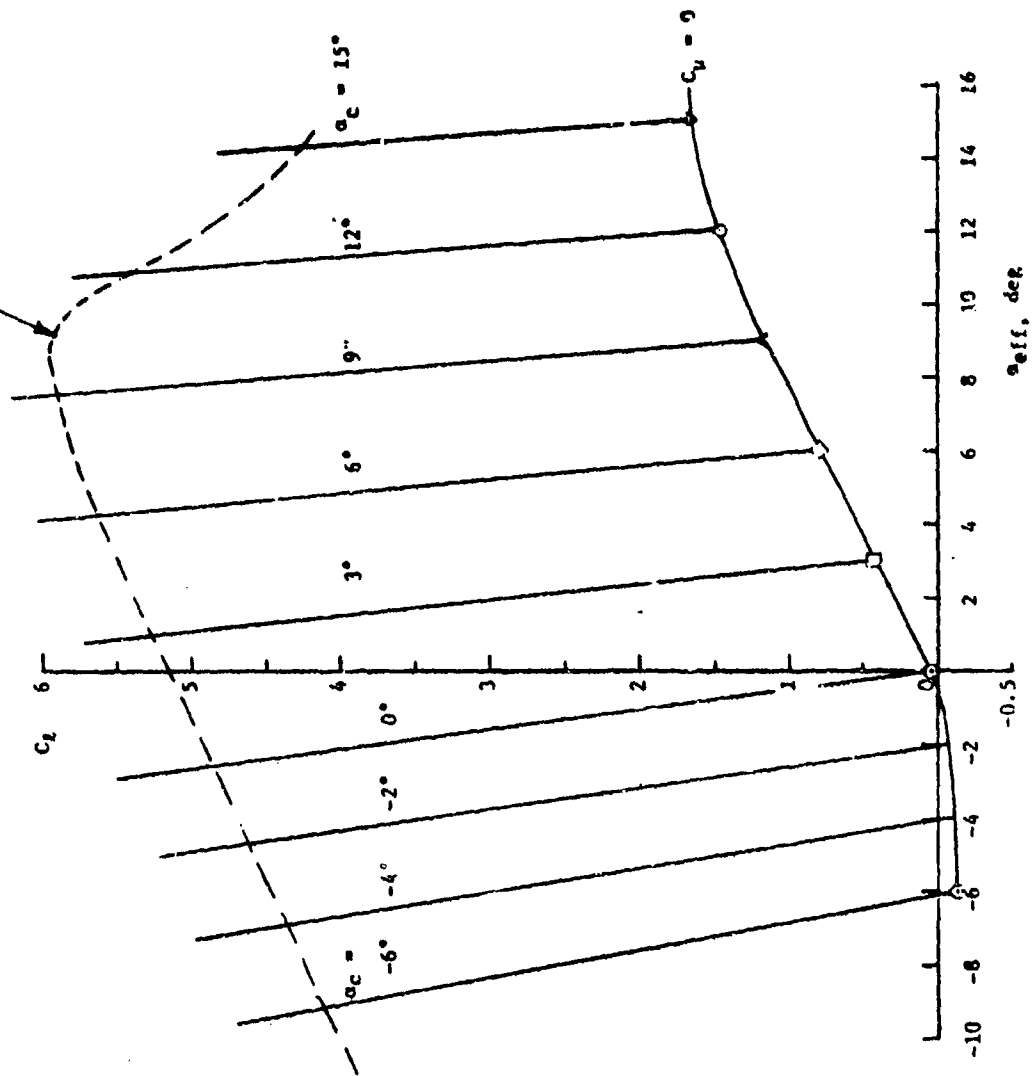


Figure 24 - Effective Incidence Corrections for Configuration CCH 241

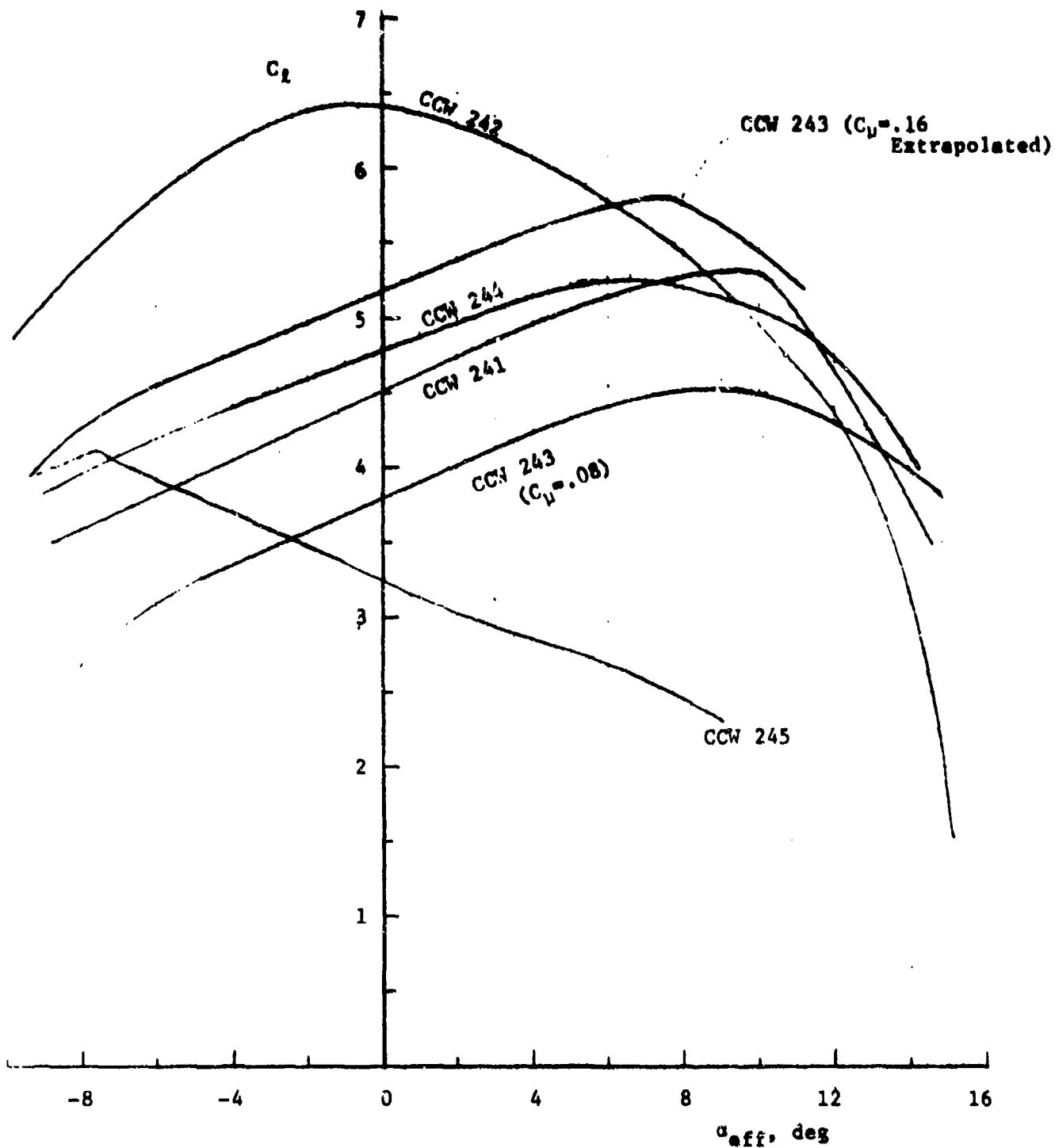


Figure 25 - Lift Curve Comparison for the 64A-212/CCW Airfoils At
 $C_u = 0.16$, $\alpha_g \leq 15^\circ$, $h = .027''$, $q = 30$ psf

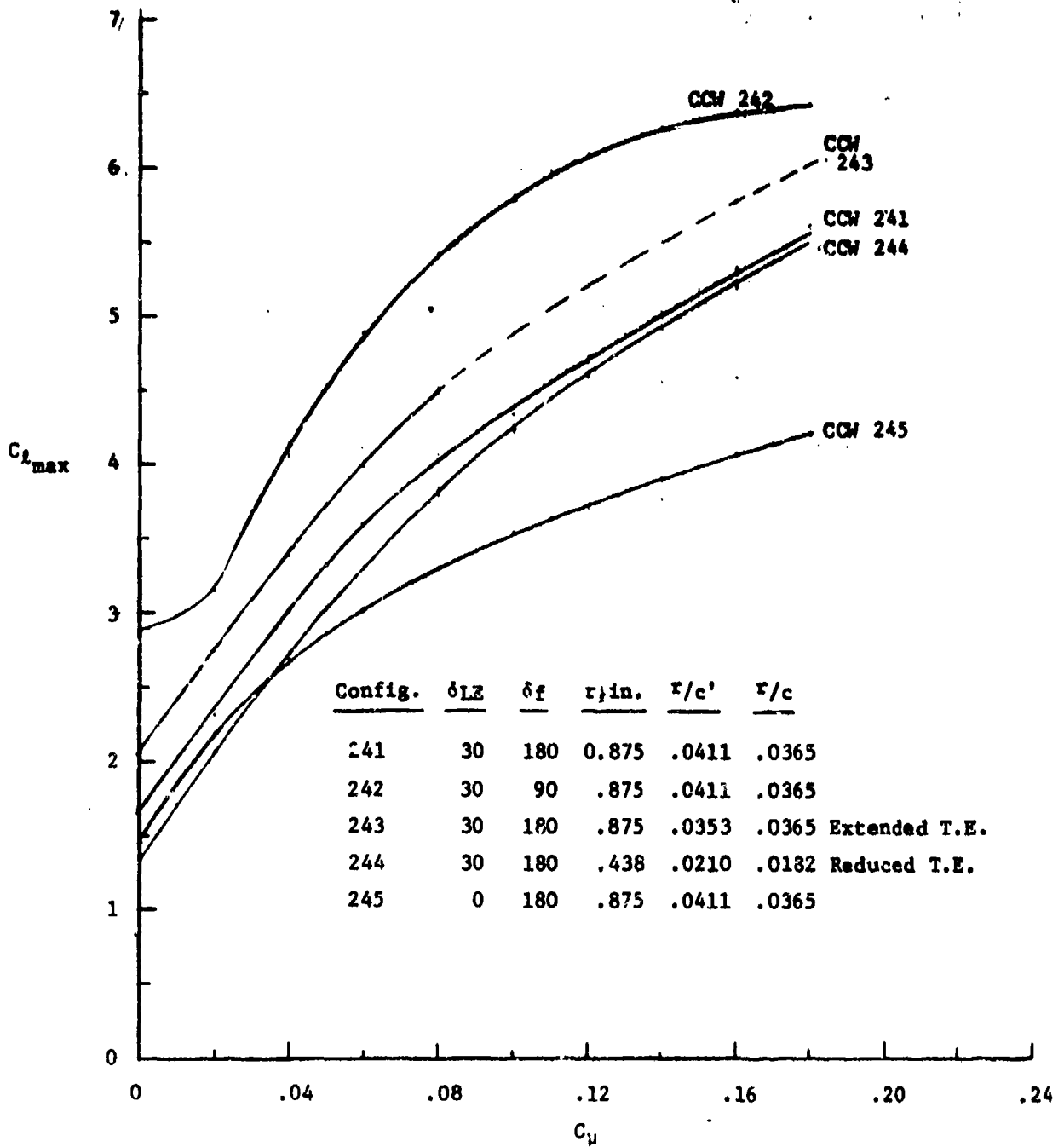


Figure 26 - Maximum Lift Coefficients within Test Limitations for
 5 Configurations of a C.C. Wing on a 2-D NACA
 64A212 Airfoil ($\alpha_g \leq 15^\circ$, $h = .027''$, $q = 30$ psf)

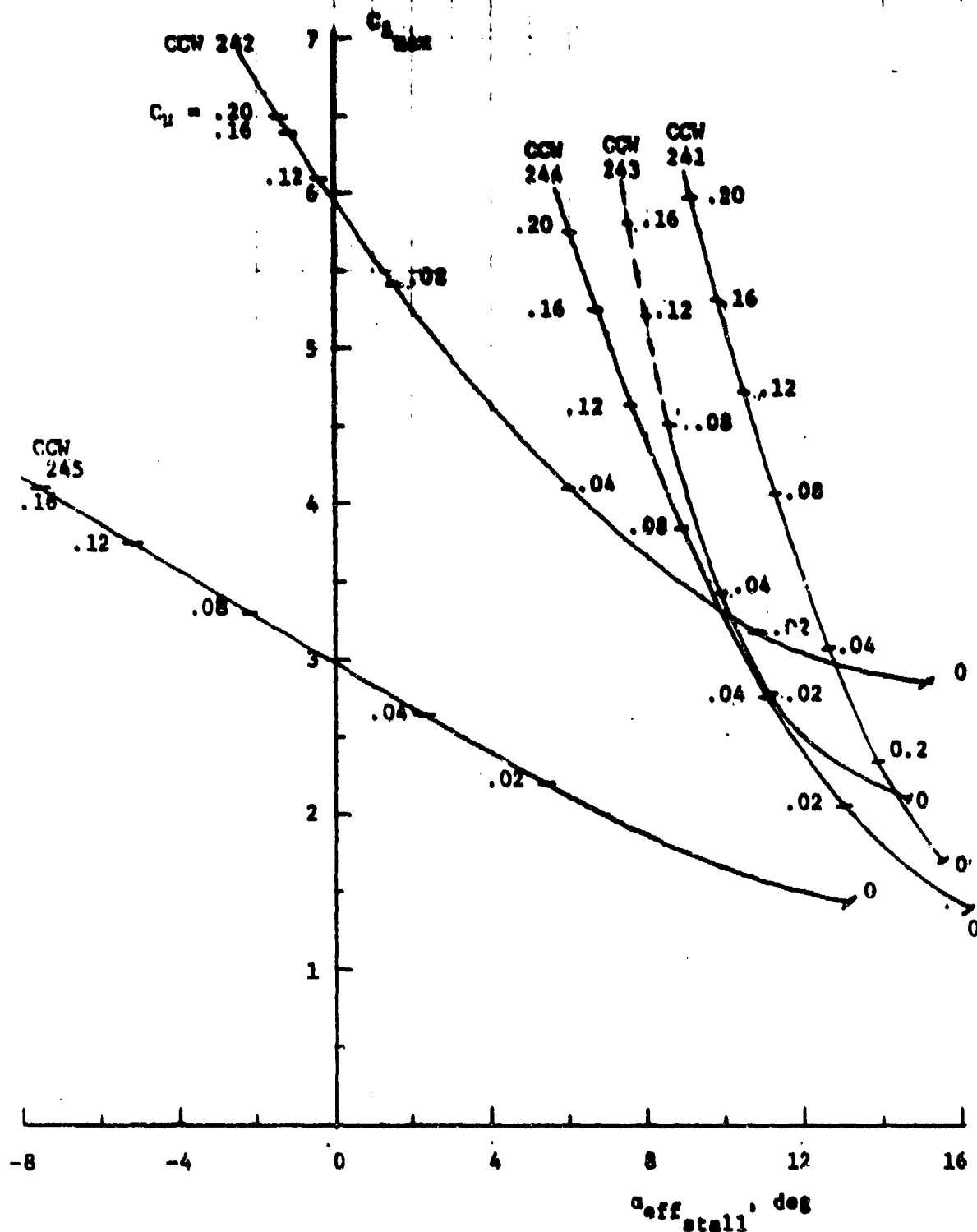


Figure 27 - $C_{L_{max}}$ and Stall Angles for the 64A-212/CCW Airfoils ($h = .027''$, $q = 30$ psf)

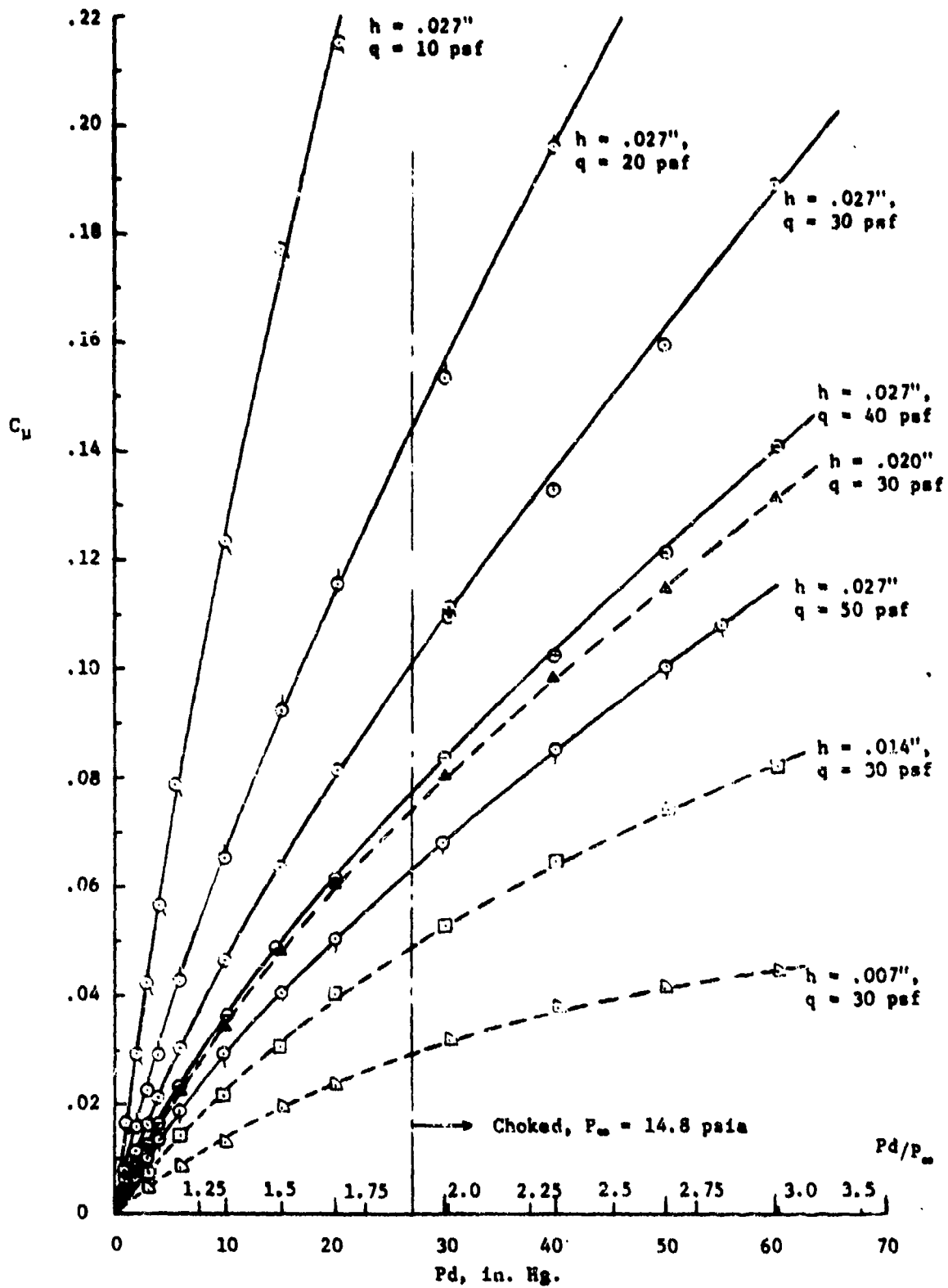


Figure 28 - Slot Height and Dynamic Pressure Effects on C_L ,
 CCW 241, $\alpha_g = 9^\circ$, $c = 24''$

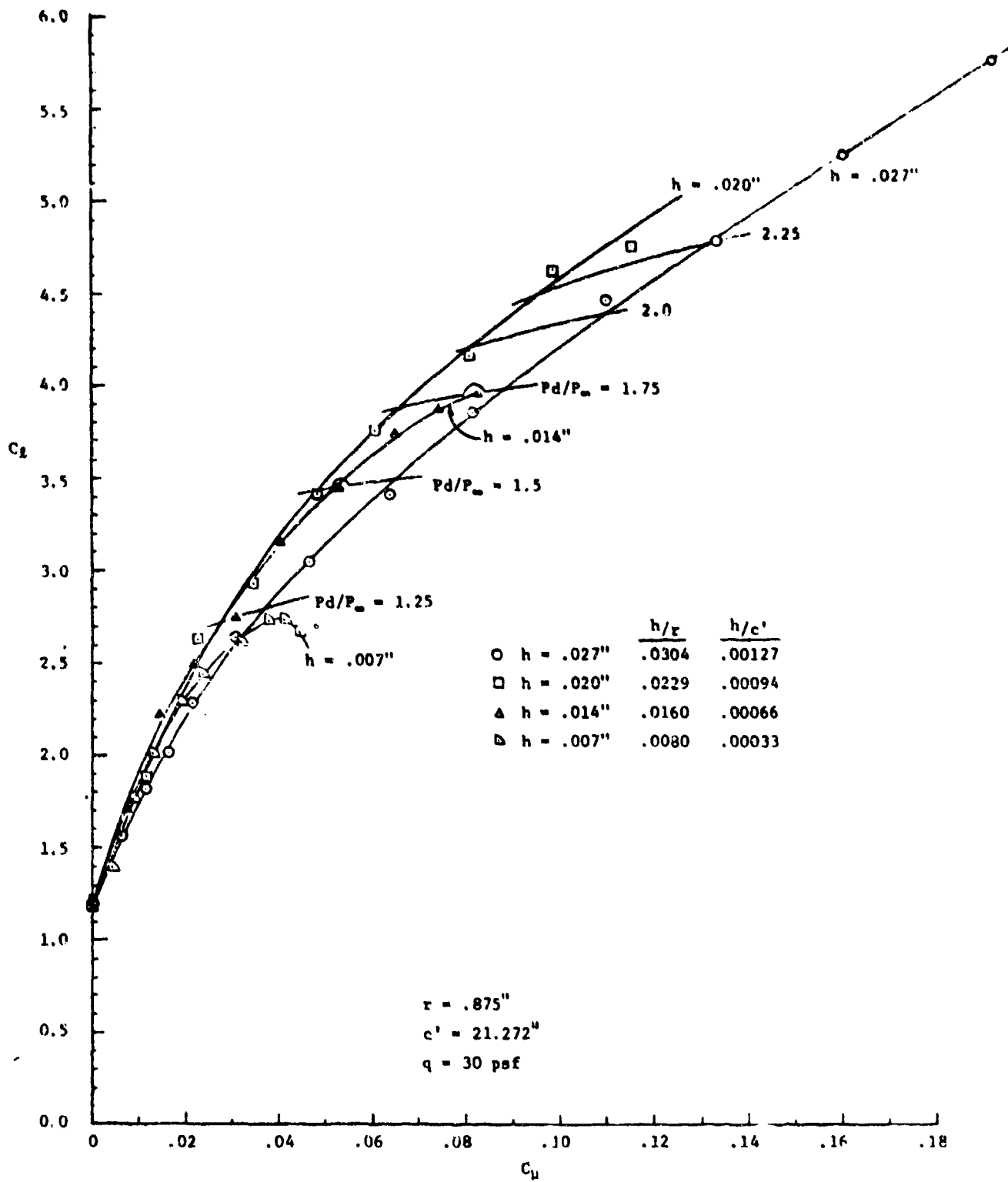


Figure 29 - Slot Height and Pressure Ratio Effects on CCW 241,
 $\alpha_c \approx 9^\circ$

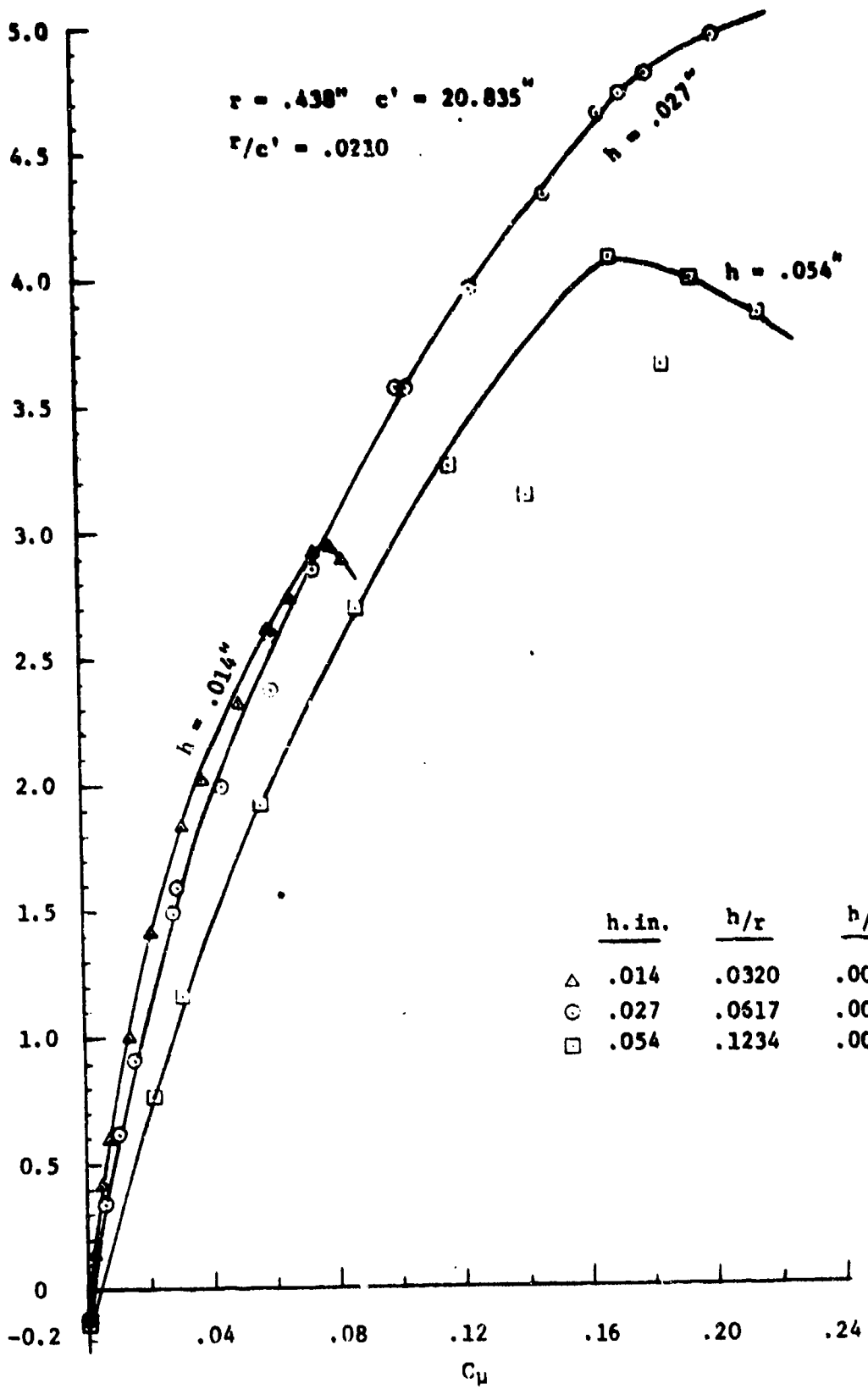


Figure 30 - Slot Height Effects on CCW 244, $\alpha_c = 0^\circ$

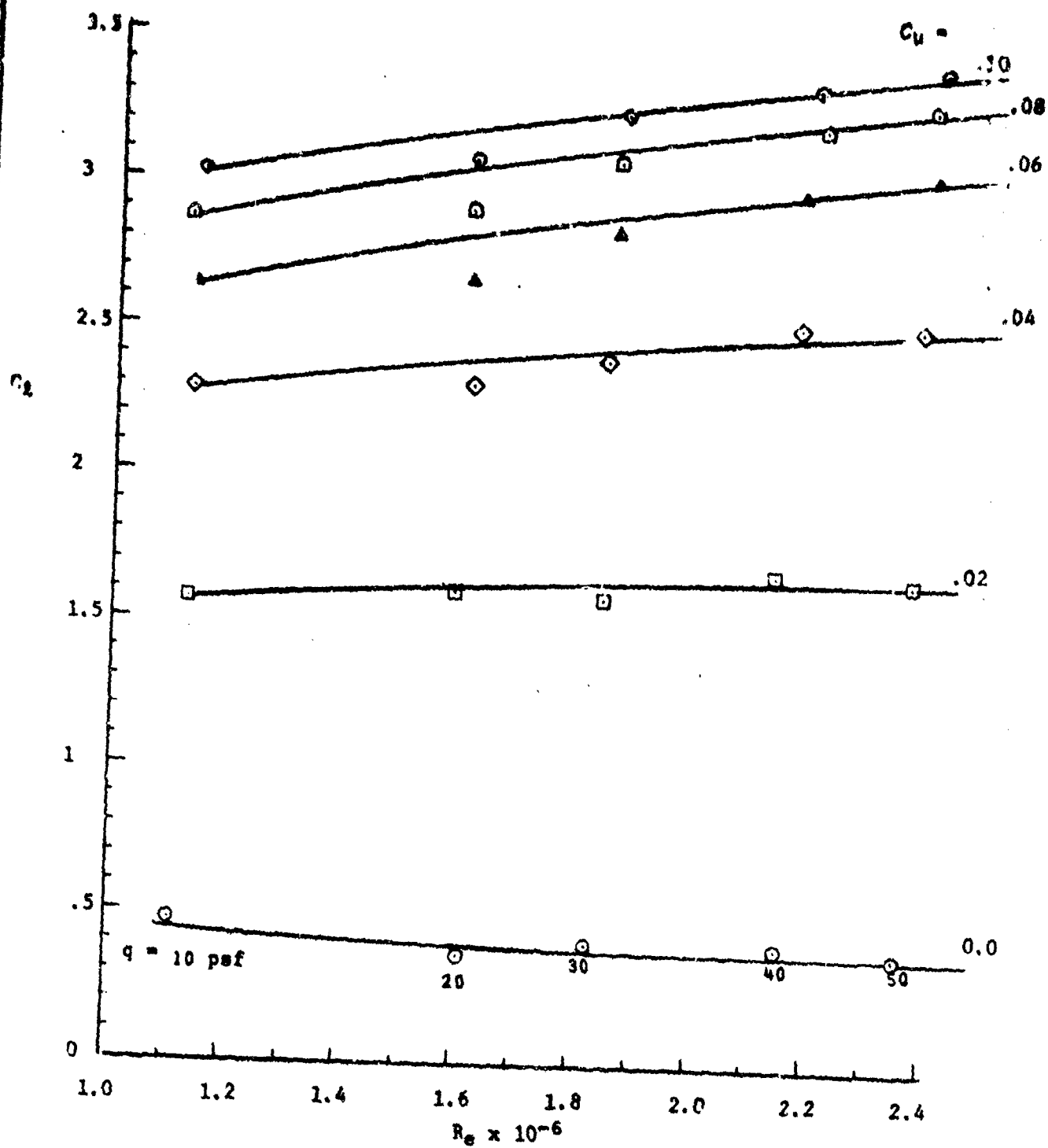


Figure 31 - Effect of Reynolds Number on Lift, CGW 245
 ($\delta_{LE} = 0^\circ$, $\delta_F = 180^\circ$). $\alpha_c = 0^\circ$, $h = .027''$

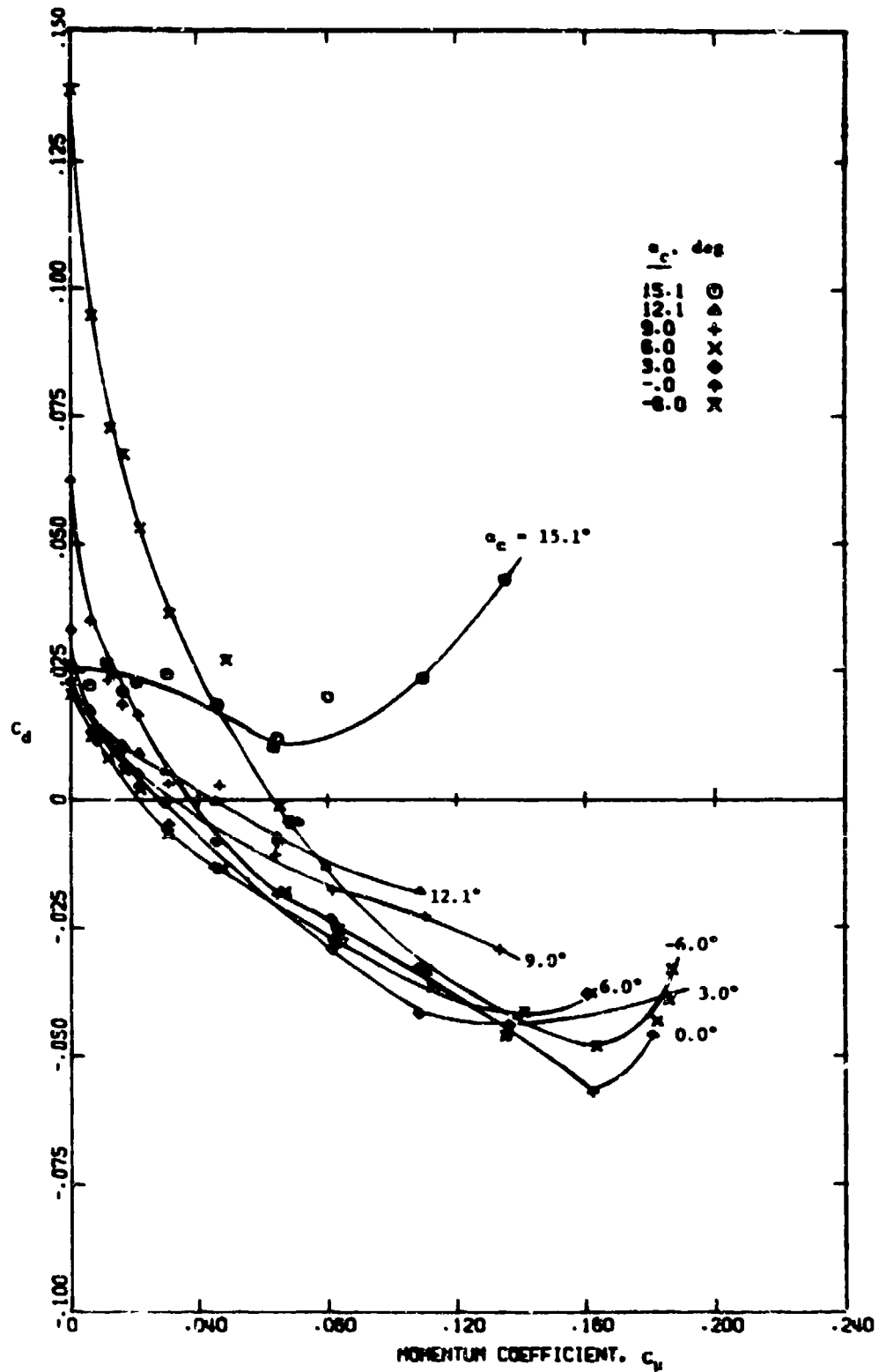


Figure 32 - Drag as a Function of Blowing for NACA 64A-212/CCW Airfoils, $q = 30$ psf, $R_e \approx 1.98 \times 10^6$, $h = 0.027''$
 (a) CCW 241, $\delta_f = 180^\circ$, $\delta_{LE} = 0^\circ$

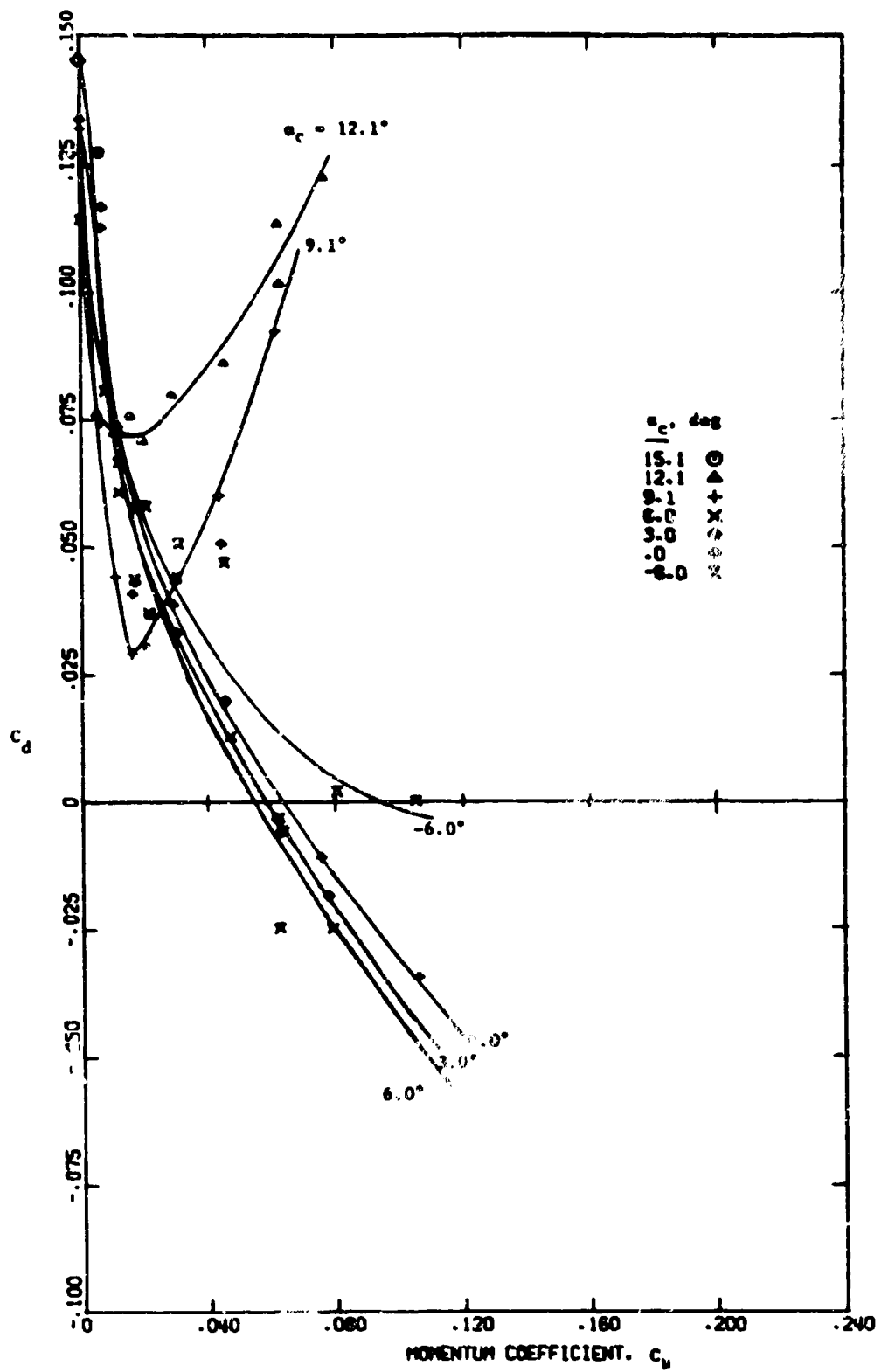


Figure 32 - (Continued)

(b) CCW 242, $\delta_f = 90^\circ$, $\delta_{LE} = 30^\circ$

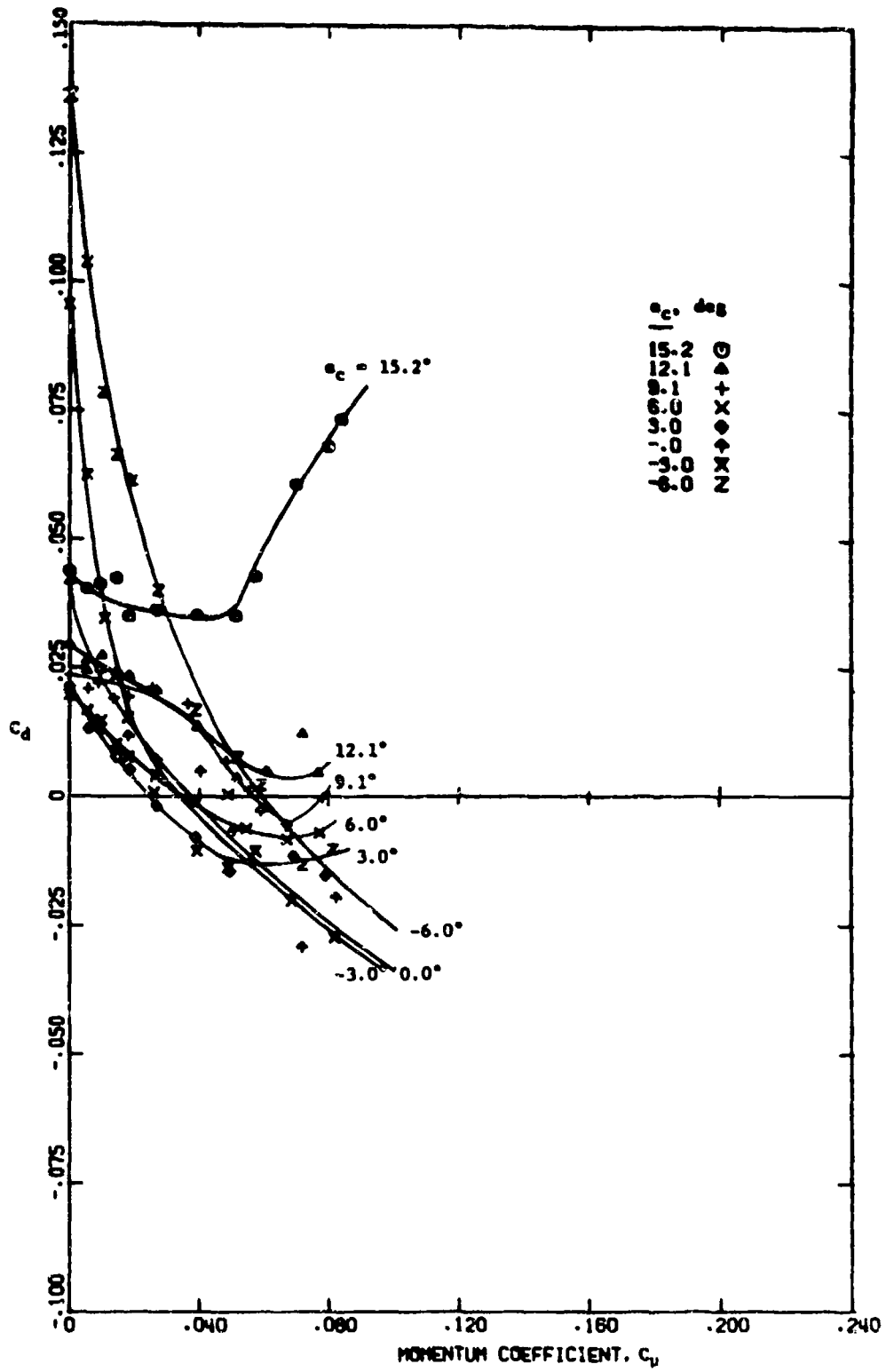


Figure 32 - (Continued)
(c) CCW 243, Extended T.E., $\delta_{LE} = 30^\circ$

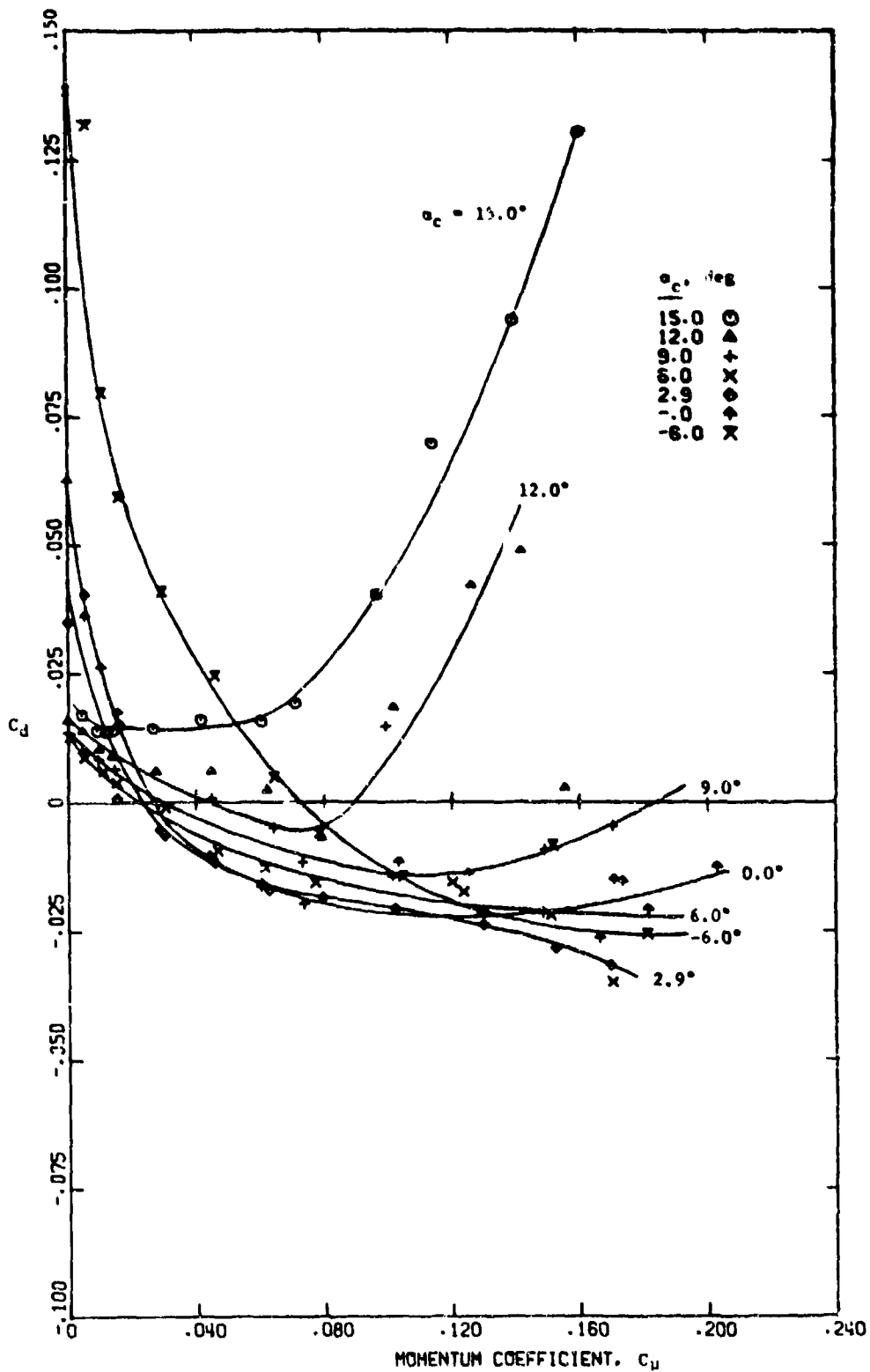


Figure 32 - (Continued)

(d) CCW 244, Reduced T.E., $\delta_{LE} = 30^\circ$

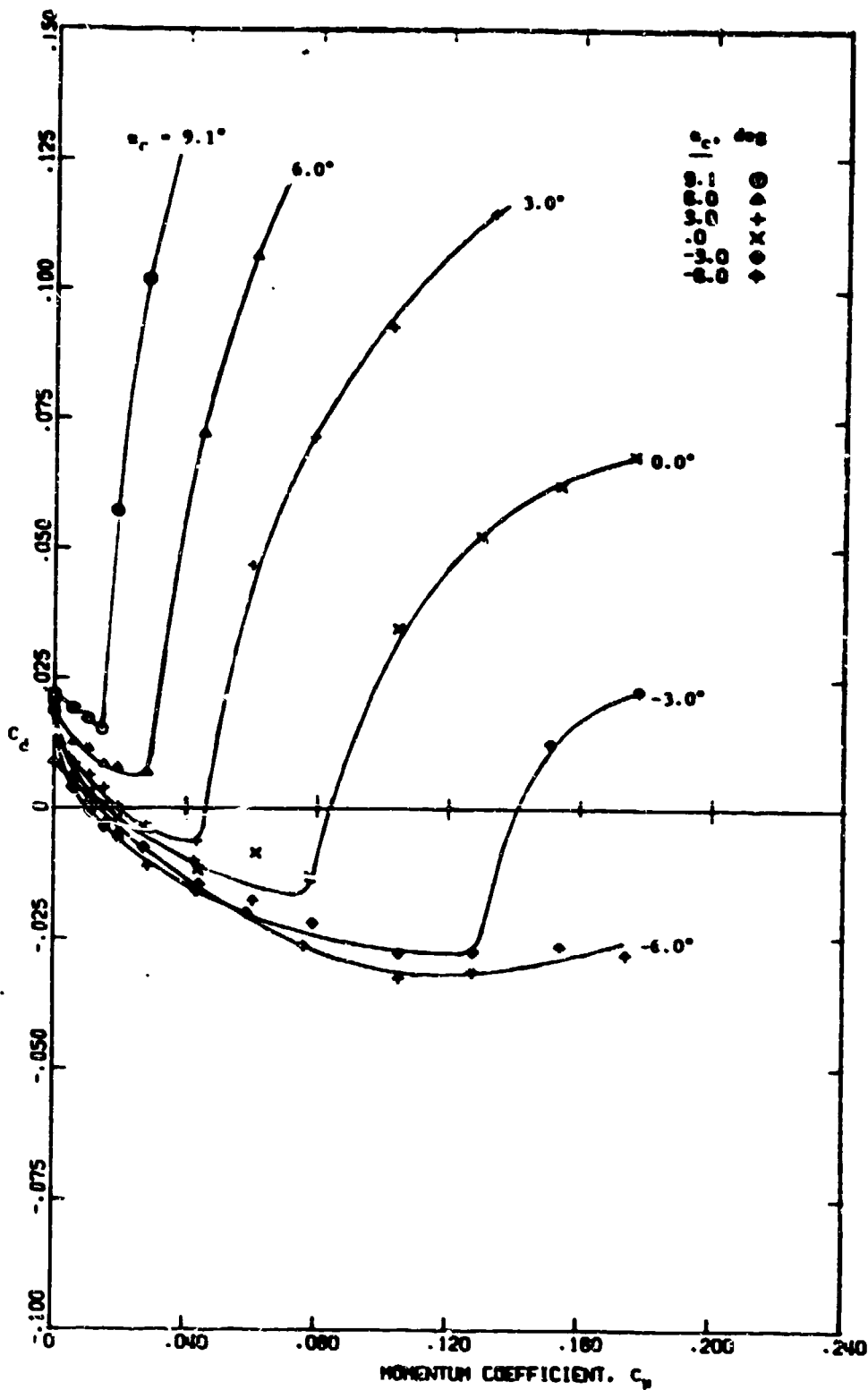


Figure 32 - (Concluded)

(e) CCW 245, $\delta_f = 180^\circ$, $\delta_{LE} = 0^\circ$

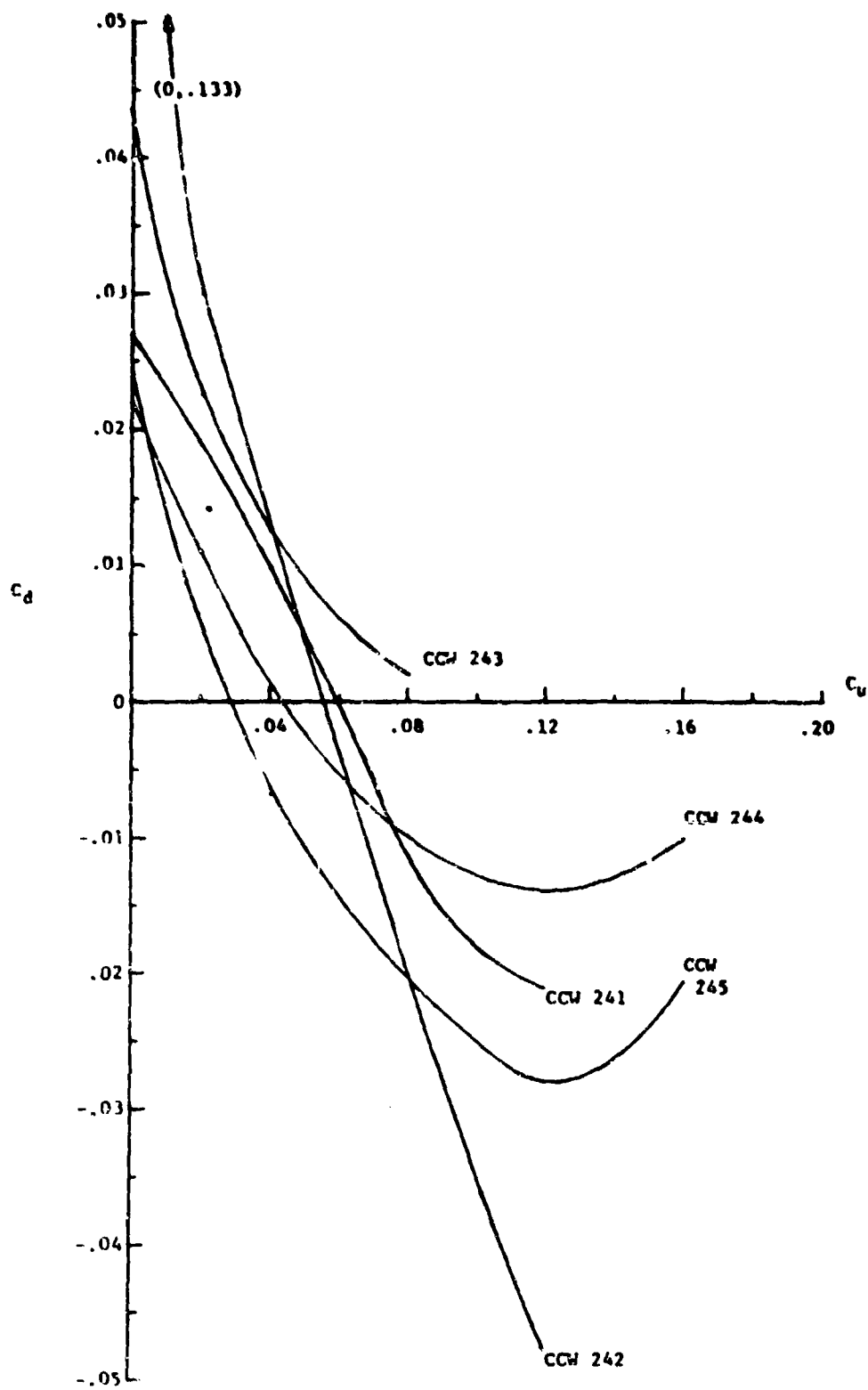


Figure 33 - Drag Coefficient at $C_{l_{max}}$ within Test Limits for NACA
64A-212/CCW Airfoils,
 $\alpha_g \leq 15^\circ$, $h = 0.027''$, $q = 30$ psf

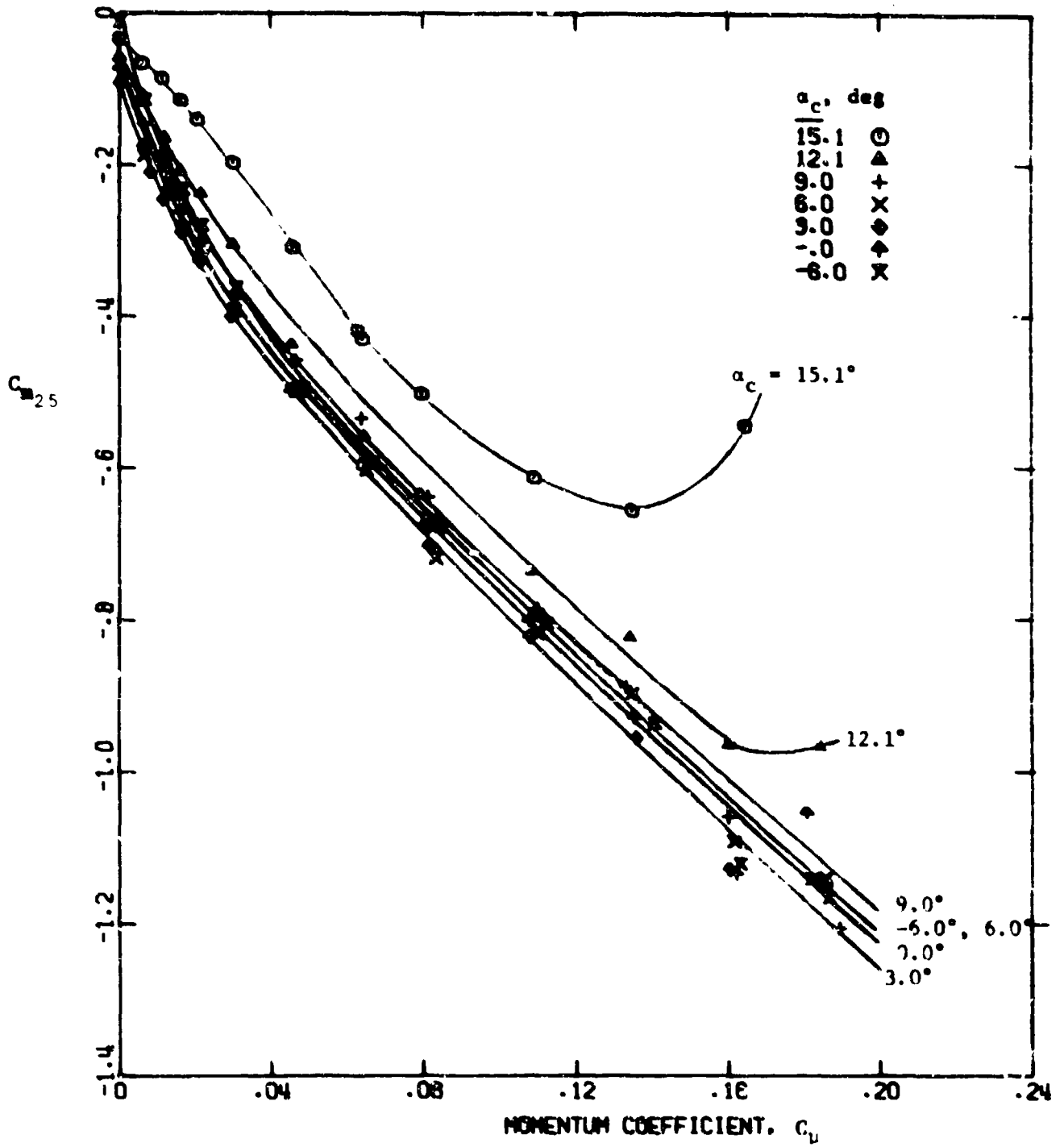


Figure 34 - Pitching Moment Variation with Blowing for CCW 241,
 $h = 0.027''$, $q = 30$ psf

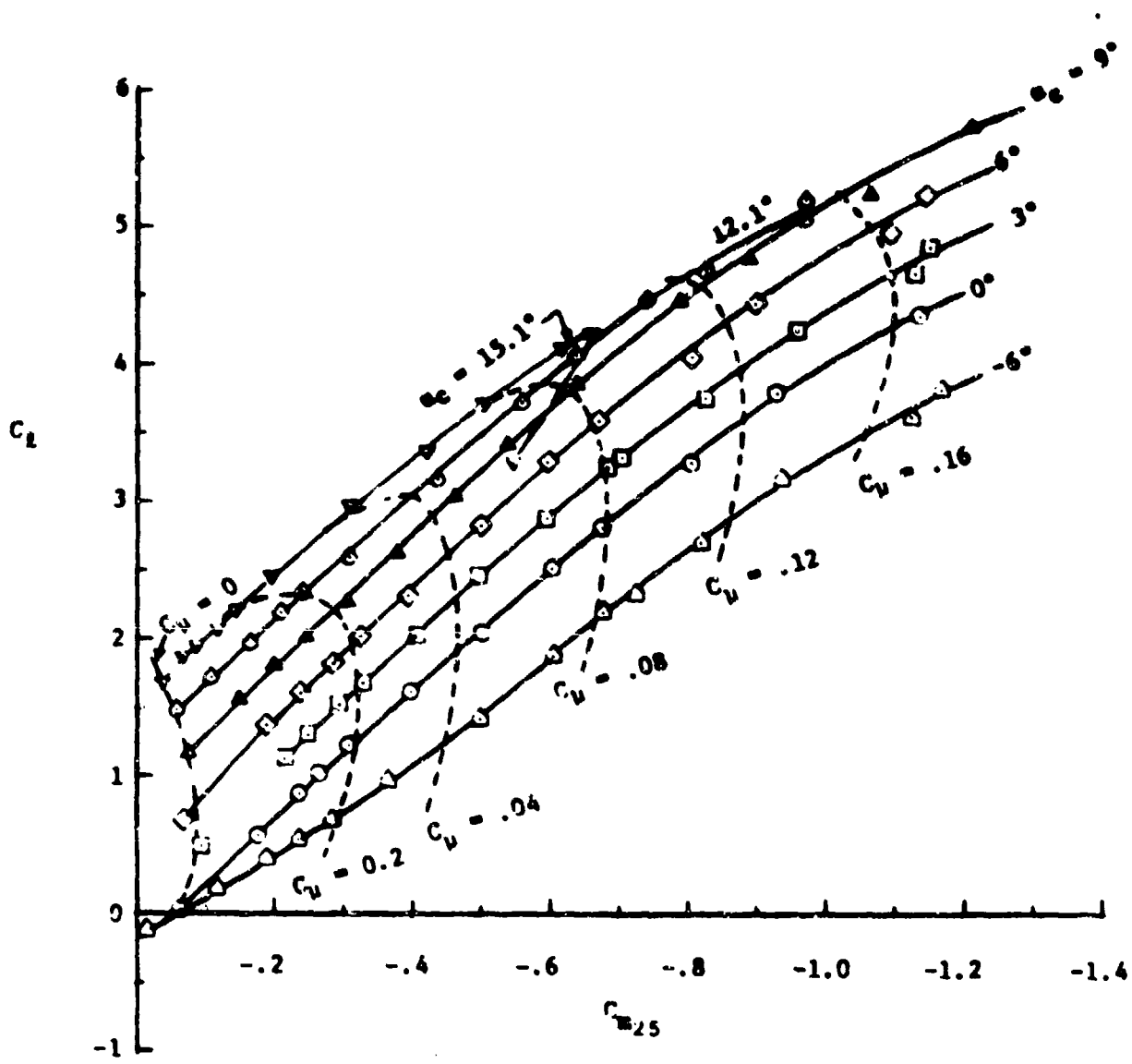


Figure 35 - Pitching Moment as a Function of Lift, Incidence and C_{μ}
 for NACA 64A-212/CCW Airfoils ($h = .027''$, $q = 30$ psf)
 (a) CCW 241, $\delta_f = 160^\circ$, $\delta_{LE} = 30^\circ$

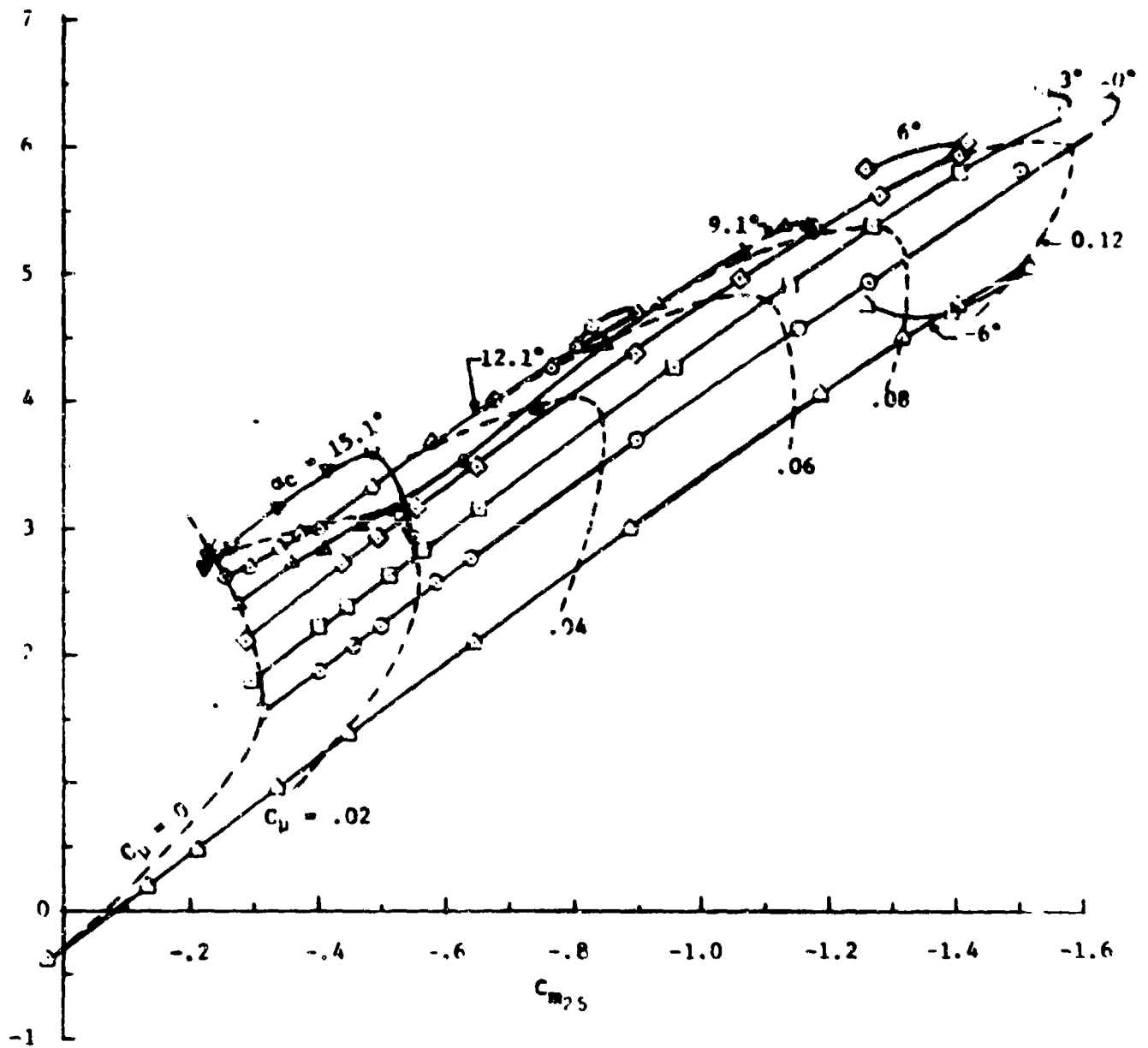


Figure 35 - Continued
 (b) CCW 242, $\delta_f = 90^\circ$, $\delta_{LE} = 30^\circ$

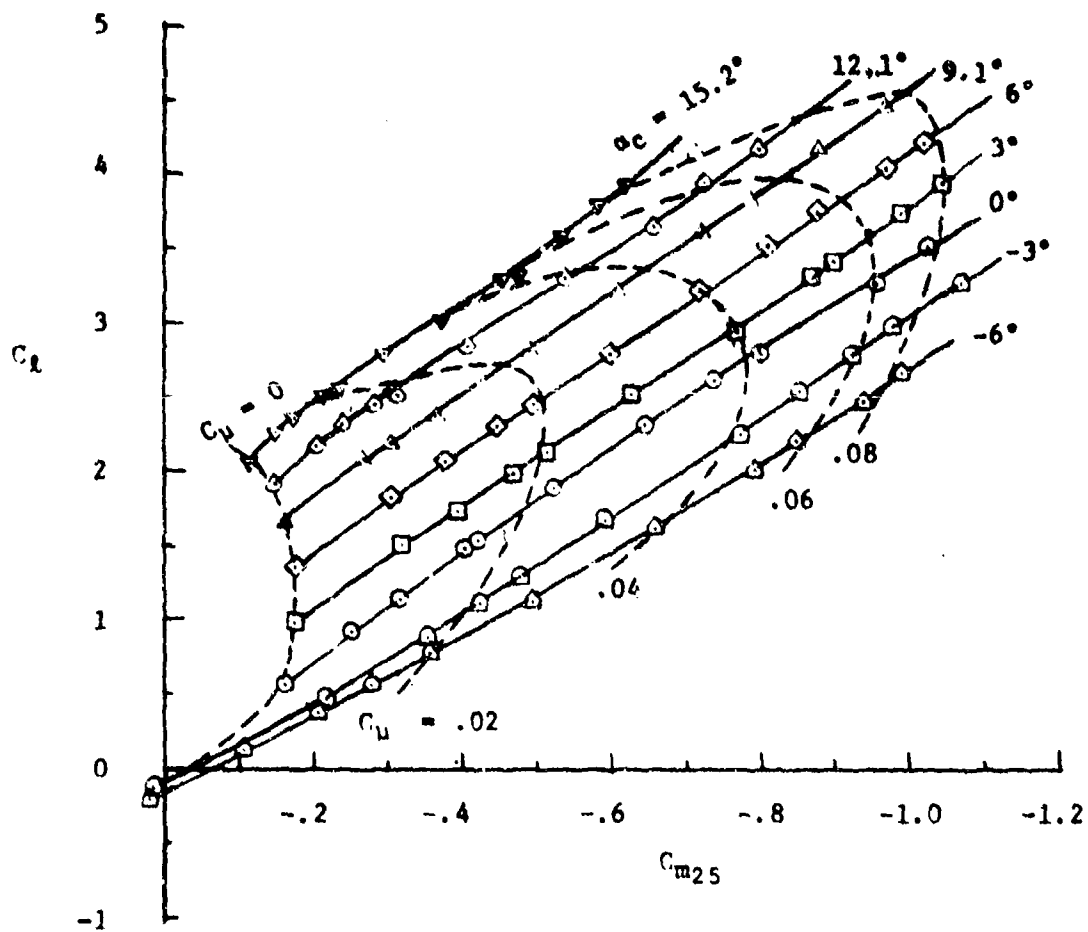


Figure 35 - Continued
(c) CCW 243, Extended T.E., $\delta_{LE} = 30^\circ$

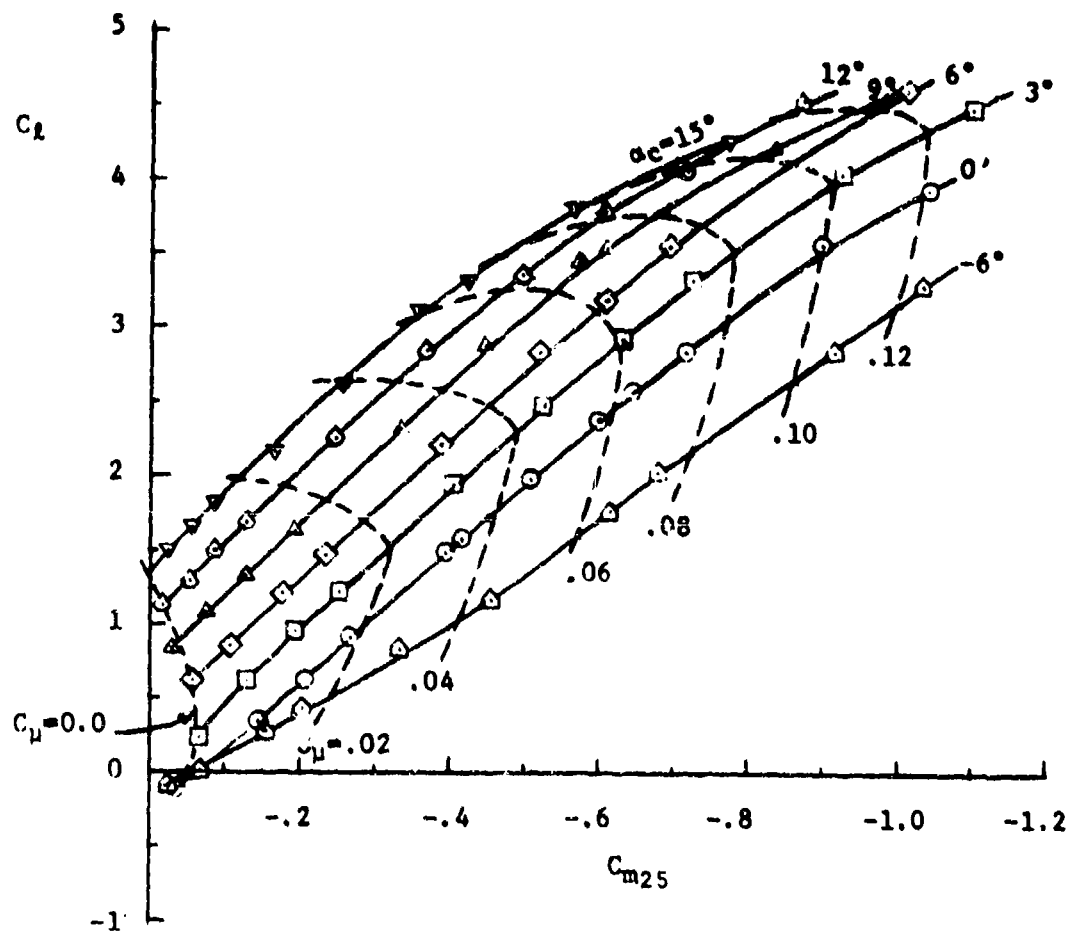


Figure 35 - Continued
 (d) CCW 244, Reduced T.E., $\delta_{LE} = 30^\circ$

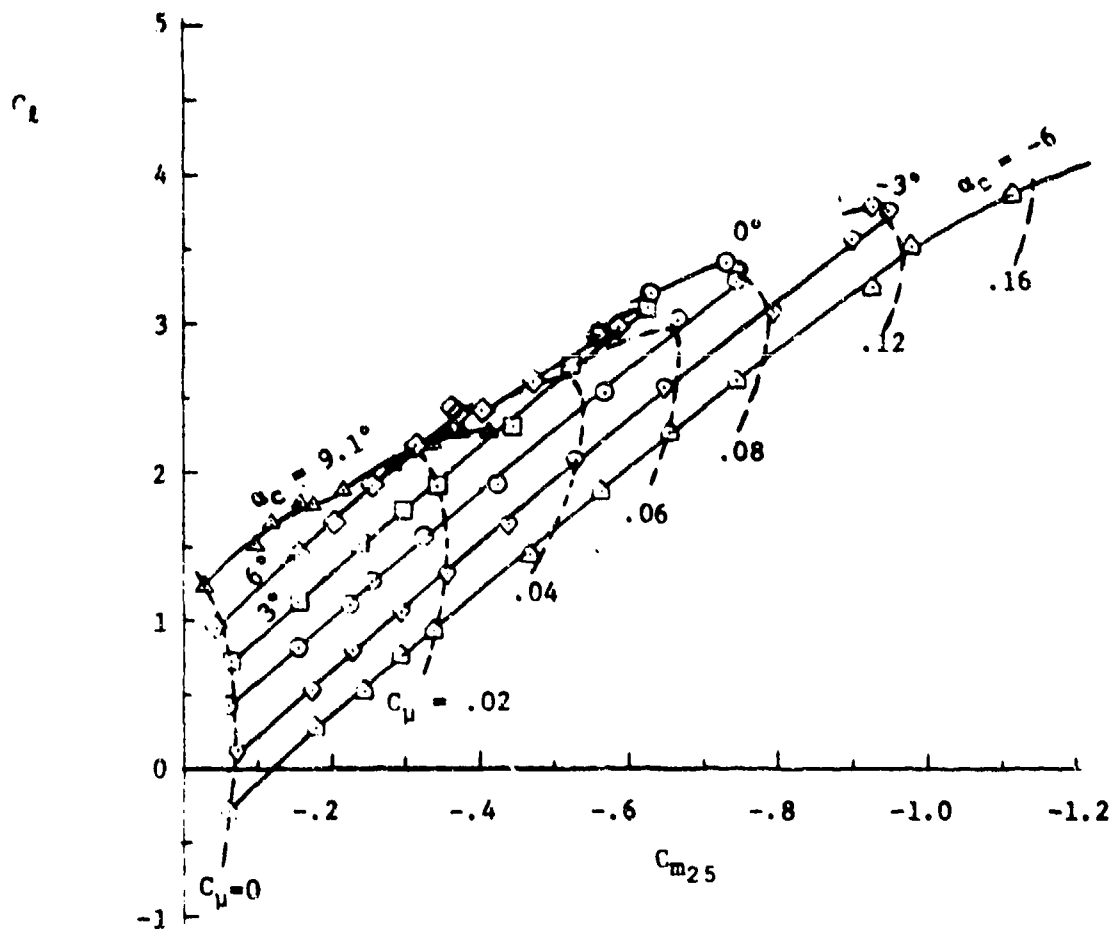


Figure 35 - Concluded
 (e) CCW 245, $\delta_f = 180^\circ$, $\delta_{LE} = 0^\circ$

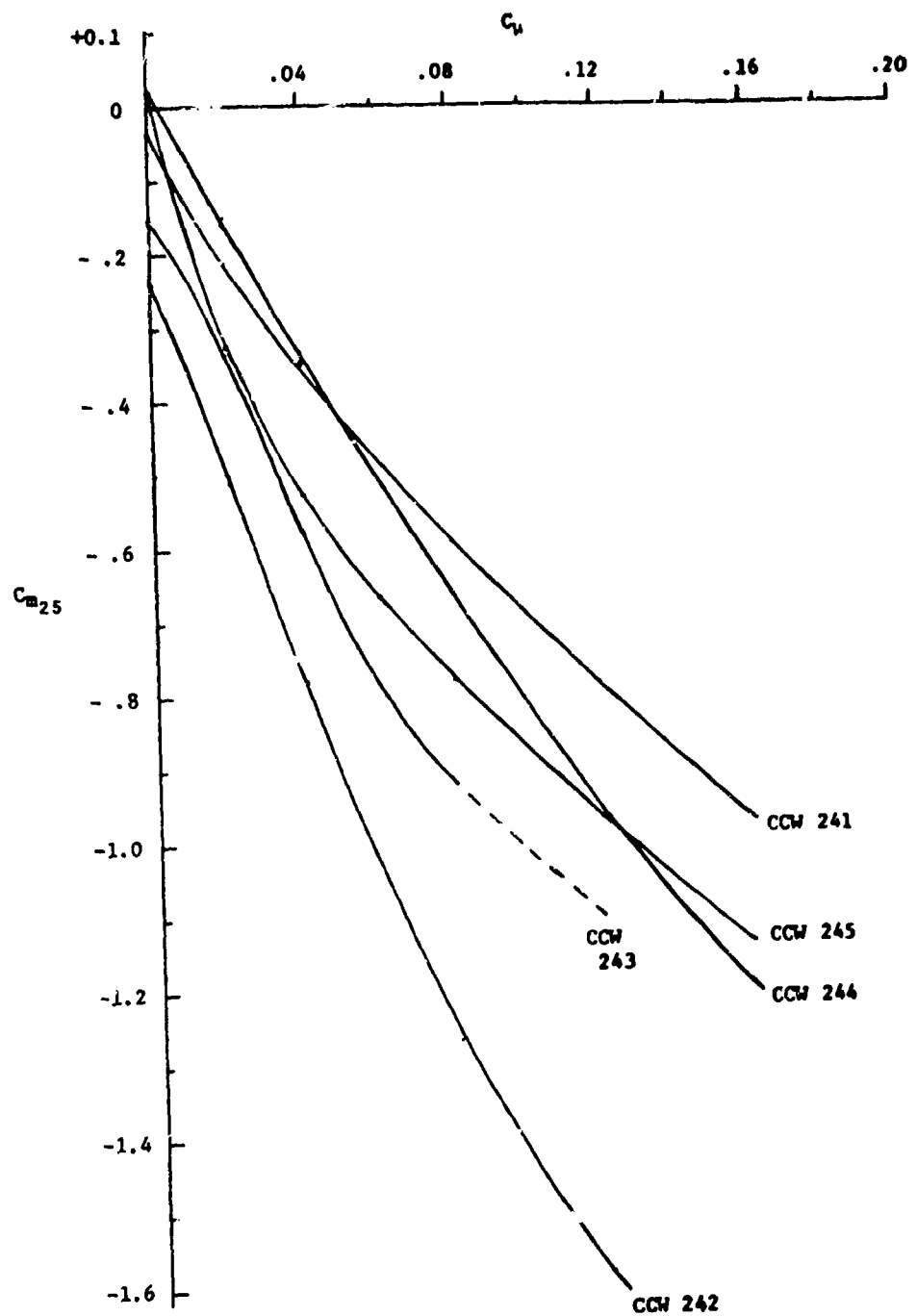


Figure 36 - Pitching Moment Coefficient at $C_{l_{max}}$ within Test Limits
 for NACA 64A-212/CCW Airfoils, $\alpha_g \leq 15^\circ$,
 $h = 0.027''$, $q = 30$ psf

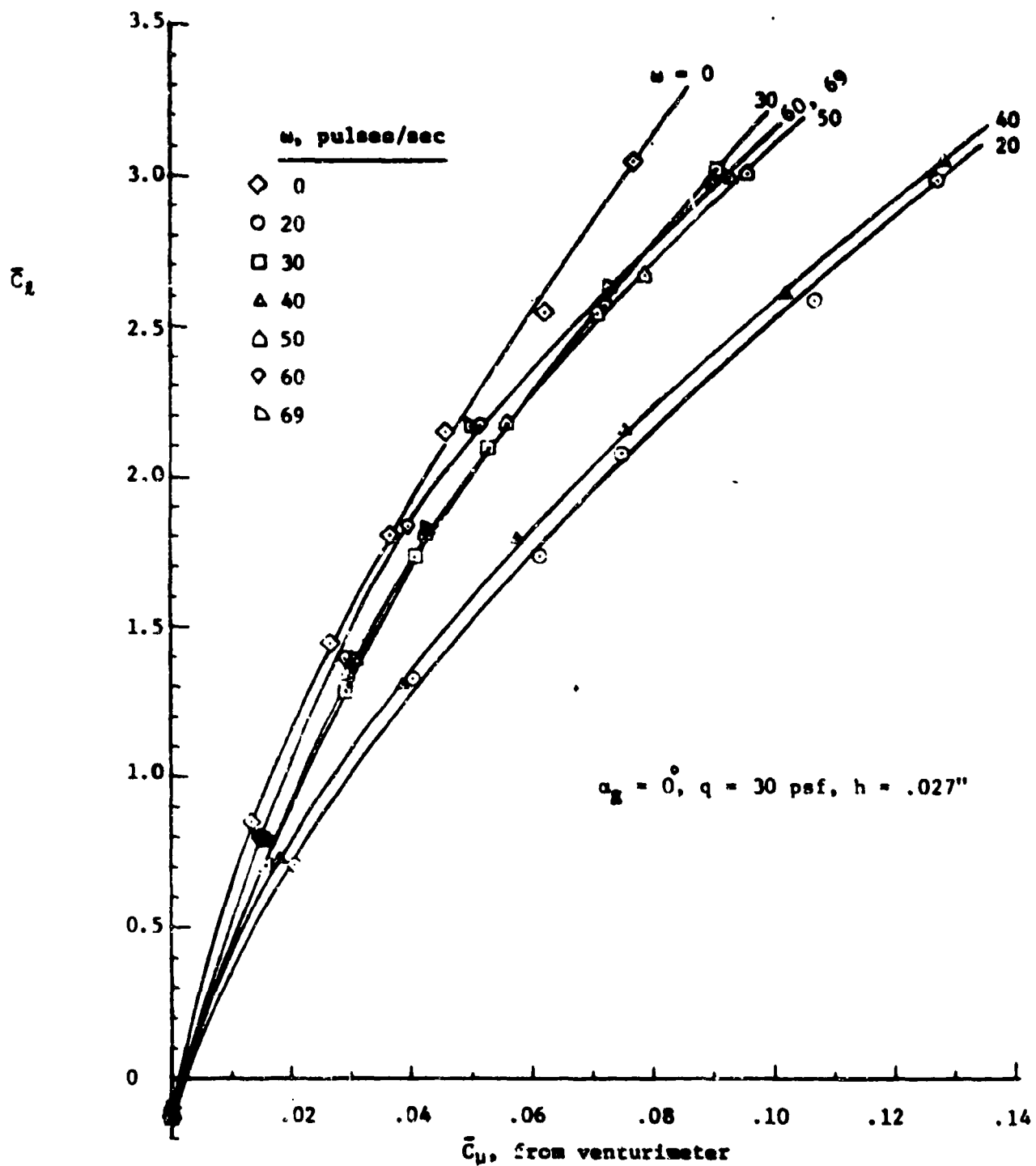


Figure 37 - Mean Lift and Momentum Coefficients as Functions of Pulsing Rate, CCW 244

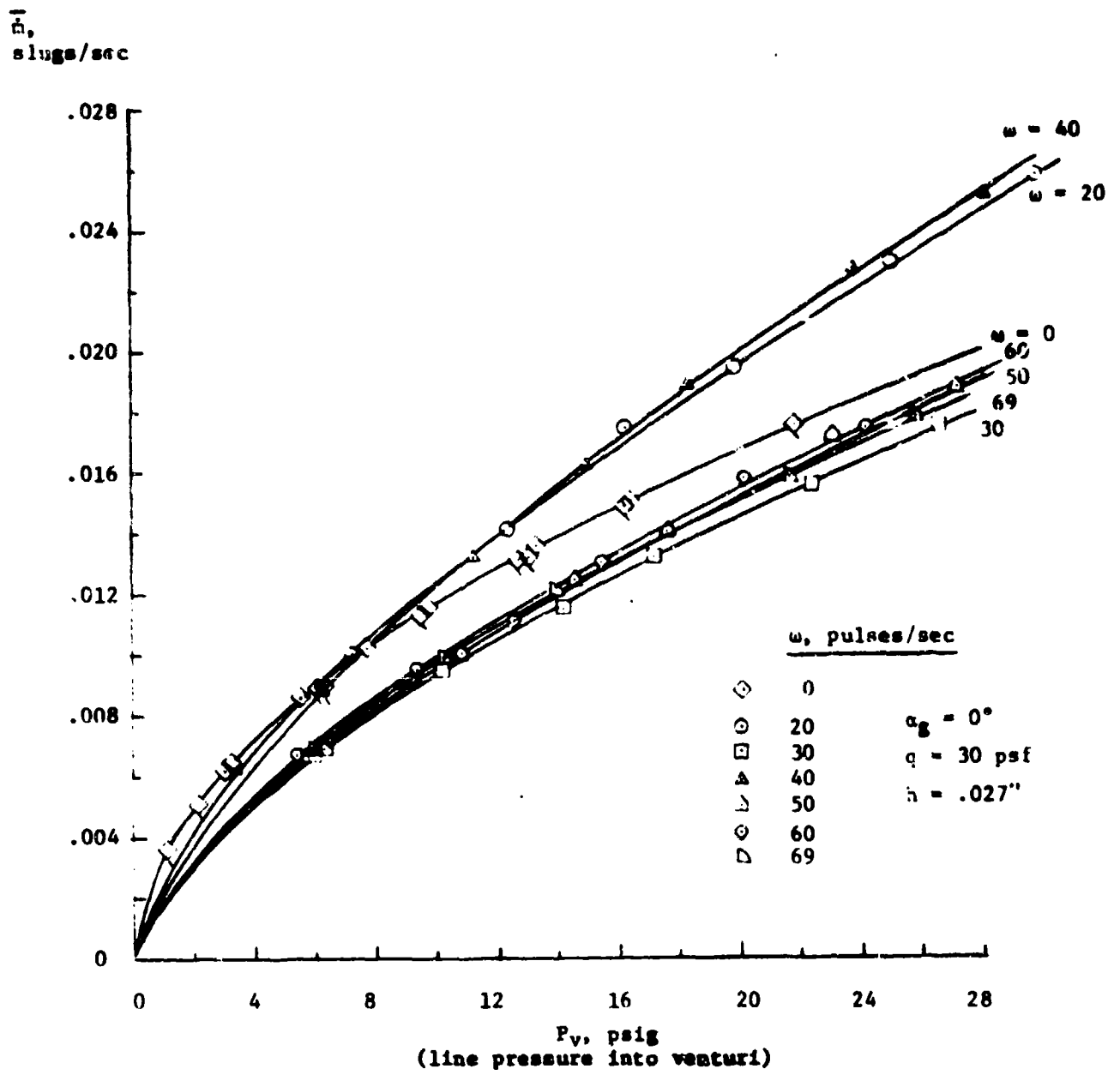


Figure 38 - Mean Mass Flow Measured by the Venturimeter, CCW 244

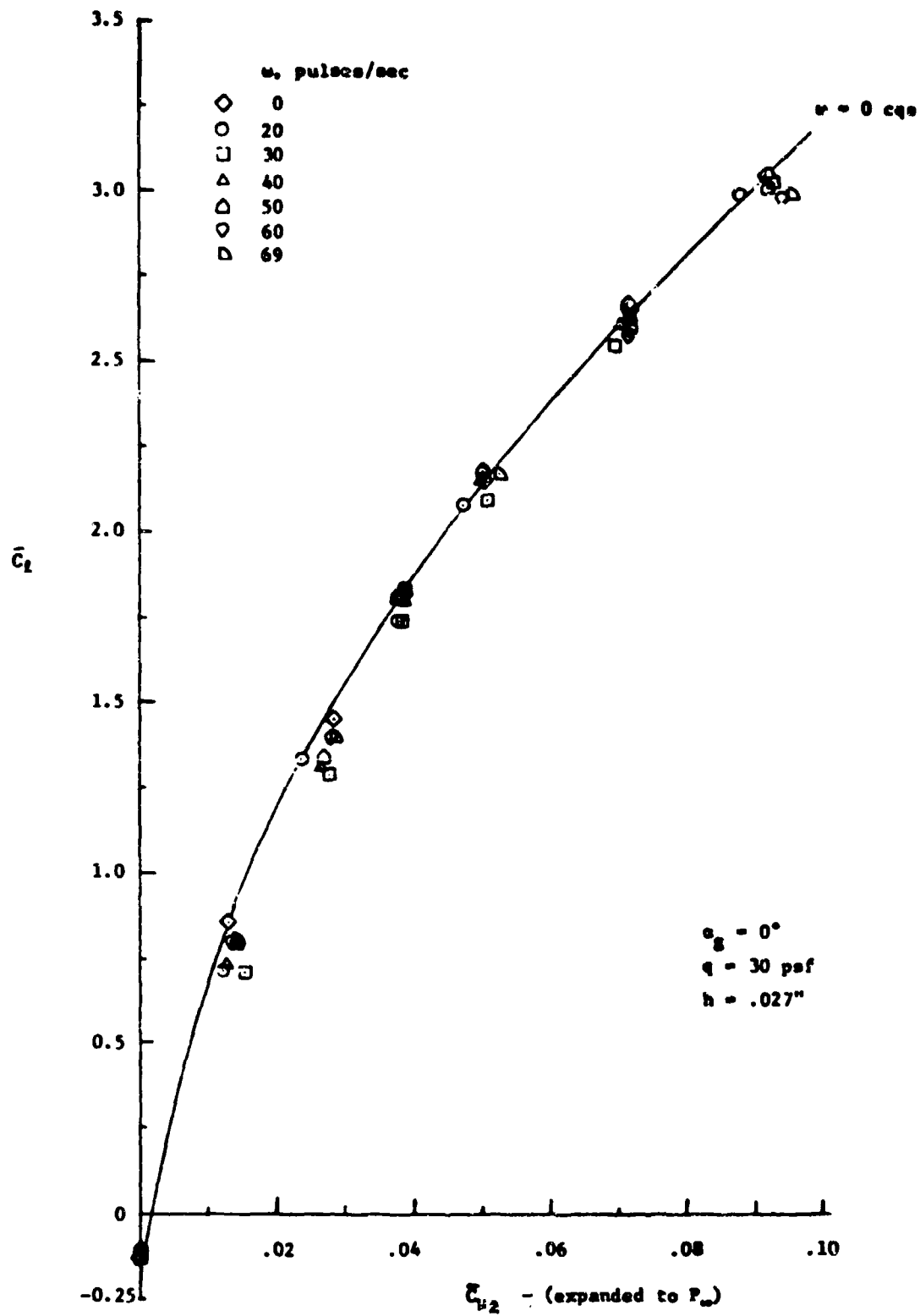


Figure 39 - Corrected Mean Lift and Momentum Coefficients as Functions of Pulse Rate, CCW 244

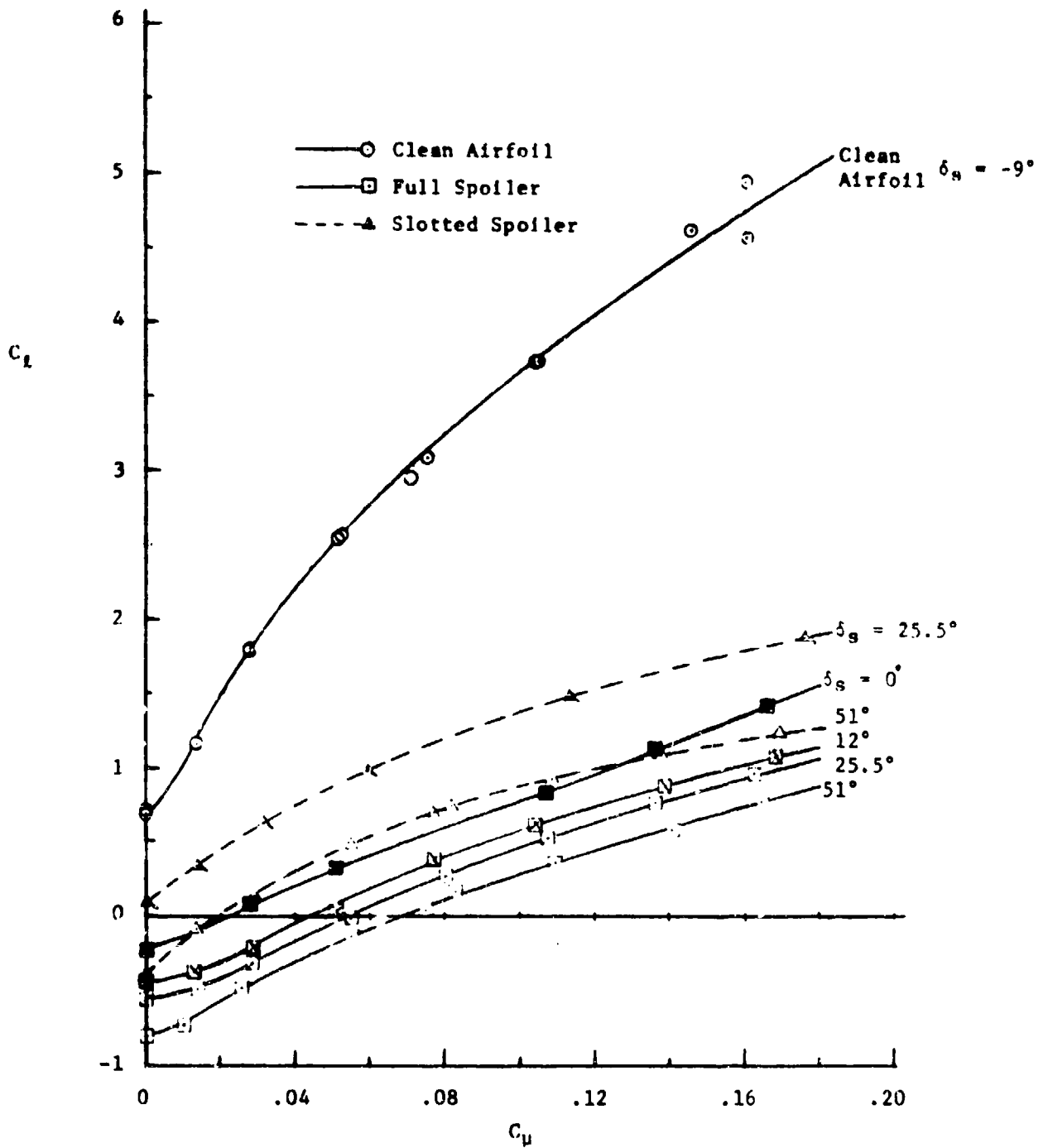
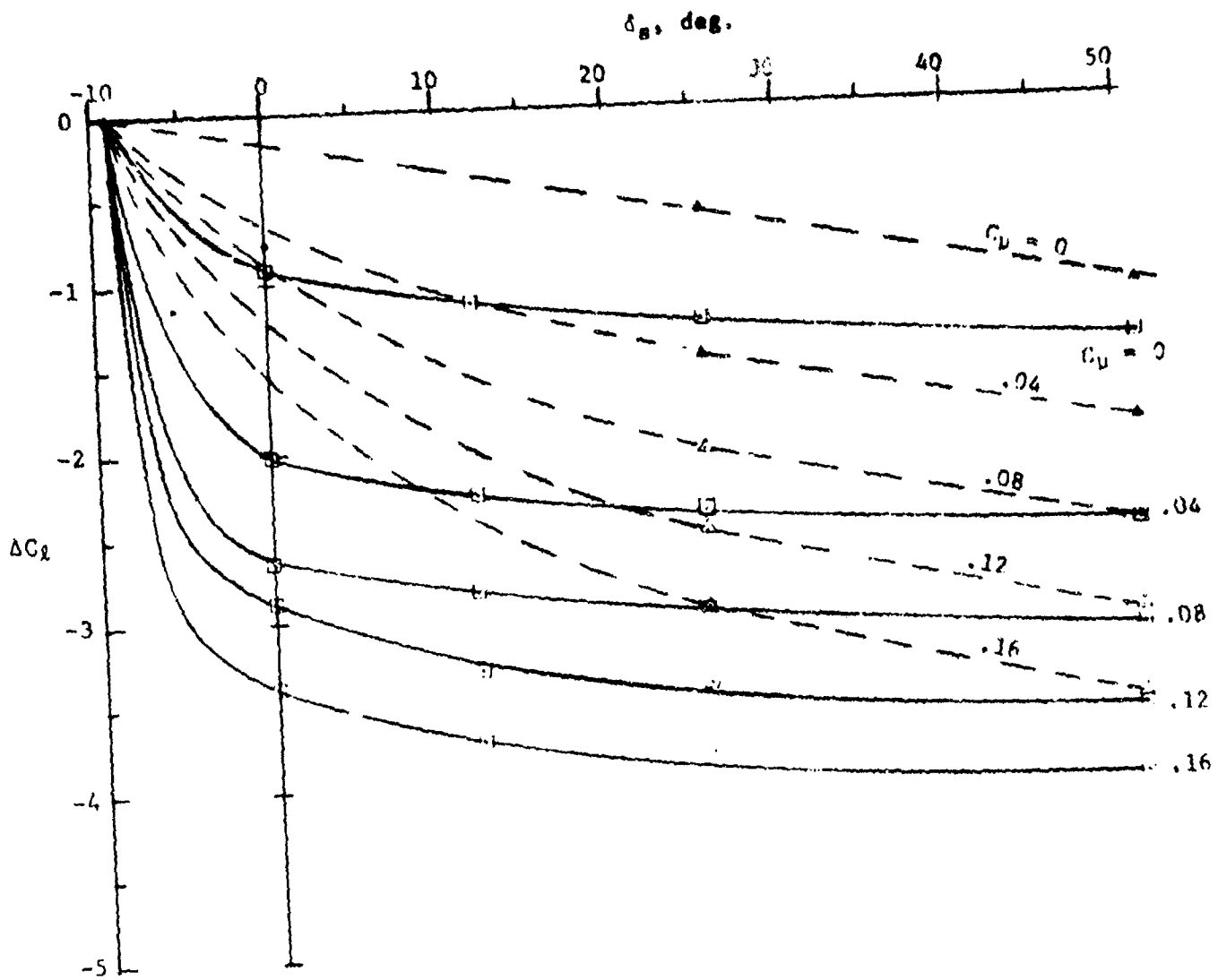


Figure 40 - Effect of Spoiler Deflection on Lift of Elliptical C.C. Airfoil ($\alpha_g = 0^\circ$, $q = 20$ psf, $h = .009''$)



$$\Delta C_l = C_l - C_{l_{clean}}$$

$\alpha_B = 0^\circ, q = 20 \text{ psf}, h = .009''$

—□— Full Spoiler

--△-- Slotted Spoiler

Figure 41 - Lift Loss as a Function of Spoiler Deflection

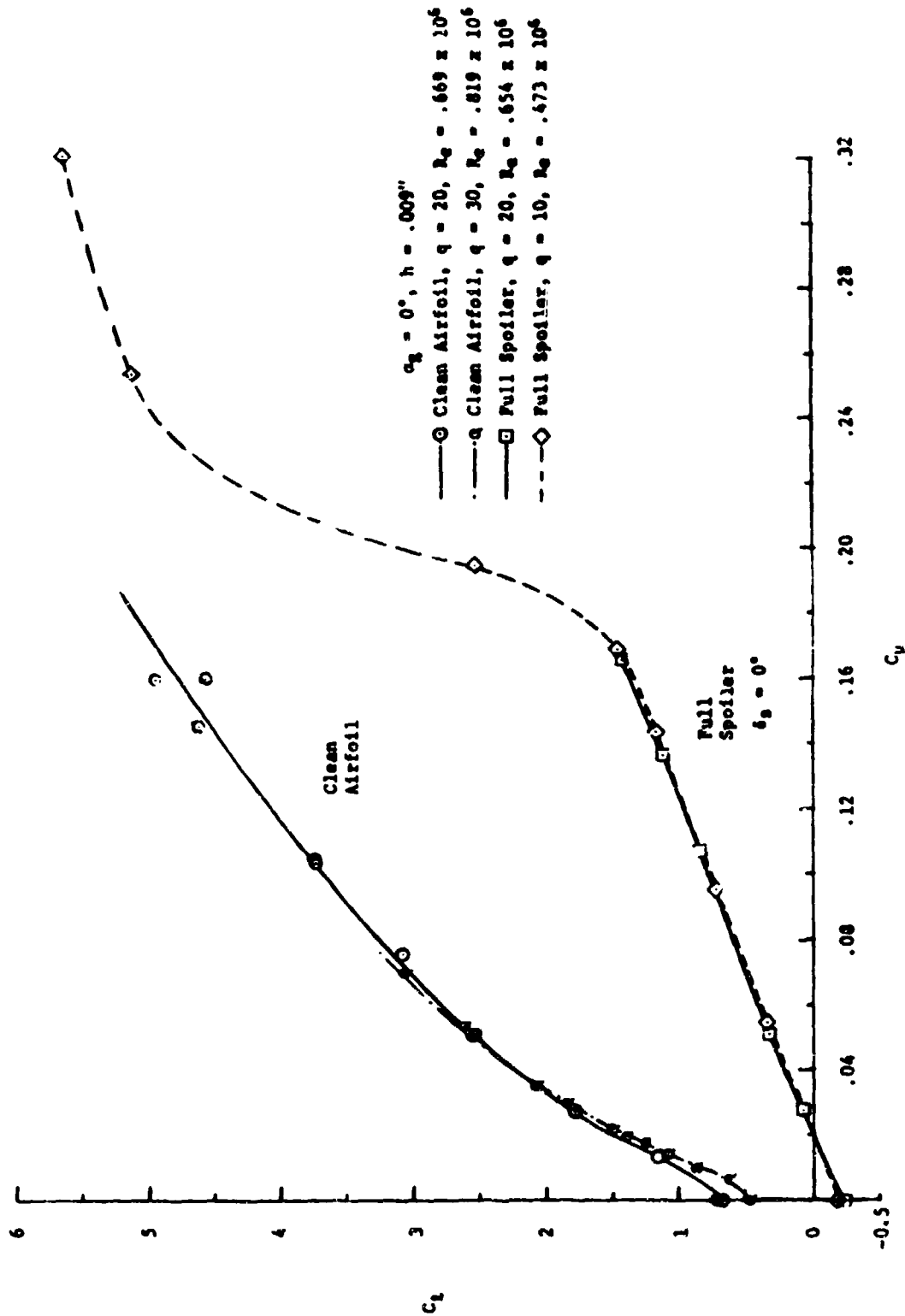


Figure 42 - Reynolds Number and Flow Reattachment Effects on Elliptical C.C. Airfoil with Spoiler

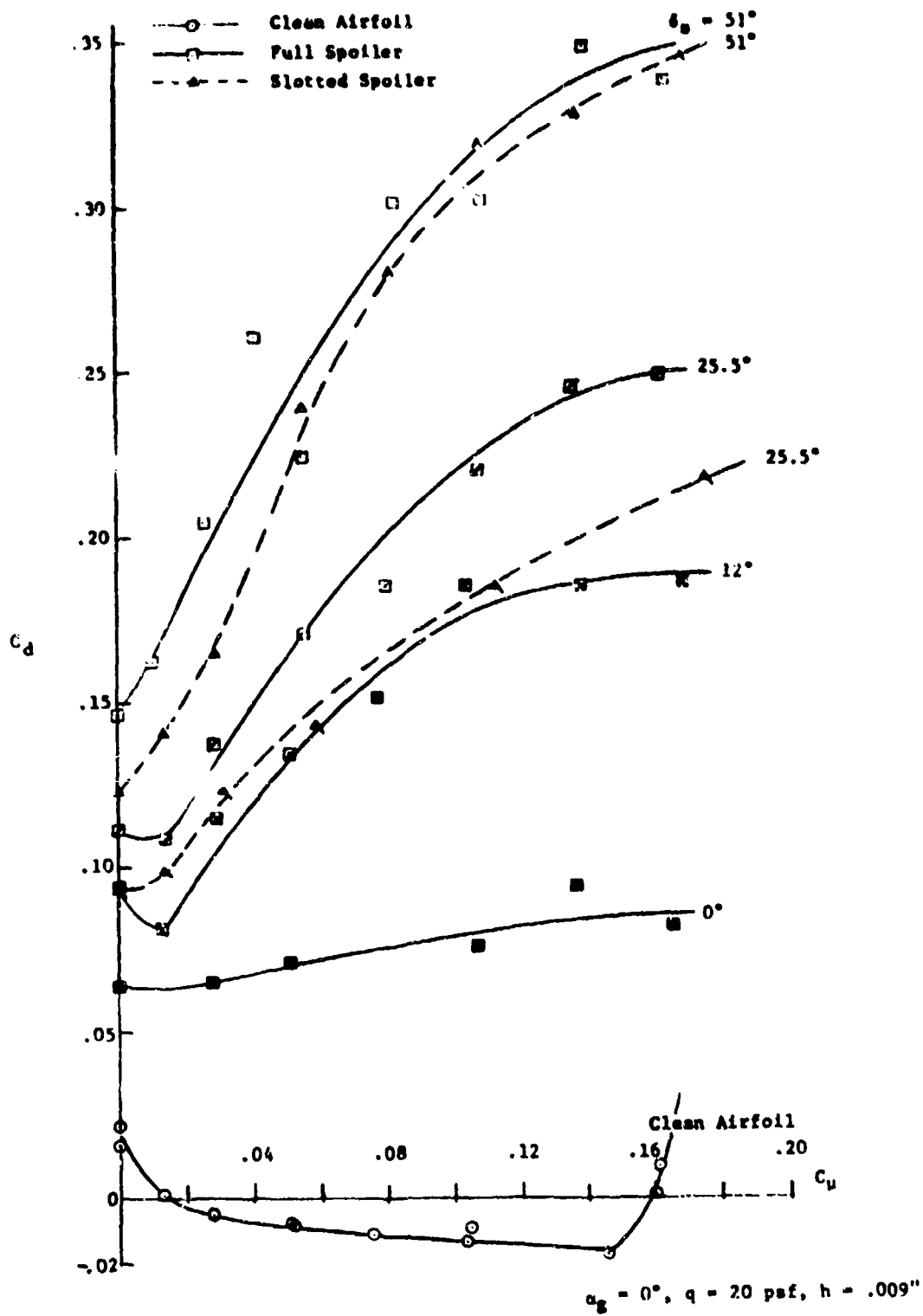


Figure 43 - Drag Increase due to Spoiler Deflection
on Elliptical C.C. Airfoil

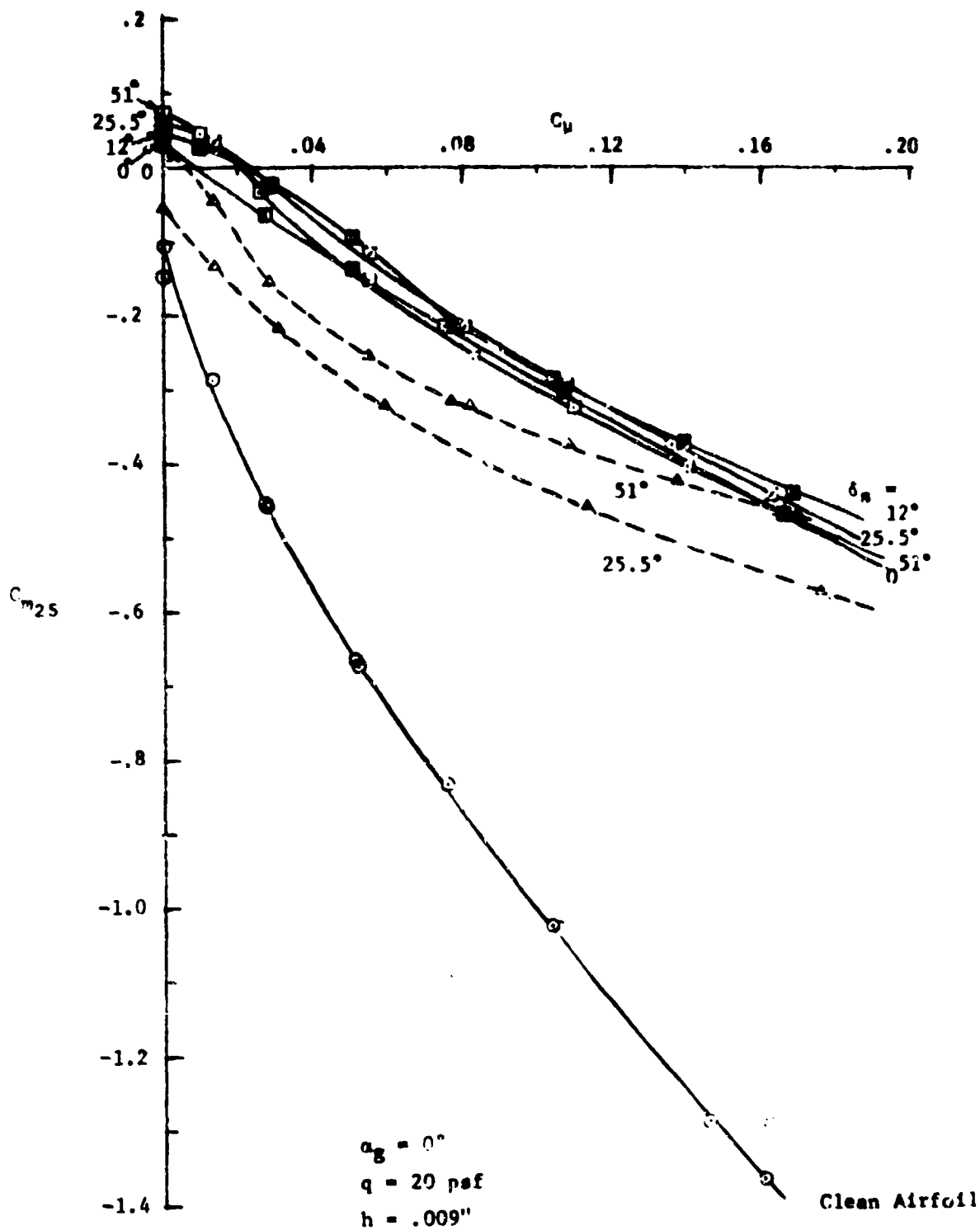


Figure 44 - Pitching Moment Variation with Spoiler Deflection