Development of Advanced Circulation Control Wing High-Lift Airfoils

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Recent experimental and flight test programs have developed and confirmed the high lift capability of the Circulation Control Wing (CCW) concept These CCW airfoils employ tangential blowing of engine bleed air over circular or near circular trailing edges and are capable of usable lift coefficients three times those of simple mechanical flaps Earlier versions of these blown airfoils made use of relatively complex leading and trailing edge devices which would have to be retracted mechanically for cruise flight In a continuing program to reduce the complexity, size, and weight of the CCW system, several series of advanced CCW airfoils have been developed which can provide STOL capability for both military and commercial aircraft using much smaller, less complex high lift systems This paper will describe these configurations, present the experimental results confirming their aerodynamic characteristics, and also make comparisons with previous CCW and more con ventional high lift systems

Introduction

THE development of high lift airfoils employing tangential blowing over round or near round trailing edges has been underway at David Taylor Naval Ship R&D Center since 1969 [1] Recent experimental and flight test programs[2 5] have confirmed the high lift and STOL capabilities of this Circulation Control Wing (CCW) concept As applied to a typical fixed wing aircraft, the concept em ploys engine bleed air to pneumatically augment the wing's circulation lift and has generated section lift coefficients three times those of simple mechanical flaps The application of this lift to provide STOL capability was flight verified[3] in 1979 when a rather large radius (0 0365 chord) CCW trailing edge was applied to the wing of a Navy/Grumman A 6 test bed aircraft Figure 1 shows the wing fold airfoil section evaluated two dimensionally prior to the flight demonstrator development Figure 2 records the increased lifting capability provided by the trailing edge blowing The effectiveness of this round CCW trailing edge in augmenting wing lift resulted in significant STOL performance and heavy lift potential [4 6] A demonstrated 140% increase in usable, trimmed lift coef ficient produced reductions of 35% in approach speed, 60% in takeoff distance and 65% in landing ground roll relative to the standard A 6 Flight speeds as low as 67 knots were achieved by the A 6/CCW aircraft

These flight results confirmed CCW as a simple and ef fective blown STOL system and also identified several im provements needed before the system could be incorporated into production aircraft The large trailing edge radius demonstrated on the A 6/CCW aircraft ensured high lift augmentation but was not acceptable from a cruise drag standpoint It would either have to be mechanically retracted or its size reduced to the point where the base thickness was no longer a penalty A second problem area was the leading edge device required to prevent flow separation during the high circulation associated with STOL operation Whereas the 37 5 deg slat deflection on the two dimensional model had proved sufficient the flight demonstrator maximum deflection was mechanically limited to 25 deg Therefore an increased leading edge radius was added to the testbed air craft and it performed quite satisfactorily However for cruise flight it too would have to be retracted or the mechanical actuator/track system revised to allow greater deflection

In order to address these areas of needed improvement a program has been underway since the flight test to develop ad vanced CCW airfoils by reducing the complexity size, and weight of the CCW system without penalizing its lift aug menting capability The program has two specific goals: 1) to develop an advanced CCW airfoil which would in corporate a smaller trailing edge blown plenum, and non deflecting leading edge device (these would be within the contour of an existing supercritical airfoil which could replace current state of the art wing sections) and 2) to develop improved versions of CCW which are compatible with existing thin wings such as those already on the A 6 and other current high performance aircraft In both cases, maintaining lift augmentation while reducing drag and complexity have been the dominant objectives of the program The following sections will discuss the design considerations and ex perimental evaluations involved in the development of these airfoils and compare their performance to the earlier relatively complex CCW configurations

Design Considerations

CCW/Supercritical Airfoil

It appeared that the above goals were attainable by taking advantage of the large leading and trailing edge thickness of a typical bluff trailing edge supercritical airfoil Not only does this airfoil section geometry appear quite compatible with the incorporation of aft plenum, slot and small radius trailing edge, it also generates the improved transonic cruise performance afforded by increased critical Mach number and delayed drag rise The developmental approach taken was to combine a typical proven supercritical section with a set of baseline CCW trailing edge parameters closely matching those of the A 6/CCW aircraft, and then experimentally evaluate the characteristics produced by progressively reducing the trailing edge size until it was compatible with the supercritical airfoil aft contour The NASA 17% thick supercritical airfoil of Ref 7 had been both wind tunnel and flight tested, and therefore had a suitable reference data base The airfoil thickness produces a large bluff leading edge radius of 4 28% chord which is of such substantial size that it

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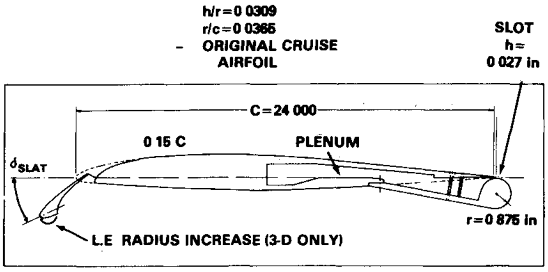

Fig 1 A 6/CCW wing fold airfoil section (64A008 4/CCW); δ_{SLAT} = 37 5 deg, large trailing edge radius

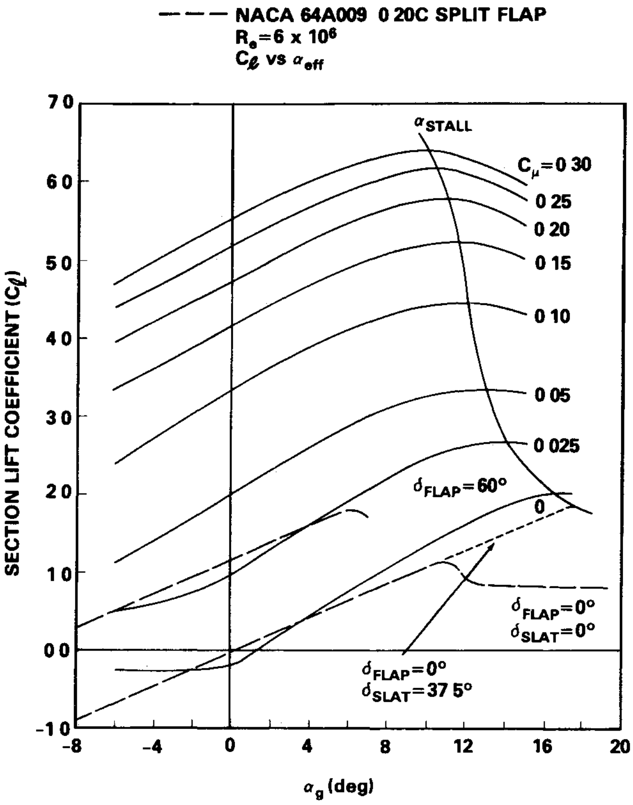

Fig 2 Lift characteristics of the 64A008 4/CCW airfoil; δ_{SLAT} = 37 5 deg, r/c = 0 0365

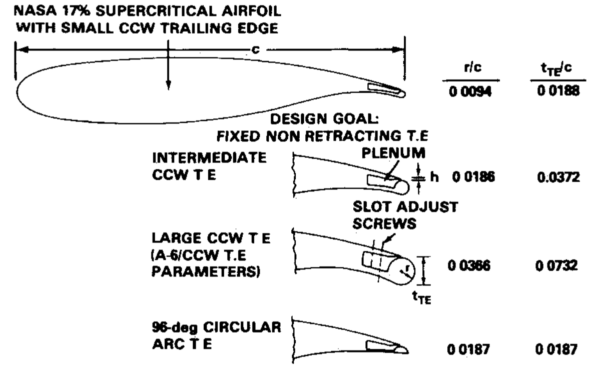

Fig 3 CCW/supercritical airfoil model geometries

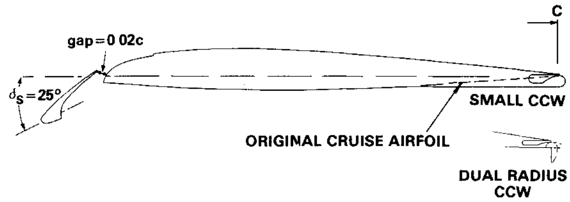

Fig 4 Incorporation of the small CCW geometries on the A 6/64A008 4 airfoil

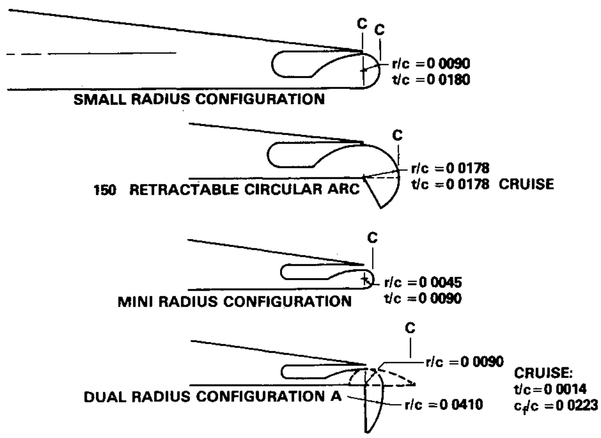

Fig 5 A 6/CCW small trailing edge detail and parameters

could substitute for a mechanical leading edge device and thus further simplify the high lift configuration To parametrically vary the model trailing edge geometry the A 6/CCW design radius to chord ratio of 0 0365 was taken as a baseline reference value, halved to give r/c = 0 0186 and halved again to give r/c = 0 0094 The smallest trailing edge diameter (0 0188c) is thus slightly greater than twice the 0 008c trailing edge thickness of the baseline supercritical airfoil These model configurations are shown in Fig 3 where the pertinent CCW trailing edge parameters are also identified The terms r h c and c represent trailing edge radius, jet slot height, original baseline airfoil chordlength, and effective airfoil chordlength including the radius, respectively Since detailed discussion of the characteristics of these four airfoils is given in Refs 8 and 9 only the smallest radius con figuration will be included in the following discussion of results

A 6/CCW Airfoils

Because high performance aircraft typically employ thinner sections with sharp trailing edges, a second program was undertaken to extend the above smaller trailing edge CCW/supercritical configurations to these thin airfoils Because a data base was already established for the A 6 airfoil section it was selected as the reference thin airfoil The 8 4% airfoil of Fig 1 was modified to accept the CCW trailing edges shown in Figs 4 and 5 The "small" radius (r/c = 0 009) is the same trailing edge configuration used with the supercritical airfoil while the "mini" radius is half that size, yielding a cruise trailing edge diameter of 0 009c Neither of these configurations is intended to be retracted in cruise, being one fourth and one eighth the size of the original flight test trailing edge The retractable circular arc con figuration uses a simple rotating segment to produce 150 deg of jet turning arc (as measured from the slot) when deflected for high lift, retracting to 96 deg and a trailing edge thickness of 0 0178c in cruise The configuration thus has a cruise base thickness slightly less than the small round configuration but a radius approximately twice as large for effective jet turning The dual radius configuration is in effect a very short chord (0 0223c) blown flap—with several important differences It pivots about a lower surface hinge point with a radius the same as the above single radius configuration (0 009c), and deflects to 90 deg The aft upper surface is not straight like the

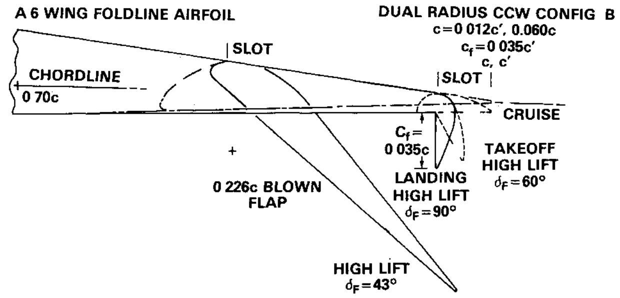

Fig 6 Dual radius CCW and blown flap configurations

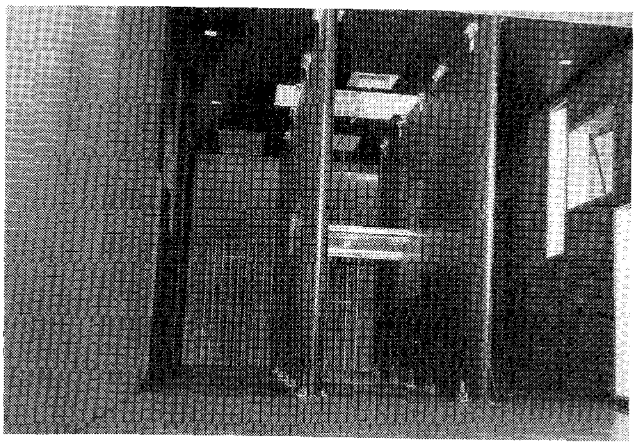

Fig 7 Airfoil installed in the DTNSRDC 3×8 ft subsonic two dimensional inserts

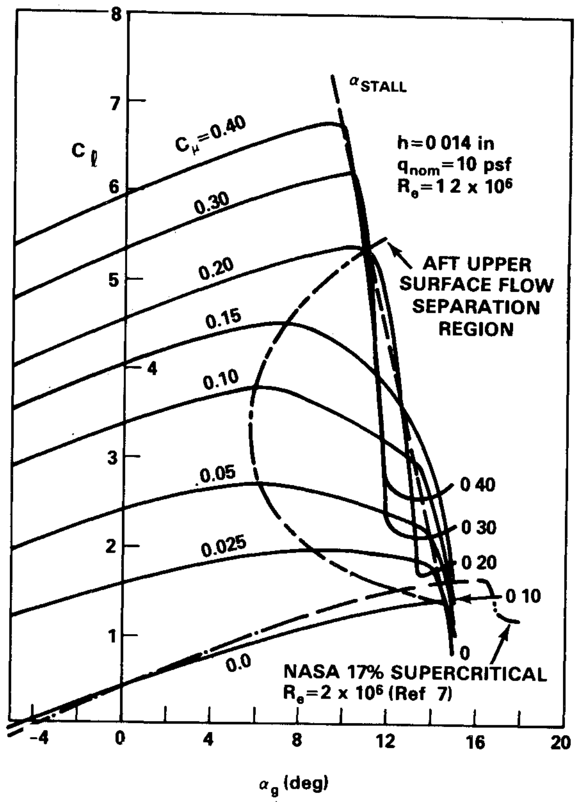

Fig 8 Variation in lift with incidence at constant blowing for the small trailing edge CCW/supercritical airfoil

conventional blown flap, but is a second much larger radius, 0 041c This produces a downstream CCW radius *larger* than the original flight demonstrator, but a cruise trailing edge thickness exactly the same as the clean A 6 airfoil, 0 0014c The second radius adds additional jet deflection so that when the flap is deflected 90 deg, the jet angle is 122 deg from the slot Jet attachment at this deflection should be enhanced by the larger radius Two additional blown configurations were constructed and tested and are shown in Fig 6 The 0 226c blown flap is a Grumman Aerospace Corporation design[10] employing a straight aft upper surface with a radius down stream of the slot when the flap is deflected A second dual radius CCW trailing edge, configuration B, has a larger flap chord than the first and is intended to produce more lift due to geometric camber when the blowing is off Its radii are in creased (because the hinge point moves forward) to 0 012 and 0 060c , but the cruise trailing edge thickness remains 0 0014c Two additional deflection angles have been added 0 deg (cruise) and 60 deg (intermediate lift at reduced drag, intended as a takeoff configuration) The jet turning angles for the 0 60 , and 90 deg flap deflections are thus 33 93, and 123 deg respectively from the jet exit plane parallel to the chord

Mention should be made of the design blowing momentum coefficient, C_μ (to be defined in the following section) Ex pected full scale values are functions of bleed mass flow, available pressure and the flight velocity (a function of weight, incidence, lift coefficient obtained with blowing, and engine vertical thrust component) For the A 6/CCW flight demonstrator using existing bleed from its J 52 P8B turbojet engines available C_μ ranged up to 0 30 However since current high performance aircraft may employ turbofan engines with less bleed capability a limit on available momentum for these engines was estimated to yield 0 05 $<C_\mu<$0 15 Thus for the majority of the thin airfoil small trailing edge data C_μ will be limited to approximately 0 17

Experimental Apparatus and Technique

The 3 ft span, two dimensional models described above were mounted between the 3×8 ft subsonic two dimensional wall inserts installed in the DTNSRDC 8×10 ft subsonic tunnel (Fig 7) Lift and moment coefficients were obtained by numerical integration of surface static pressures near the midspan as recorded by a 144 port scanivalve system The drag coefficient was obtained from integration of wake momentum deficit as measured on a fixed wake rake spanning nearly 8 ft from floor to ceiling All reported force and moment coefficients are based on c , since this is considered to be the undeflected cruise reference chord The value c' may differ from c, the original clean airfoil chord, in that the slot is located at the original airfoil trailing edge, and thus the new small CCW devices extend somewhat aft The momentum coefficient C_μ was calculated as $\dot{m}V_j/(qc\ )$, where $\dot{m}$ is the mass flow per unit slot span as measured by venturimeter, and V_j is the isentropic jet velocity calculated from measured conditions using the equation in Ref 5 Model installation, test apparatus and technique, data reduction and corrections, and monitoring of tunnel two dimensionality were all con ducted as reported in Ref 5 (Appendix A) and Ref 11

Results and Discussion

CCW/Supercritical Airfoil

The small radius configuration of Fig 3 was evaluated over a geometric angle of attack range -5 deg$\leq\alpha_g\leq+15$ deg The relatively low freestream dynamic pressure of 10 psf (Re=1 2×10^6) yielded C_μ values up to 0 40 instead of the 0 17 limit mentioned above Lift data for a slot height of 0 014 in are presented in Fig 8 as functions of incidence and blowing If these plots are compared to the state of the art A 6/CCW airfoil data of Fig 2 which was run at a larger slot height and Reynolds number, two trends are noticeable First, the CCW/supercritical airfoil with a radius only 25% as large produces lift that is slightly greater than the A 6/CCW

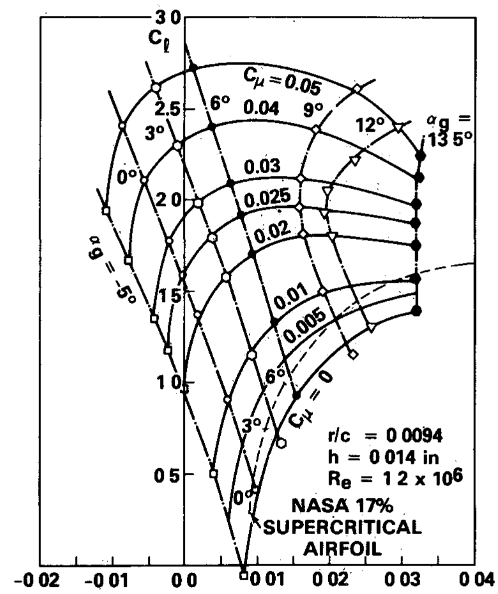

Fig 9 Drag polars for the small trailing edge CCW/supercritical airfoil at low blowing

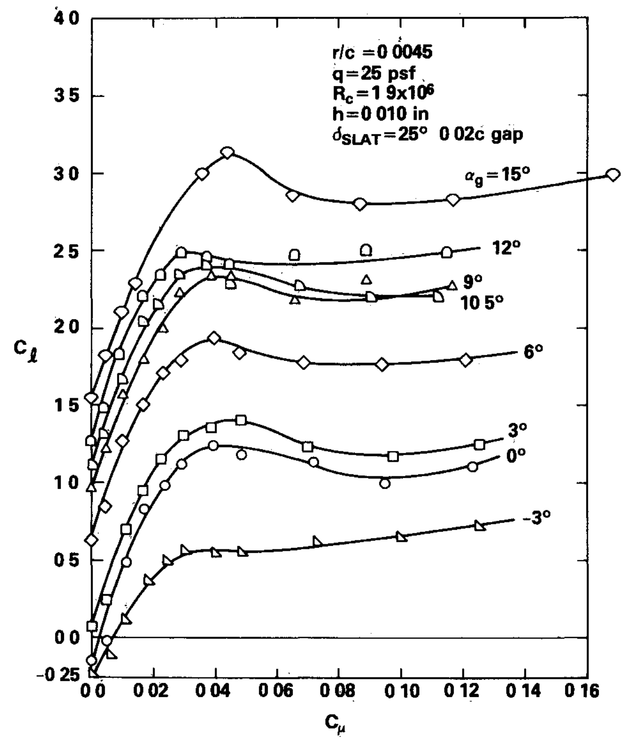

Fig 10 Lift due to blowing for the mini radius A 6/CCW airfoil

airfoil at low α and C_μ, since the A 6 slat imparts a download under these conditions Second, the undeflected bulbous nose of the supercritical airfoil provides the same or better leading edge performance as the A 6 model's 37 5 deg slat, yielding almost identical stall angle at any given $C_{\ell_{max}}$

The apparent deficits in certain of the lift curves (primarily for 6 deg$\leq \alpha_g \leq$12 deg and $C_\mu <$0 20) are due to flow separation on the supercritical airfoil cambered aft upper surface between the crest and the slot (This condition is discussed in Ref 12 and is not a leading edge separation) The separated flow is re entrained at higher C_μ, and the deficits disappear The same correction should occur at higher Reynolds numbers

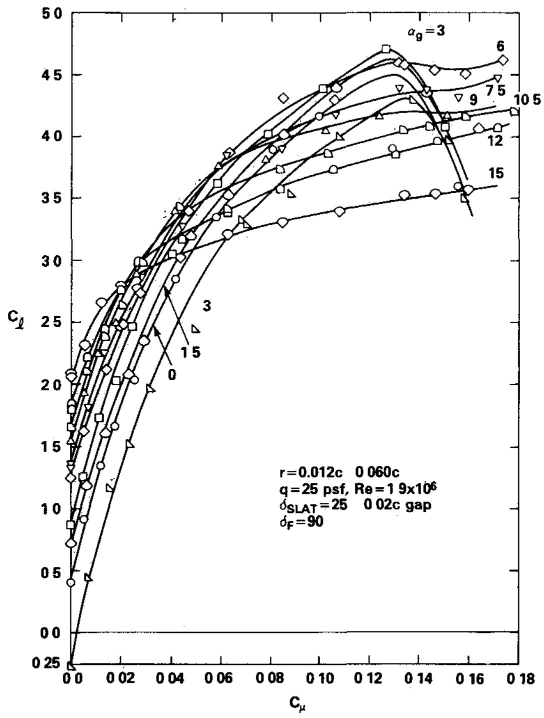

Fig 11 Lift due to blowing for dual radius configuration B; c_f=0 035c

Table 1 Comparison of unblown drag coefficient

Airfoil	C_ℓ	C_d	α_g, deg
64_3 418	0 40	0 0063	0 7
Baseline supercritical	0 40	0 0084	0 0
Small CCW, r/c =0 0094	0 40	0 0087	−0 7
Large CCW, r/c =0 0366	0 40	0 0145	−3 7

Drag polars for the small radius airfoil at low blowing values are compared in Fig 9 with the baseline 17% super critical airfoil The drag values of the baseline airfoil are slightly lower than those of the CCW/supercritical airfoil with no blowing (ΔC_d=0 0006 at α_g=0 deg); however, the drag of the CCW airfoil can be reduced to that of the baseline airfoil by blowing at $C_\mu \leq$ 0 003 at typical values of cruise incidence Additional blowing will reduce the drag even further but an analysis of engine thrust loss due to required bleed should be considered For $Re=2\times10^6$ and a typical cruise C_ℓ of 0 4 unblown drag values for the small radius and a larger radius CCW/supercritical airfoil are compared with both the baseline supercritical and a typical sharp trailing edge airfoil in Table 1 At equal cruise lift, the drag of the baseline and small CCW airfoil is nearly equal Thus, the high lift device of the small CCW/supercritical airfoil may be left exposed for cruise conditions with essentially no subsonic drag penalty

A 6/CCW and Blown Flap Airfoils

Lift Generation

The various CCW and blown flap configurations of Figs 4 6 were evaluated extensively over a range of subsonic dynamic pressures, angle of attack, and jet slot height The data comparisons which follow are intended primarily to show the effect of configuration geometry changes on lift augmen tation in the moderate blowing range of $C_\mu <$0 17 It should be noted that while the original large radius A 6/CCW was tested with a 37 5 deg slat deflection (in order to keep flow attached at high circulation levels associated with C_μ up to 0 30), the majority of the current tests were conducted with a

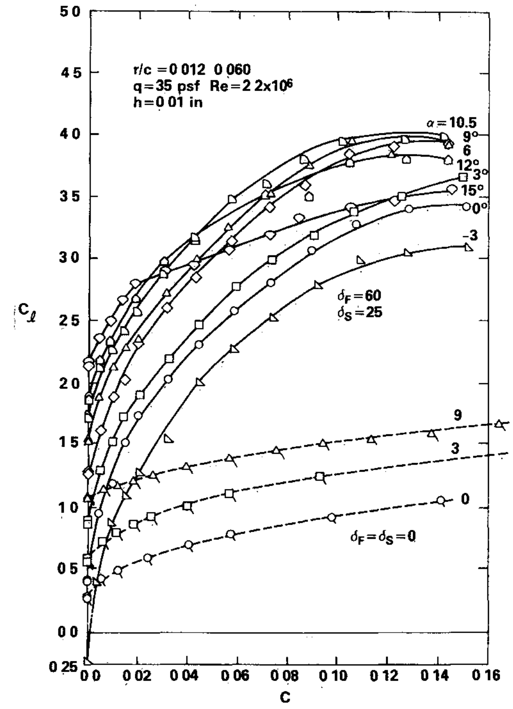

Fig 12 Lift due to blowing for dual radius configuration B; $\delta_F = 0$ and 60 deg

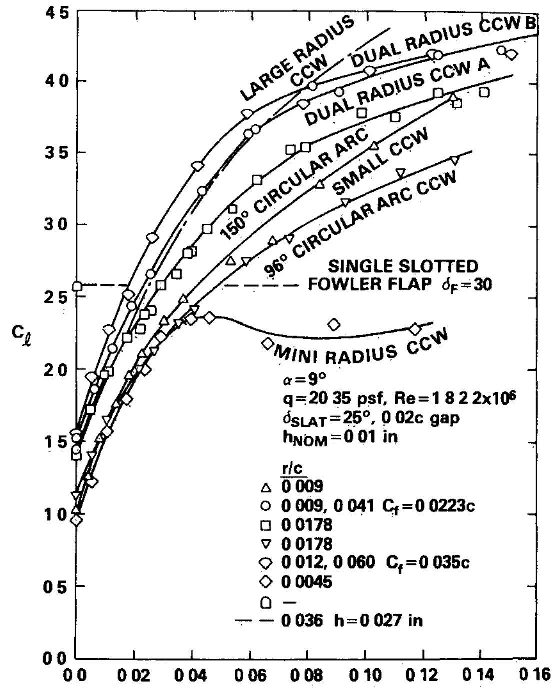

Fig 14 Comparative blown lift configurations; $\alpha_g = 9$ deg

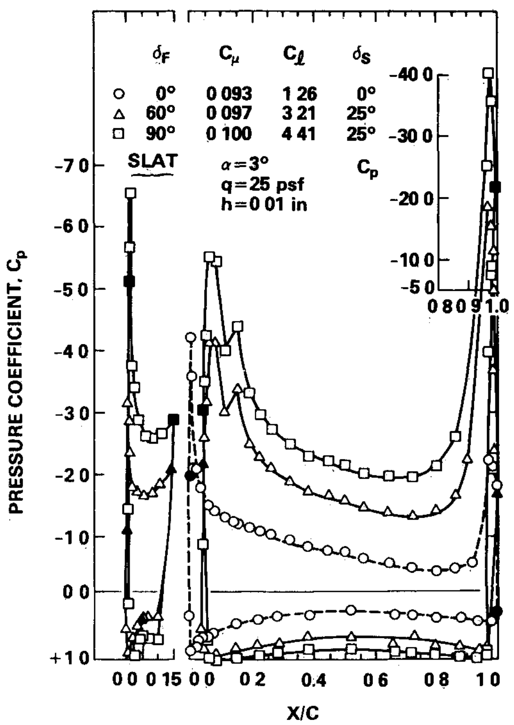

Fig 13 Pressure distributions for dual radius configuration B; $c_f = 0\ 035c$

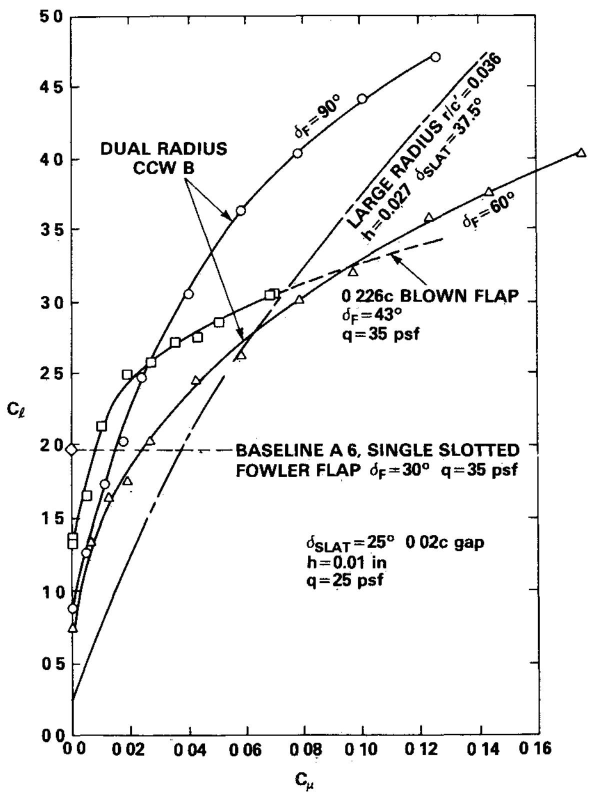

Fig 15 Comparative lift capability; $\alpha_g = 3$ deg

slat deflection of 25 deg and a 0 02c gap This is the slat setting on the production A 6 and it was originally thought to be more appropriate for the lower blowing levels This choice did not prove appropriate in certain cases, as will be discussed later

Lift resulting from blowing at constant geometric angle of attack is shown in Figs 10 and 11 for the two extremes in trailing edge radius size: 0 0045c for the mini radius con figuration, and 0 060c for the larger radius of the dual radius configuration B airfoil For the smallest radius (Fig 10), lift maxima occur at about $C_\mu = 0\ 04$, and augmentation beyond that is reduced This same trend was noted in Refs 8 and 9 for the small radius supercritical airfoil once certain pressure ratios were exceeded In Fig 10 that pressure ratio for the mini radius is about 1 4 to 1 5, but the ratio was considerably higher for the CCW/supercritical section with twice the radius It becomes apparent that higher pressure ratios combined with smaller radii are not conducive to in creased jet turning and lift augmentation The favorable

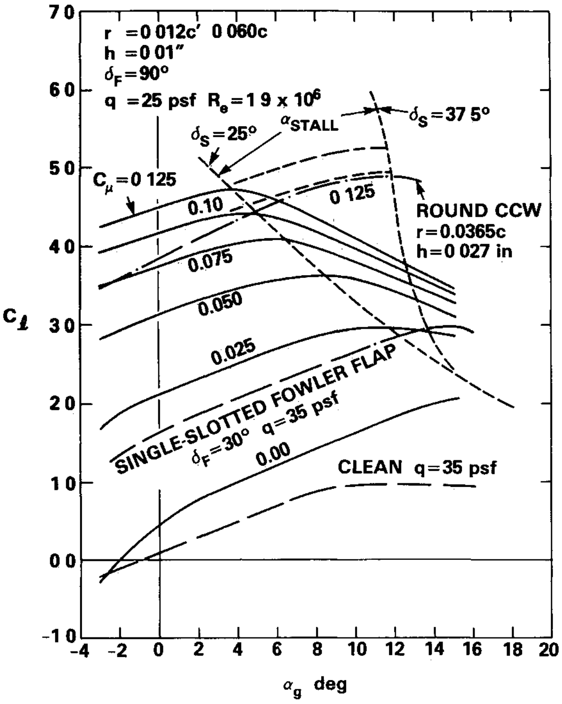

Fig 16 Lift variation with incidence for dual radius CCW con figuration B; $c_f = 0\ 035c$

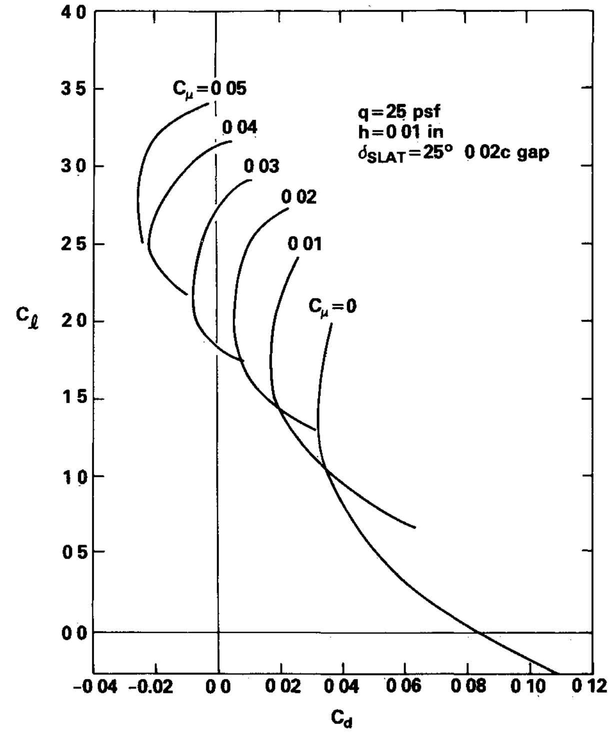

Fig 18 Drag polars at constant blowing for dual radius CCW configuration A; $c_f = 0\ 0223c$

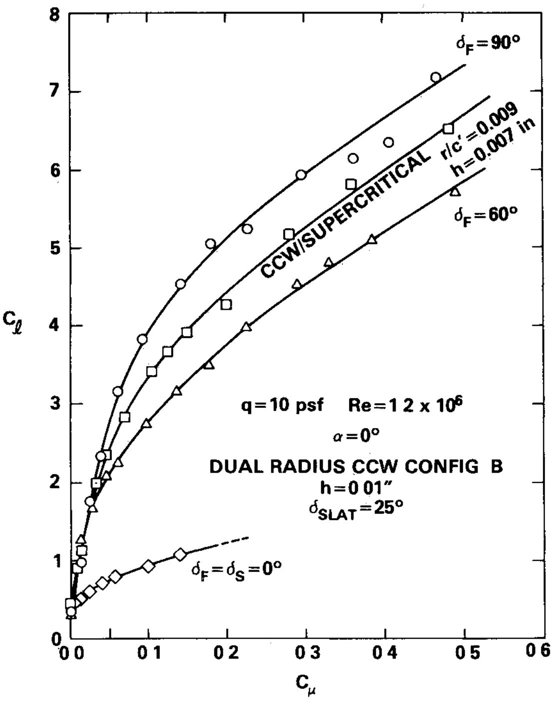

Fig 17 Lift at higher blowing rates, $\alpha_g = 0$ deg

effect of increased trailing edge radius is emphasized in Fig 11 for the largest dual radius CCW configuration B The radius just downstream of the slot is 2 67 times that of Fig 10 while the secondary radius is 13 3 times as large This secondary radius, which is 64% larger than that of the original CCW airfoil of Fig 1 is very effective in turning the jet and enhancing lift Furthermore, the camber provided by the 90 deg flap deflection adds 0 5 to 0 6 to the unblown lift coefficient In addition to the increase in lift dual radius configuration B pushes the lift peaks that occurred at $C_\mu = 0\ 04$ in Fig 10 up to $C_\mu = 0\ 13$ (pressure ratio of 2 2) At angles of attack greater than 3 deg the peaks are minimal or nonexistent Reference 8 data for the CCW/supercritical airfoil indicate that these peaks may be moved to higher C_μ by reducing the jet slot height or further increasing the radius Leading edge stall occurs at high lift and incidence due to insufficient slat deflection

Reduction in flap deflection reduces the airfoil geometric camber as well as the maximum angle through which the jet may turn Those effects are shown in Fig 12 for 0 and 60 deg flap deflection The 0 deg case becomes essentially a 33 deg jet flap, while the 60 deg flap produces 93 deg of jet turning and appreciable lift The advantages of these two con figurations are: 1) lower drag due to reduced projected area and 2) increased jet thrust recovery The 60 deg flap could thus be effectively employed as a takeoff setting

The pressure distributions in Fig 13 give further insight into the above discussion The increased suction peaks produced over the trailing edge radii indicate why the lift is more than tripled by increasing the flap deflection from 0 to 90 deg at $C_\mu \doteq 0\ 10$ The $C_p = -40$ value shows why the larger radii are more effective: they are more able to prevent the high velocity jet from separating from the radius before sufficient turning is produced The increased suction spike on the slat leading edge points to the nearness of leading edge stall at this slat deflection Note in this figure, that the slat pressures are plotted normal to the chord rather than deflected, and that the slat is retracted for the 0 deg flap case, since it represents a cruise configuration The small spike at $x/c = 0\ 15$ is due to the exposed cove on the main airfoil into which the slat trailing edge retracts in cruise The solid symbols are the leading and trailing edges of each separate element

A 6 High Lift Airfoil Comparison

A summary comparison of all the above A 6 high lift configurations is presented in Fig 14 for a typical geometric incidence of 9 deg The large radius CCW airfoil data from Fig 2 have been adjusted to 25 deg slat deflection as a basis for comparison Only the two dual radii configurations are superior to the original large configuration in lift, and they fall below its performance at higher C_μ because the jet is limited to a maximum turning angle of 123 deg For the full round large CCW jet turning can continue on to 150 deg or

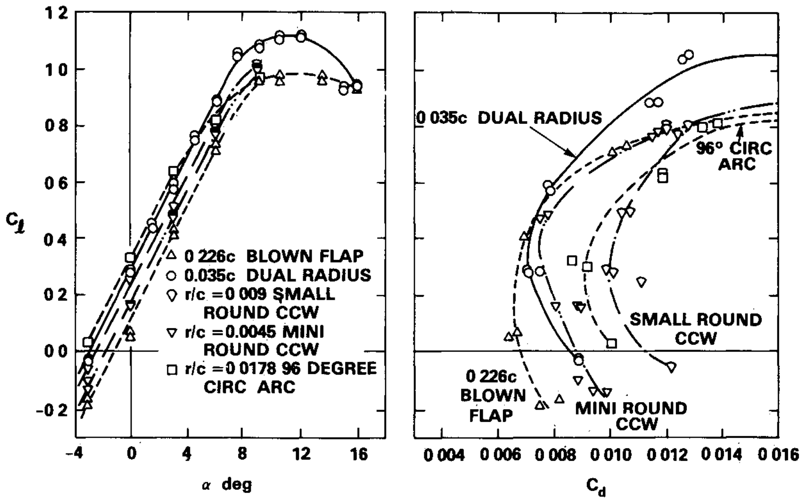

Fig 19 Blowing off clean airfoil comparison

more However from a mechanization and drag standpoint this large CCW is impractical and thus most of the con figurations shown offer significant operational improvement To serve as a reference to the actual airplane, the single slotted semi Fowler flap ($c_F = 0\ 30c$) employed on the A 6 was also tested in connection with the Grumman test of Ref 10 For C_μ in the range of 0 05 or greater, all CCW airfoils tested exceeded the mechanical flap's capability except for the mini radius configuration A similar comparison is shown in Fig 15 for $\alpha_g = 3$ deg and includes the 0 226c blown flap con figuration [10] The leading edge stall problem is now avoided at this lower incidence and the dual radius exceeds its Fig 14 performance at higher blowing Both the 60 deg dual radius and the 0 226c blown flap behave in the typical blown flap manner; once flow is turned to the flap upper surface angle the lift variation becomes nearly linear with C_μ instead of the parabolic function typical of a round CCW For $C_\mu > 0\ 026$ the 90-deg flap dual radius exceeds the 0 226c blown flap lift, even though it is less than one sixth the chord length The blown flap is superior at low and no blowing due to the extra camber produced by its longer chord length All three of the CCW configurations can double the lift of the baseline single slotted flap in the $C_\mu < 0\ 16$ range; the 0 226c blown flap cannot

Lift variation with angle of attack is shown in Fig 16 for the larger flap dual radius CCW and for the 37 5 deg slat configuration from Fig 2 Clearly, leading edge stall limits $C_{\ell_{max}}$ at higher blowing This is improved considerably by increased slat deflection With the same 37 5 deg slat, the dual radius configuration offers significantly higher $C_{\ell_{max}}$ than the original large radius CCW For baseline comparison, both the clean A 6 airfoil and the single slotted flap A 6 airfoil data from Ref 10 ($Re = 2\ 2 \times 10^6$) are shown

The effect of extending the available blowing range was investigated by reducing the dynamic pressure to 10 psf so that available pressure and mass flow would yield higher C_μ Figure 17 shows the high lift obtained by the larger chord dual radius CCW in comparison to the CCW/supercritical Because the secondary radius exceeds that of the supercritical airfoil, so also does the lift The generation of C_ℓ approaching 8 at 0 deg incidence appears quite promising, should the increased C_μ be available In these higher blowing ranges lift is nearly a linear function of C_μ for either blown flap or full round CCW trailing edge

Drag Variation with Blowing

Drag polars at constant C_μ are shown in Fig 18 for the shorter flap dual radius CCW configuration A but the trends are similar for the other CCW geometries In general, for a constant α_g increase in C_μ results in reduced drag as thrust is recovered from the jet itself In this figure the initial high drag levels at low C_μ and incidence are due to separated flow on the 90 deg flap and on the slat lower surface (at no blowing and $\alpha_g = 0$ deg it is operating at -25 deg local incidence) These data are, of course, two dimensional values and do not address the three dimensional induced drag component due to lift, which will become the dominant drag value for finite wing configurations Additional drag and pitching moment data are discussed in Ref 13

Blowing off Comparison

A major design goal of an improved high lift airfoil was to minimize any cruise drag penalty The various A 6 blown airfoils tested above are compared in their clean con figurations in Fig 19 where slat flap, and circular arc trailing edge are retracted; small and mini CCW trailing edges are left deployed but the slat is retracted The clean blown flap is considered to be the same configuration as the clean cruise airfoil As the CCW trailing edge thickness in creases, so too does the aft camber and resulting lift due to camber; the 96 deg circular arc shifts the lift curve upwards by an increment of 0.21 over the clean airfoil Along with this thickness, camber and lift increases cause a corresponding drag increase as shown by the drag polars The one exception is the dual radius configuration, whose large secondary radius ends in a thin near sharp trailing edge thus avoiding aft surface flow separation In fact, for $C_\ell > 0\ 5$, the dual radius yields less drag than the clean airfoil probably because the clean airfoil requires higher angle of attack to reach the same C_ℓ Reference 13 also compares these unblown airfoils, with flaps and slats extended, to the large radius original CCW airfoil of Fig 1 The minimum drag of the unblown 90 deg flap dual radius CCW is about 40% that of the larger radius original CCW and occurs at much higher C_ℓ At the same C_ℓ (say 1 0) the unblown dual radius drag is 25% that of the large radius, and it is less at higher C_ℓ In general, the drag levels of these small trailing edges show considerable im provement over those of the original larger trailing edge radius

Conclusions and Recommendations

A series of reduced size CCW trailing edge configurations has been developed and subsonically evaluated in a program to reduce the complexity, size and weight of the CCW high lift system, while maintaining the high lift previously generated and reducing or eliminating the unblown cruise drag penalty of the thick trailing edge The following con clusions resulted from those investigations:

1) A small round trailing edge could be incorporated into the existing aft contour of a thick supercritical airfoil On this airfoil a radius one fourth the size of the original A 6/CCW

airfoil yielded slightly greater lift than that for $0.036c'$ radius, producing lift coefficients near 7.0 at $\alpha = 0$ deg. Furthermore, the large undeflected leading-edge radius of the supercritical airfoil provided the same leading-edge stall prevention as the 37.5-deg slat of the A-6/CCW

2) Base drag was sufficiently reduced by the small trailing-edge radius so that unblown subsonic C_d was nearly the same as the baseline supercritical airfoil or could be reduced to less than the baseline by a minimal amount of blowing.

3) Of the single-radius CCW configurations applied to the thin A-6 airfoil section, the largest radii produced the greatest lift, as long as there was sufficient arc length to maintain jet turning. Too small a radius produced lift reductions once a certain blowing pressure ratio was reached.

4) The dual-radius CCW provided an effective means to maintain a large radius, sufficient jet turning, and a thin trailing edge for cruise. A $0.035c'$ flap length dual-radius configuration produced greater lift than the original thick $0.036c'$ radius A-6/CCW; at $\alpha_g = 0$ deg, C_ℓ greater than 7 was generated from $C_\mu < 0.5$, compared to the baseline single slotted mechanical flap C_ℓ of 1.6 at the same incidence.

5) In the clean configuration with no flap deflection, subsonic drag for the dual-radius configuration was nearly the same or slightly less than the A-6 cruise airfoil. Lift due to trailing-edge camber could allow cruise at lower angle of attack, thus resulting in a reduced drag level.

These results suggest the strong potential of two advanced forms of the Circulation Control Wing airfoil: 1) a CCW/supercritical no-moving-parts configuration with no need for a deflecting leading- or trailing-edge device, and transition from the cruise to high-lift modes by initiation of blowing, and 2) a thinner high-performance CCW airfoil with a small-chord dual-radius flap and some type (blown or mechanical) of effective leading-edge device. The flap geometry would provide no cruise penalty (actually the availability of a blowing slot for maneuverability or cruise drag reduction could be quite beneficial), and its larger secondary radius would provide even greater lift than large single-radius configurations. The strength of the dual-radius airfoil lies in its ability to provide a large turning radius, arc length, and jet exit angle accompanied by a very simple conversion to a nearly conventional cruise airfoil.

These data confirm that two families of improved CCW airfoils can, in fact, generate excellent STOL performance with little or no subsonic cruise penalty and without the weight, complexity, and size of conventional mechanical or powered high-lift systems. The remaining unknown is the effect of the trailing-edge geometries on the airfoil characteristics in high subsonic or transonic flow This concern will be addressed in transonic two-dimensional wind tunnel investigations now being undertaken as part of the DTNSRDC program for development of these advanced airfoils.

References

[1]Englar, R. J., Stone, M. B., and Hall, H., "Circulation Control—An Updated Bibliography of DTNSRDC Research and Selected Outside References," DTNSRDC Rept. 77-0076, Sept. 1977

[2]Englar, R. J., Hemmerly, R. A., Moore, W H., Seredinsky, V., Valckendere, W G., and Jackson, J. A., "Design of the Circulation Control Wing STOL Demonstrator Aircraft," *Journal of Aircraft*, Vol. 18, Jan. 1981, pp. 51-58.

[3]Pugliese, A. J. and Englar, R. J., "Flight Testing the Circulation Control Wing," AIAA Paper 79-1791, Aug. 1979.

[4]Englar, R. J., "Development of the A-6/Circulation Control Wing Flight Demonstrator Configuration," DTNSRDC Rept. ASED-79/01, Jan. 1979.

[5]Englar, R. J., "Subsonic Two-Dimensional Wind Tunnel Investigations of the High Lift Capability of Circulation Control Wing Sections," DTNSRDC Rept. ASED-274, April 1975.

[6]Nichols, J. H. Jr., Englar, R. J., Harmis, M. J., and Huson, G. G., "Experimental Development of an Advanced Circulation Control Wing System for Navy STOL Aircraft," AIAA Paper 81-0151, Jan. 1981.

[7]McGhee, R. H. and Bingham, G. H., "Low-Speed Aerodynamic Characteristics of a 17-percent Thick Supercritical Airfoil Section, Including a Comparison Between Wind-Tunnel and Flight Data," NASA TM X-2571, July 1972.

[8]Englar, R. J., "Low-Speed Aerodynamic Characteristics of a Small, Fixed-Trailing Edge Circulation Control Wing Configuration Fitted to a Supercritical Airfoil," DTNSRDC Rept. ASED-81/08, March 1981.

[9]Englar, R. J., "Development of an Advanced No-Moving Parts High-Lift Airfoil," *Proceedings of ICAS/AIAA Aircraft Systems and Technology Conference*, ICAS-82-6.5.4, Aug. 1982, pp. 951-959.

[10]"Wind Tunnel Test Report-2D NSRDC Test of a 64A008.4 Mod Airfoil, Blown Flaps Phase," Grumman Aerospace Corporation Rept. No. WS-128( )-R-4, Vol. I, Feb. 1983.

[11]Englar, R. J. and Ottensoser, J., "Calibration of Some Subsonic Wind Tunnel Inserts for Two-Dimensional Airfoil Experiments," DTNSRDC Rept. ASED AL-275, Sept. 1972.

[12]Englar, R. J., "Two-Dimensional Subsonic Wind Tunnel Test of a Cambered 30-Percent Thick Circulation Control Airfoil," DTNSRDC Rept. ASED AL-201, May 1972.

[13]Englar, R. J. and Huson, G. G., "Development of Advanced Circulation Control Wing High Lift Airfoils," AIAA Paper 83-1847 July 1983.