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A Recontoured, Upper Surface Designed to Increase the Maximum Lift Coefficient of a Modified NACA 65 (0.82) (9.9) Airfoil Section

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NOMENCLATURE

C_p	pressure coefficient, $\frac{P_L - P_\infty}{q_\infty}$
c	airfoil chord, m (in.)
c_d	section drag coefficient
c_ℓ	section lift coefficient
c_m	section pitching moment coefficient referenced to quarter chord
H	shape factor, $\frac{\delta^*}{\theta}$
K	upper surface thickness parameter
M	Mach number
p	static pressure, N/m^2 (lb/ft^2)
q	dynamic pressure, N/m^2 (lb/ft^2)
Re	Reynolds number based on free-stream conditions and airfoil chord
s	distance along airfoil surface, m
u	velocity, m/sec
x	airfoil abscissa, m (in.)
y	airfoil ordinate, m (in.)
α	angle of attack, deg
δ^*	displacement thickness, m
θ	momentum thickness, m

Subscripts

max	maximum
min	minimum
L	local
∞	free-stream conditions

N84-17144#

SUMMARY

A wind-tunnel test was conducted to assess the effectiveness of a recontoured upper surface to increase the maximum lift coefficient of a modified NACA 65 (0.82) (9.9) airfoil section. The recontoured airfoil was slightly thicker when compared to the original airfoil. The modification was confined to the forward 50% of the chord. The recontoured and original airfoils were tested at Mach numbers of 0.3 and 0.4 and at Reynolds numbers of 2.3×10^6 and 4.3×10^6.

The recontoured airfoil showed a higher maximum lift coefficient, lower drag coefficients, and similar pitching moment characteristics when compared with the original airfoil section at all test conditions. At lift coefficients near the design value, the recontoured airfoil had only slightly less drag than the original profile did, whereas at high lift coefficients the drag of the recontoured airfoil was substantially lower.

The improvements found for the recontoured airfoil of the present study are similar to those found during previous investigations of recontoured 6-series airfoils with less camber.

INTRODUCTION

Previous experimental evaluations of a recontoured upper surface of the NACA 64_1-212 and the NACA 63_2-215 airfoil sections showed that substantial increases in the maximum lift coefficients were achieved at Mach numbers of 0.2, 0.3, and 0.4 and at Reynolds numbers between 1.9×10^6 and 2.5×10^6 (refs. 1 and 2). The improvements in maximum lift of these airfoil sections were achieved by reducing the adverse pressure gradients near the leading edge along the upper surface at high angles of attack. Both of the above sections had low camber which is typical of many high-performance single and twin engine business aircraft designed over the last 40 years.

The current investigation was conducted to assess the effects of a recontoured upper surface of a highly cambered 6-series airfoil typical of propeller and compressor blade sections. The airfoil chosen for this study was an NACA 65 (0.82) (9.9) airfoil with a circular arc camber which was the profile used at the 83% radial station of the compressor blades in the 40- by 80- by 120-Foot Wind Tunnel at Ames Research Center. The wind-tunnel results reported herein provide an evaluation of the design methodology of references 1 and 2 at lower thickness-chord ratios and greater camber.

The type of recontouring studied here is useful for the retrofitting of existing lifting surfaces when the permissible change to the airfoil's profile is limited to relatively small changes brought about by manufacturing constraints.

THEORETICAL AIRFOIL RECONTOURING

The technique used to recontour the modified NACA 65 (0.82)(9.9) airfoil section is similar to the method described in references 1 and 2. The upper surface thickness was increased by adding the function $Kx^{1/2}(1 - x)/e^{8x}$ to the ordinates of the upper surface of the normalized airfoil. The parameter, K, was increased incrementally and the pressure distribution was analyzed for each value of K by using Program H (ref. 3). The four parameters considered during the design process were the boundary layer shape factor H, the separation parameter $[(\theta/u)(du/ds)]$, the peak pressure at the leading edge at high angle of attack, and the pressure gradient which follows the peak pressure. The most useful parameter, and the one which dictated the amount of thickness to be added to the airfoil in this investigation, was the peak pressure at the leading edge. The other three parameters were monitored to ensure consistency with the trend indicated by the peak pressure; i.e., if all four parameters indicated that the amount of thickness added was beneficial, the design was accepted. A plot of the peak pressure (absolute value of $C_{p_{min}}$) vs K is shown in figure 1. Note that the peak pressure decreases rapidly as K increases, until a plateau is reached. The value of K at the beginning of the plateau determined the amount of thickness to be added to the upper surface of the airfoil. This design method is based on the assumption that $C_{\ell_{max}}$ is inversely proportional to the magnitude of the peak pressure near the leading edge for attached flow. The lift coefficient shown in figure 1 is the highest value predicted to have flow attached over 95% of the upper surface of the original airfoil. It would be more effective to maximize $C_{\ell_{max}}$ directly by using a numerical optimization algorithm coupled to a Navier-Stokes code; however, such a technique does not exist, so it is necessary to rely on simpler methods such as the one used here.

The recontoured and original airfoil sections are shown in figure 2. The coordinates are given in table 1.

MODELS

Two airfoil models with the modified NACA 65 (0.82)(9.9) and the recontoured profiles were cast of aluminum epoxy material with the pressure tubing laid into the material during casting. Pressure orifices were subsequently drilled normal to the surface to meet the tubing at 25 locations on the upper surface and at 18 locations on the lower surface. Each model had a 15.24-cm (6-in.) span and chord. A model photograph is shown in figure 3.

WIND TUNNEL

The tests were conducted in the Ohio State University 6- by 22-Inch Transonic Airfoil Tunnel (ref. 4). The tunnel is a blowdown facility with perforated floor and ceiling and has a Mach number range from 0.2 to 1.07 and a Reynolds number range from 2×10^6 to 34×10^6 depending on Mach number. The tunnel has separate plenum chambers above and below the test section. An installation photograph showing a model installed in the tunnel is shown in figure 4.

TEST CONDITIONS

The section aerodynamics characteristics of the two airfoils were obtained at Mach numbers of 0.3 and 0.4 and Reynolds numbers of 2.3×10^6 and 4.3×10^6. The angles of attack ranged from approximately -4° to 17° depending on the angle of stall for each model. Data were obtained at all test conditions with free transition because the full-scale Reynolds number was attained during testing, and because of difficulty in simulating a realistic in-service surface condition on a wind-tunnel model.

Pressure coefficients were determined from surface pressure measurements. Section normal force, chord force, and pitching moment coefficients were calculated by integrating surface pressure coefficients. The pitching moment coefficients were referenced to the quarter chord point. Section profile drag was calculated from pressures measured by a traversing total pressure probe and a separate static pressure probe.

The model angle of attack can be corrected for the presence of the tunnel walls by use of the following equation:

$$\alpha_{true} = \alpha_{geom.} - 0.5c_{\ell}$$

where α_{true} is the corrected angle of attack and $\alpha_{geom.}$ is the angle of attack set during testing. The angle of attack used in this report is the geometric angle.

RESULTS AND DISCUSSION

Force Coefficients

The aerodynamic force coefficients for both airfoil sections are presented in figures 5 and 6. The recontoured airfoil exhibits a higher maximum lift coefficient than the original 6-series section at all test conditions. The increase ranges from a 10% improvement at Mach 0.4 and a Reynolds number of 2.2×10^6 to 27% improvement at Mach 0.3 and a Reynolds number of 4.3×10^6. The lift-curve slope appears to be slightly greater for the recontoured airfoil than for the original airfoil at all test conditions. The stall characteristics of the recontoured profile are somewhat more gradual than for the modified 6-series section at all test conditions. Note that the maximum lift coefficient of the recontoured airfoil is more sensitive to Reynolds number and Mach number than it is for the modified 6-series airfoil (fig. 7).

The profile drag data of figures 5 and 6 show a somewhat lower level of drag for the recontoured airfoil at moderate lift coefficients except at Mach 0.4 and a Reynolds number of 2.2×10^6 (fig. 6(a)). At higher lift coefficients the drag of the recontoured airfoil is considerably less than that of the modified 6-series section at all test conditions. The lower drag of the recontoured profile at moderate lift coefficients is opposite to the trend observed when a similar recontouring was applied to lower cambered 6-series airfoils (refs. 1 and 2). In those studies the recontouring caused a loss in laminar flow over the upper surface at lift coefficients near the design value which resulted in slightly higher profile drag. The lower drag of the recontoured section at high lift coefficients is consistent with the result found with the earlier 6-series modifications reported in references 1 and 2 and is due to improved pressure recovery over the aft region of the airfoil.

The data of figures 5 and 6 show that both airfoils have similar pitching moment characteristics. The aerodynamic center position is nearly the same for both airfoils. This result is somewhat different than that reported in references 1 and 2 where the modified airfoils were found to have a slightly more forward position of the aerodynamic center than the original 6-series airfoils had.

Pressure distributions for both airfoils are shown in figures 8 through 11. All pressure distributions show a negative trailing edge pressure coefficient at all angles of attack which is apparently caused by the fairly large trailing edge bluntness of both airfoils. Pressure distributions are shown for both Mach numbers at the higher Reynolds number only because the general shape of the curves are a weak function of Reynolds number.

The main effects of the recontouring are production of a less favorable pressure gradient over the forward 50% chord at the lower lift coefficients (compare figs. 8(a) and 10(a)), and a reduction of the peak negative pressure at the leading edge at high lift coefficients (compare figs. 8(d) and 10(d)). The reduction in favorable pressure gradient at low-lift coefficients apparently did not cause premature transition on the recontoured airfoil as indicated by the drag curves shown earlier. The reduction in adverse pressure gradient at high-lift coefficients resulted in better pressure recovery near the trailing edge of the recontoured profile (figs. 8(e) and 10(e)) which explains the higher maximum lift coefficients and greater angle of stall for the recontoured airfoil.

An analysis of compressor flow indicates that the recontoured airfoil will reduce the stall speed of the compressor by approximately 20% compared with the original 6-series airfoil (Borst, Henry V.; Private communication, May 1983).

CONCLUSIONS

A wind-tunnel test was conducted to evaluate a recontoured upper surface designed to improve the maximum lift coefficient and stalling angle of a modified NACA 65 (0.82)(9.9) airfoil section and to improve the speed margin before stall of a compressor using this airfoil. The test conditions were $M = 0.3$ and 0.4, $Re = 2.3 \times 10^6$, and 4.3×10^6. The following results were achieved:

1. Increasing the upper surface thickness over the forward 50% of the chord of the modified NACA 65 (0.82)(9.9) airfoil increased the maximum lift coefficient by 10% at $M = 0.4$ and $Re = 2.3 \times 10^6$ and by 27% at $M = 0.3$ and $Re = 4.3 \times 10^6$.

2. The recontouring had a negligible effect on the pitching moment characteristics of the modified 6-series airfoil.

3. The recontouring produced slightly lower drag at lift coefficients near the design value at most test conditions.

4. The recontoured airfoil had substantially lower drag than the modified 6-series airfoil did at high-lift coefficients.

5. The stall of the recontoured airfoil was somewhat more gradual than that of the 6-series airfoil.

6. The improvements found for the recontoured airfoil in the present study are similar to those found during previous investigations of recontoured 6-series airfoils with less camber.

7. A compressor flow analysis indicates that the recontoured airfoil will give a 20% lower speed before stall when compared to the original NACA 6-series airfoil.

REFERENCES

1. Hicks, Raymond M.; Mendoza, Joel P.; and Bandettini, Angelo: Effects of Forward Contour Modification on the Aerodynamic Characteristics of the NACA 64_1-212 Airfoil Section. NASA TMX-3293, 1975.

2. Hicks, Raymond M.; and Schairer, Edward T.: Effects of Upper Surface Modification on the Aerodynamic Characteristics of the NACA 63_2-215 Airfoil Section. NASA TM-78503, 1979.

3. Bauer, Frances; Garabedian, Paul; Korn, David; and Jameson, Antony: Supercritical Wing Sections II, Lecture Notes in Economics and Mathematical Systems. Springer-Verlag, 1975.

4. Lee, J. D.; Gregorek, G. M.; and Korkan, K. D.: Testing Techniques and Interference Evaluation in the Ohio State University Transonic Airfoil Facility. AIAA Paper 78-1118, AIAA 11th Fluid and Plasmadynamics Conference, 1978.

TABLE 1.- AIRFOIL COORDINATES

Modified NACA 65 (0.82)(9.9) airfoil coordinates			
X/C	Y_U/C	X/C	Y_L/C
0.00000	0.00000	0.99931	-0.00394
0.00354	0.00844	0.99527	-0.00327
0.00591	0.01038	0.94893	0.00180
0.01048	0.01362	0.89842	0.00491
0.02231	0.01975	0.84782	0.00634
0.04651	0.02978	0.79756	0.00667
0.07101	0.03827	0.74745	0.00606
0.09558	0.04590	0.69757	0.00492
0.14546	0.05889	0.64779	0.00321
0.19556	0.06935	0.59843	0.00122
0.24592	0.07799	0.54910	-0.00099
0.29655	0.08459	0.49991	-0.00312
0.34722	0.08937	0.45069	-0.00499
0.39805	0.09224	0.40164	-0.00650
0.44899	0.09344	0.35246	-0.00791
0.49985	0.09246	0.30315	-0.00941
0.55060	0.08935	0.25373	-0.01079
0.60127	0.08457	0.20421	-0.01206
0.65185	0.07810	0.15434	-0.01316
0.70210	0.07021	0.10423	-0.01355
0.75233	0.06090	0.07874	-0.01337
0.80223	0.05063	0.05340	-0.01259
0.85197	0.03931	0.02748	-0.01093
0.90159	0.02738	0.01440	-0.00912
0.95118	0.01522	0.00908	-0.00775
0.99675	0.00471	0.00639	-0.00655
1.00065	0.00391	0.00000	0.00000
Recontoured Airfoil Coordinates			
0.00000	0.00000	0.99931	-0.00394
0.00354	0.01363	0.99527	-0.00327
0.00591	0.01694	0.94893	0.00180
0.01048	0.02200	0.89842	0.00491
0.02231	0.03074	0.84782	0.00634
0.04651	0.04254	0.79756	0.00667
0.07101	0.05089	0.74745	0.00606
0.09558	0.05762	0.69757	0.00492
0.14546	0.06805	0.64779	0.00321
0.19556	0.07605	0.59843	0.00122
0.24592	0.08269	0.54910	-0.00099
0.29655	0.08701	0.49991	-0.00312
0.34722	0.09153	0.45069	-0.00499
0.39805	0.09366	0.40164	-0.00650
0.44899	0.09436	0.35246	-0.00791
0.49985	0.09304	0.30315	-0.00941
0.55060	0.08972	0.25373	-0.01079
0.60127	0.08479	0.20421	-0.01206
0.65185	0.07823	0.15434	-0.01316
0.70210	0.07029	0.10423	-0.01355
0.75233	0.06095	0.07874	-0.01337
0.80223	0.05066	0.05340	-0.01259
0.85197	0.03932	0.02748	-0.01093
0.90159	0.02739	0.01440	-0.00912
0.95118	0.01523	0.00908	-0.00775
0.99675	0.00471	0.00639	-0.00655
1.00065	0.00391	0.00000	0.00000

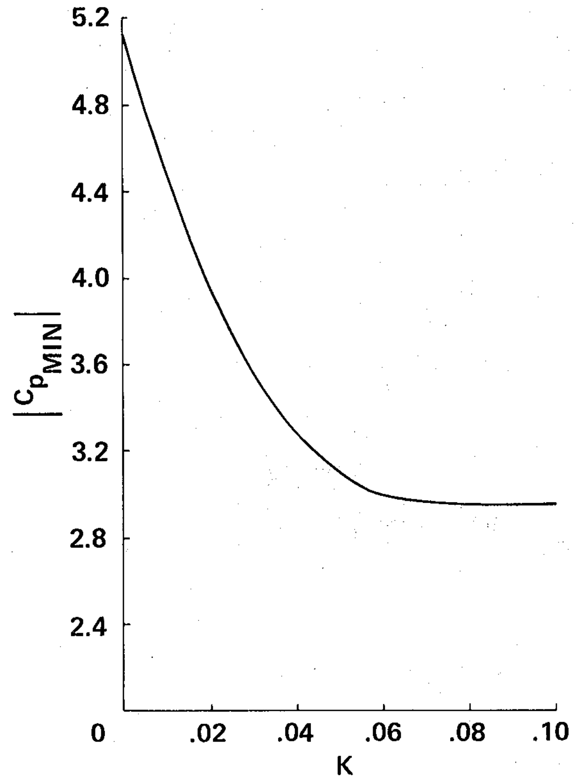


Figure 1.- Effect of forward airfoil thickness on peak pressure coefficient
$M = 0.39$, $C_\ell = 1.35$.

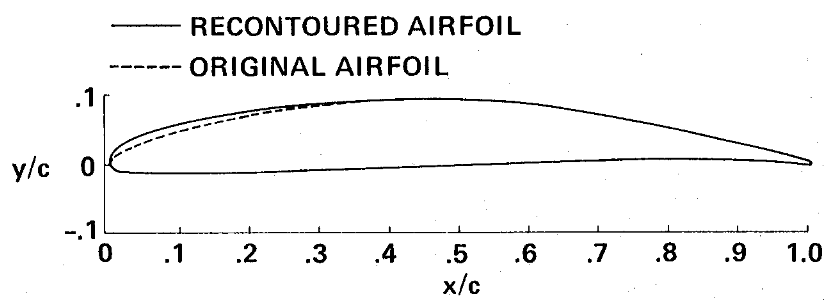


Figure 2.- Airfoil sections tested.

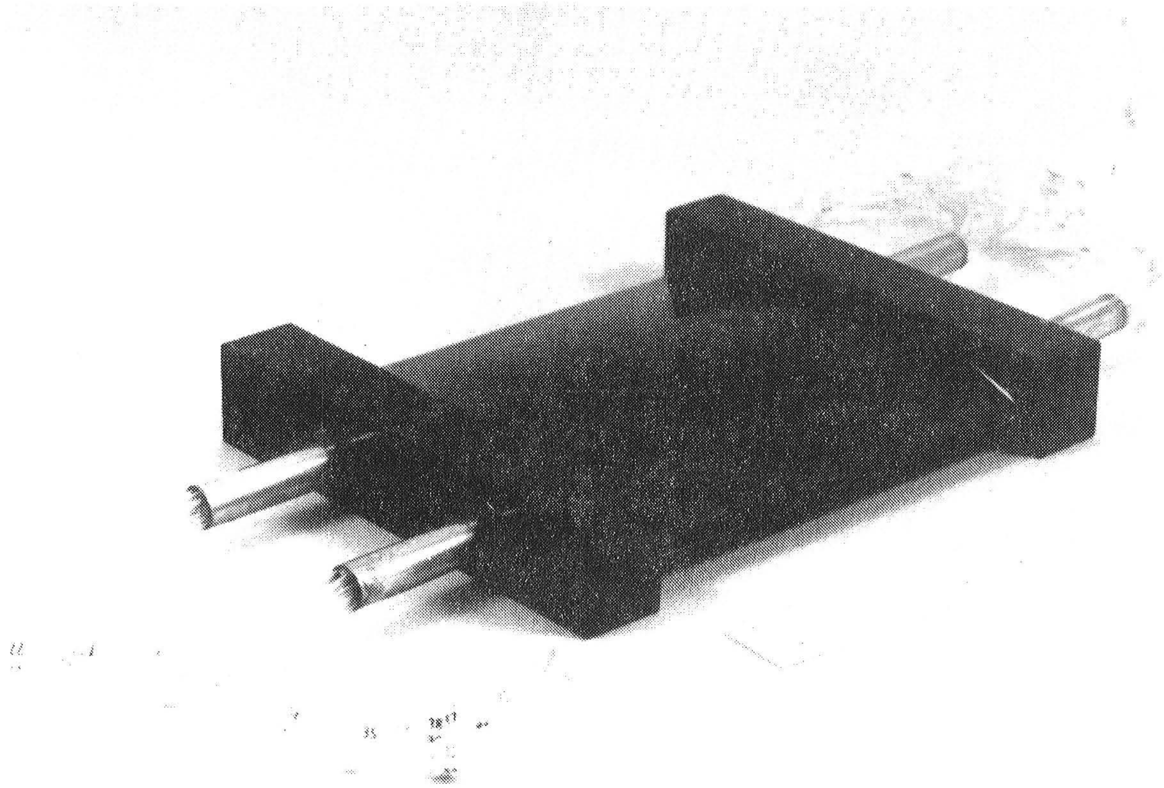


Figure 3.- Wind tunnel model.

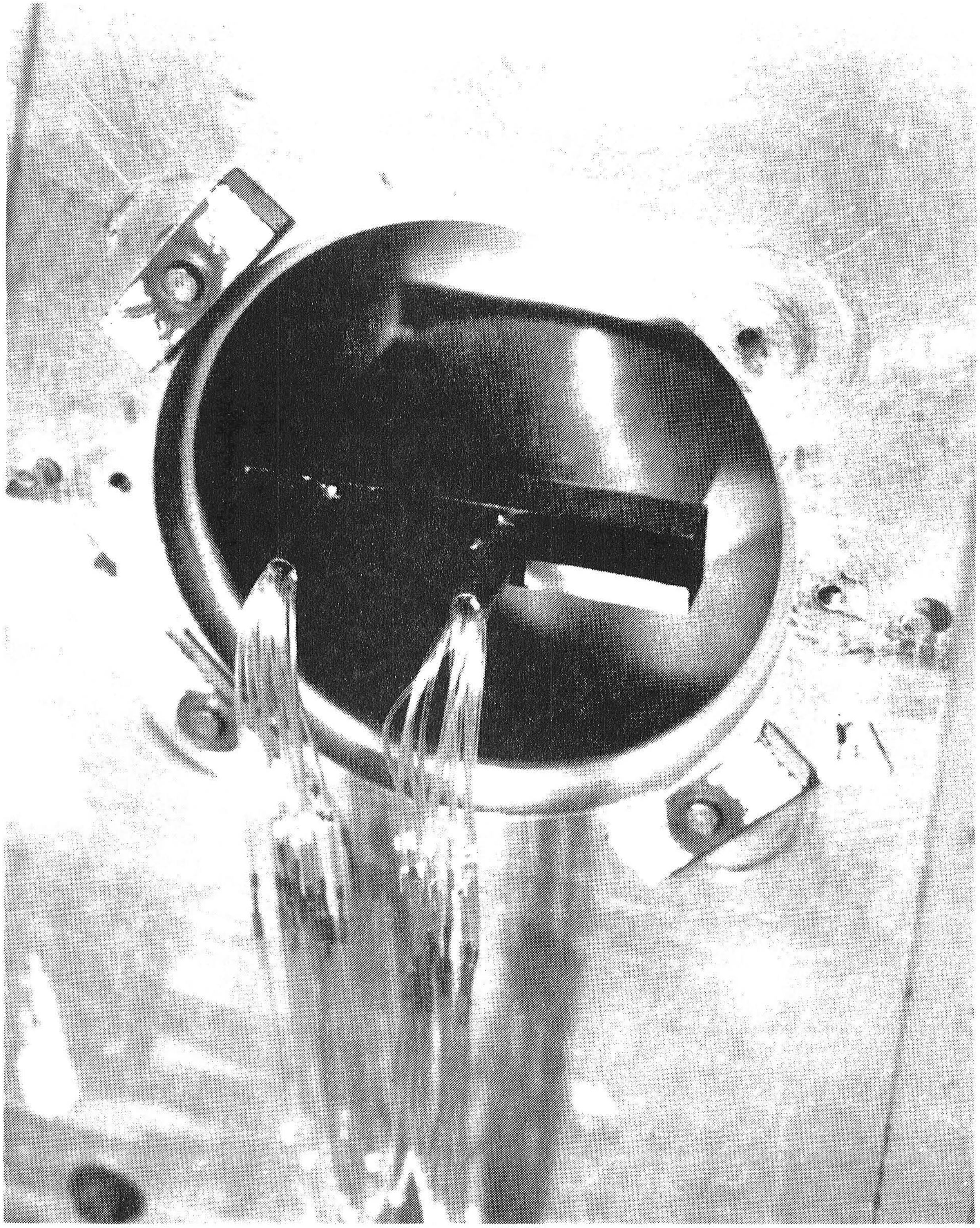


Figure 4.- Airfoil model in the Ohio State University 6- by 22-Inch Wind Tunnel.

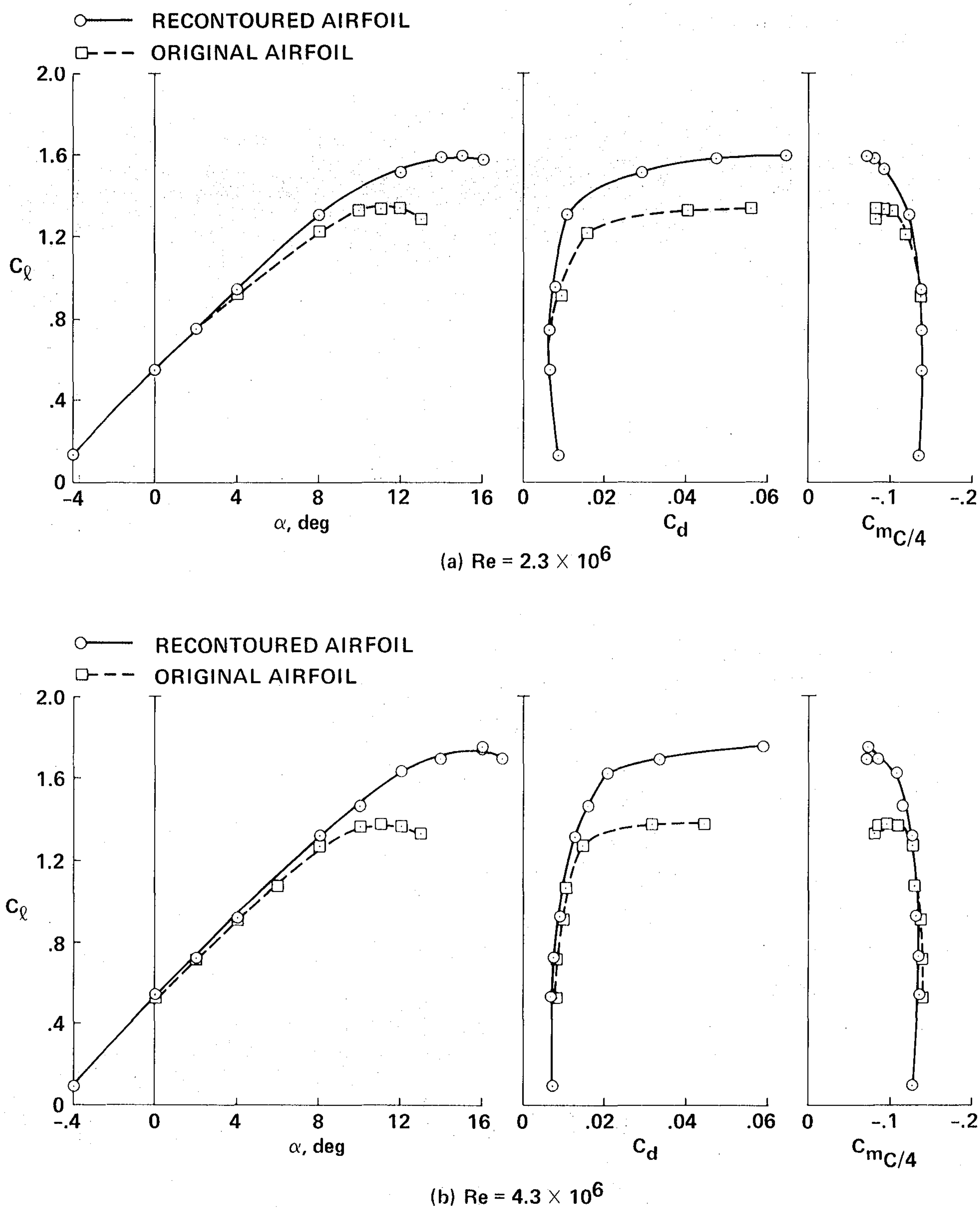
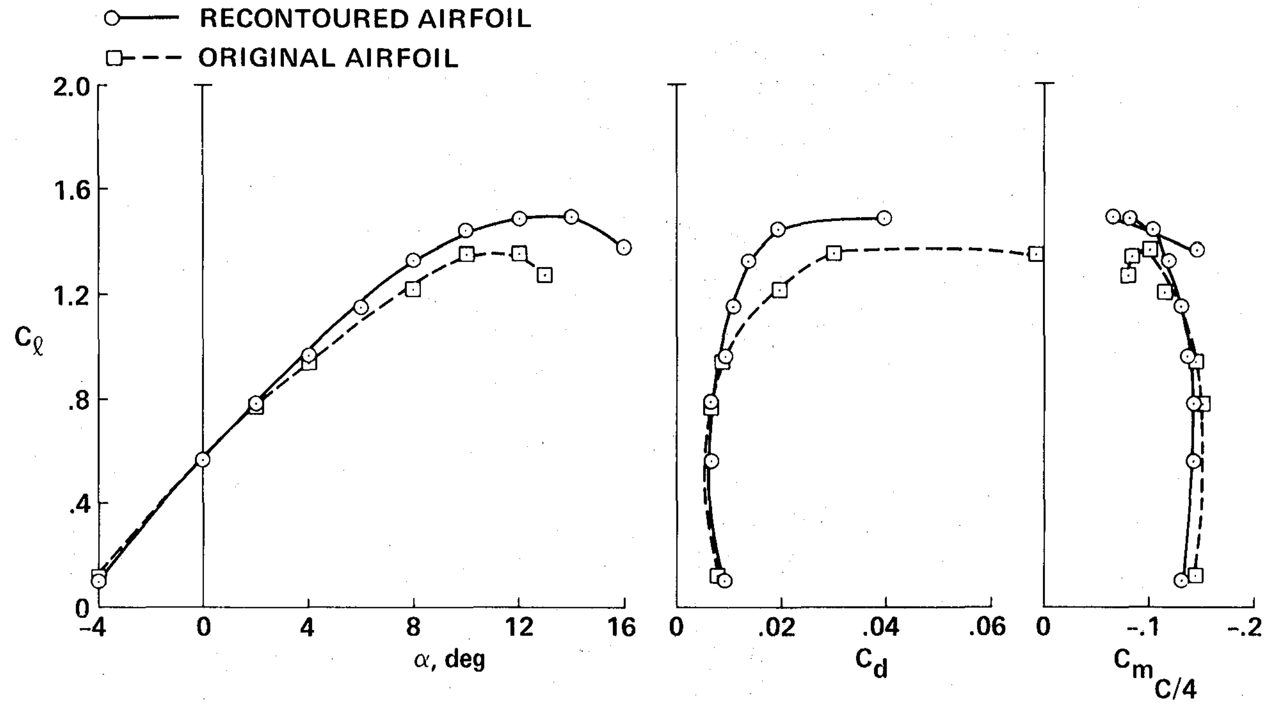
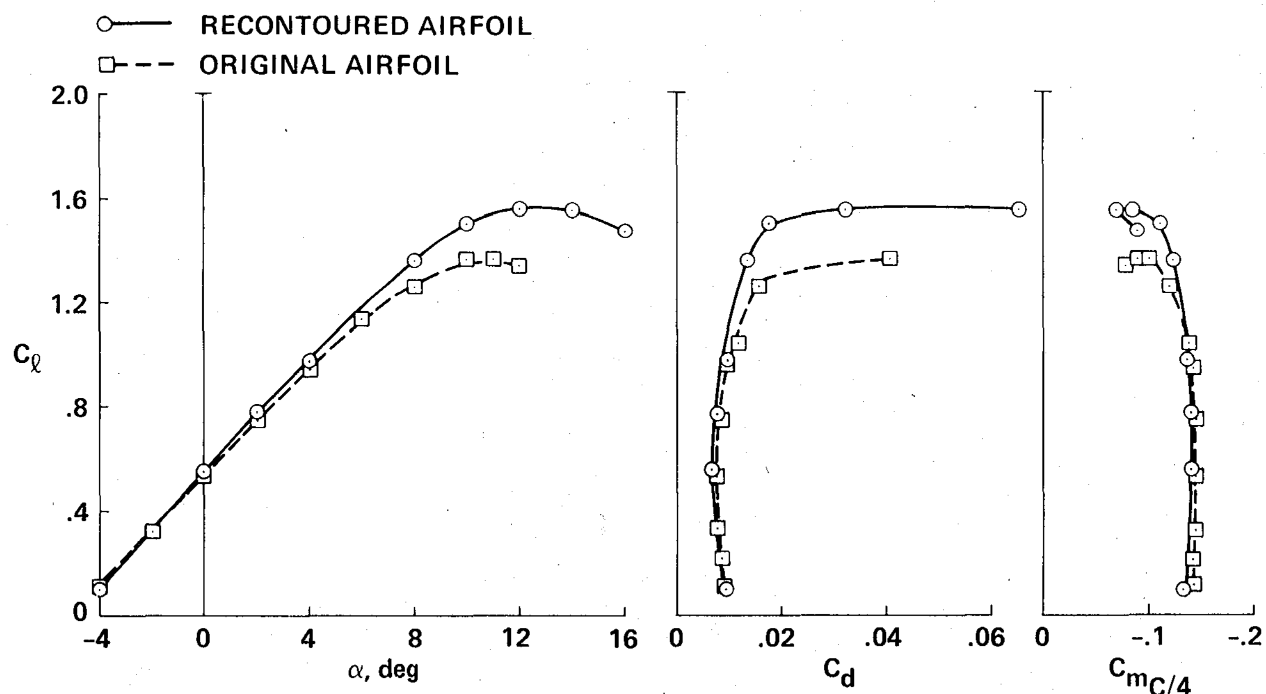


Figure 5.- Aerodynamic characteristics of the original and recontoured airfoils, M = 0.30.



(a) Re = 2.2 × 10^6



(b) Re = 4.3 × 10^6

Figure 6.- Aerodynamic characteristics of the original and recontoured airfoils, M = 0.40.

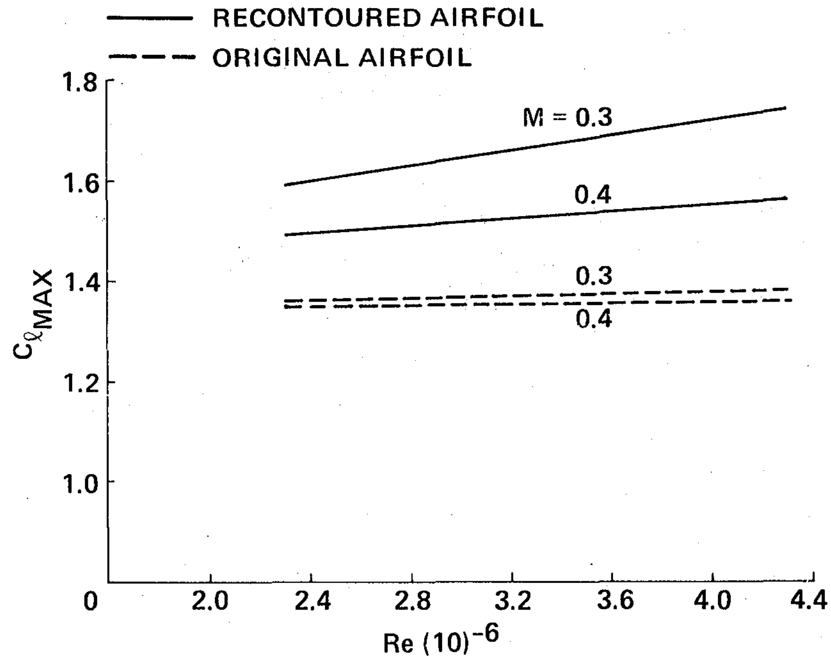


Figure 7.- Effect of Reynolds number and Mach number on the maximum lift coefficient of the original and recontoured airfoils.

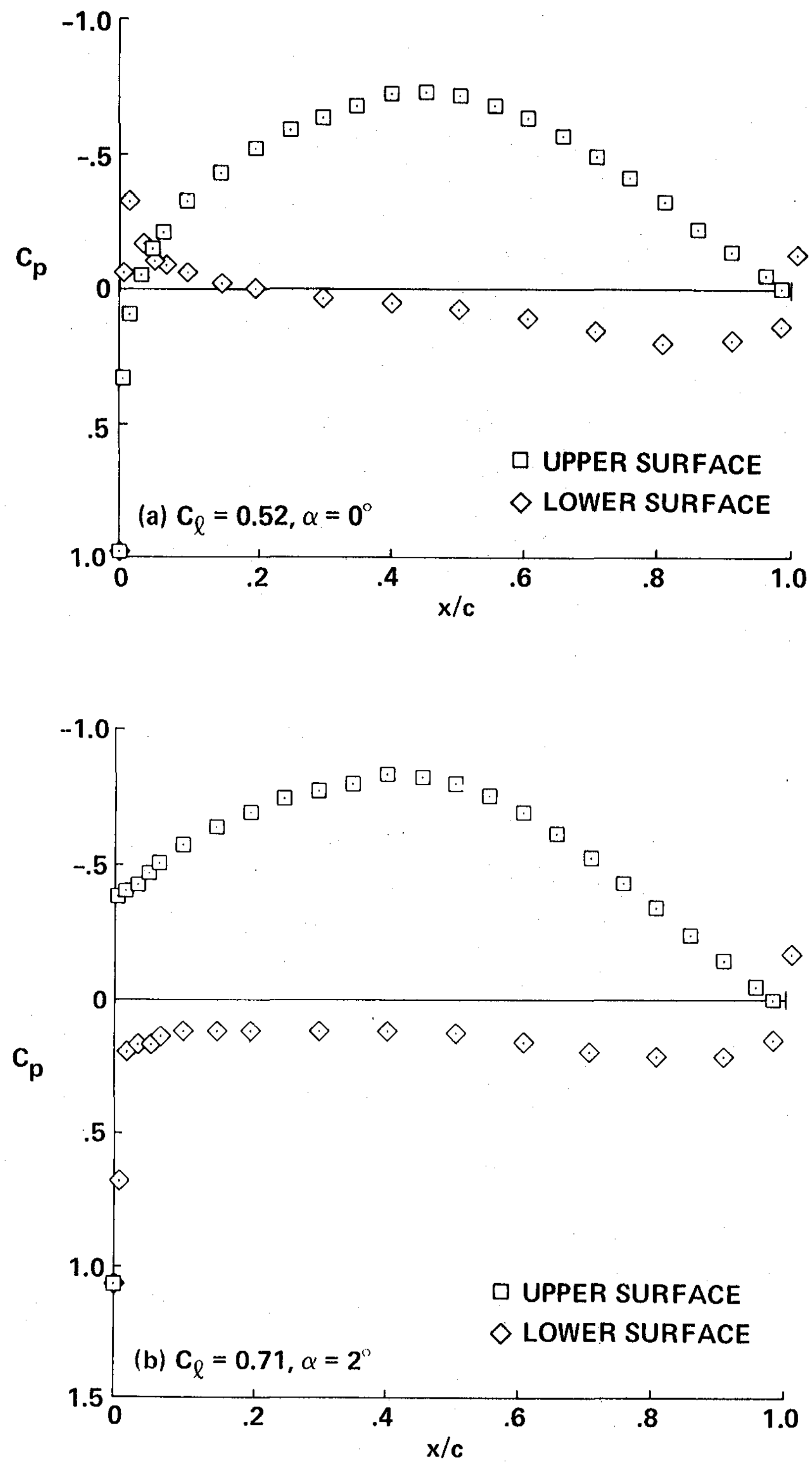
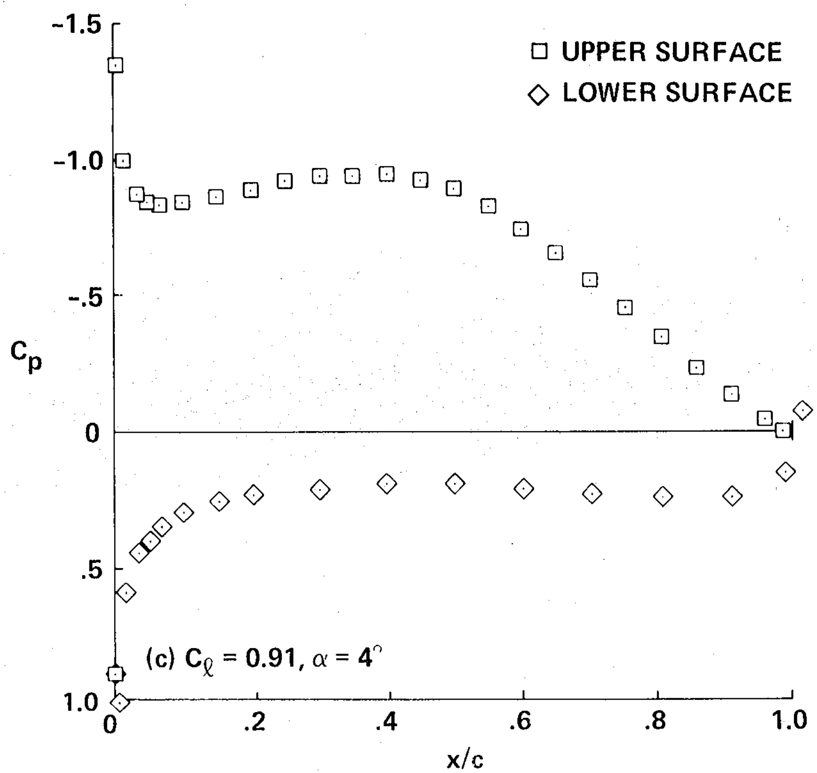
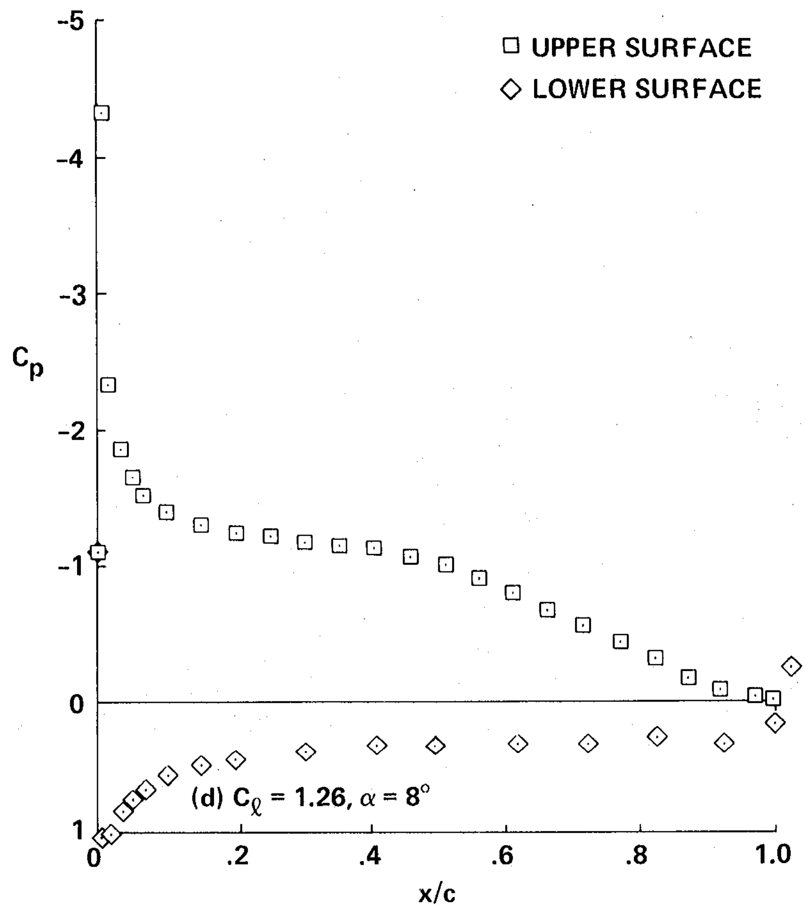


Figure 8.- Pressure distributions for the original airfoil; M = 0.30, Re = 4.3×10^6.





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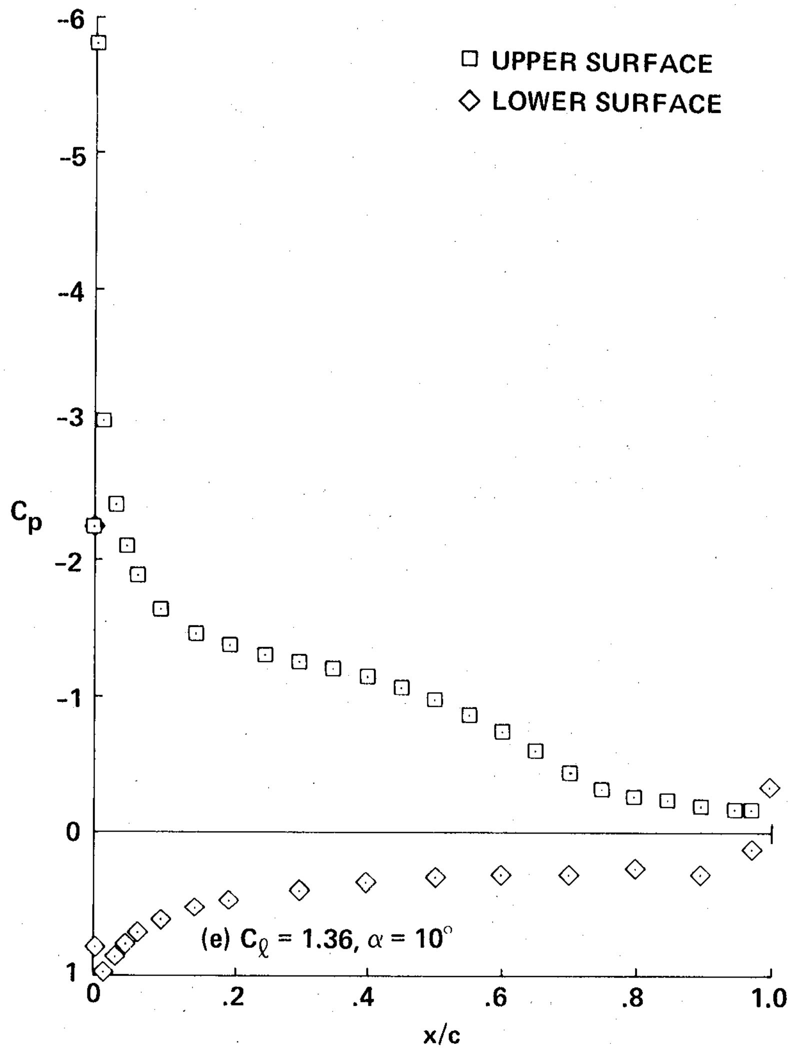

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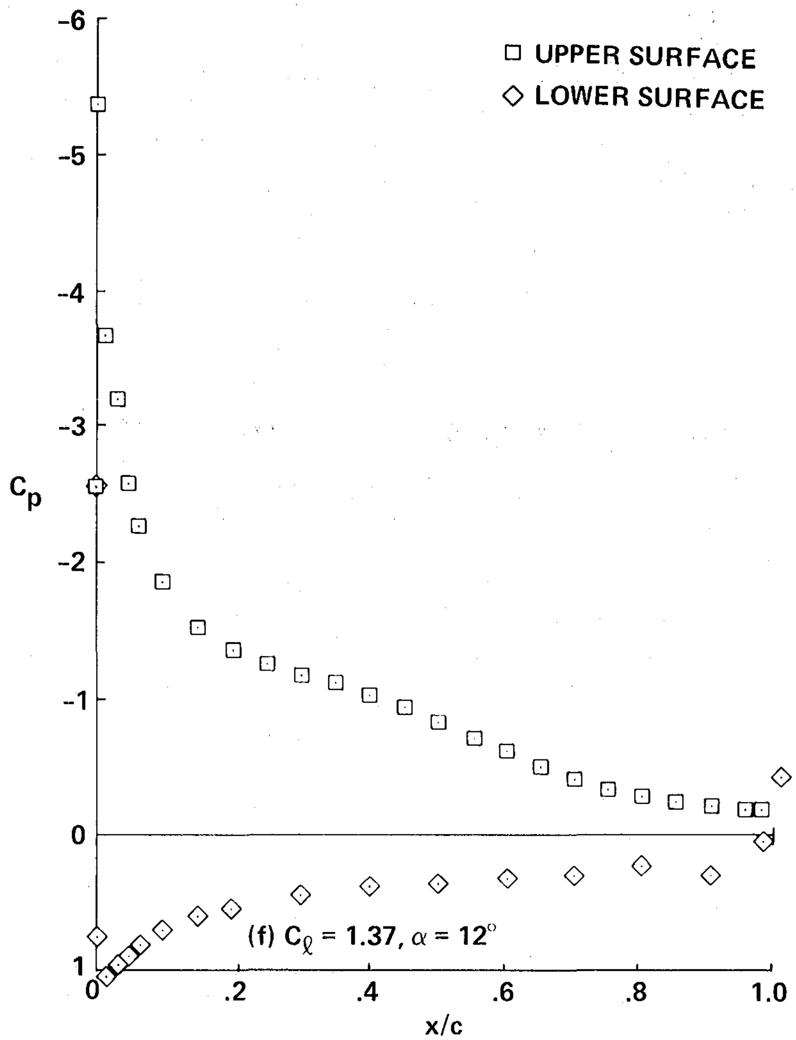

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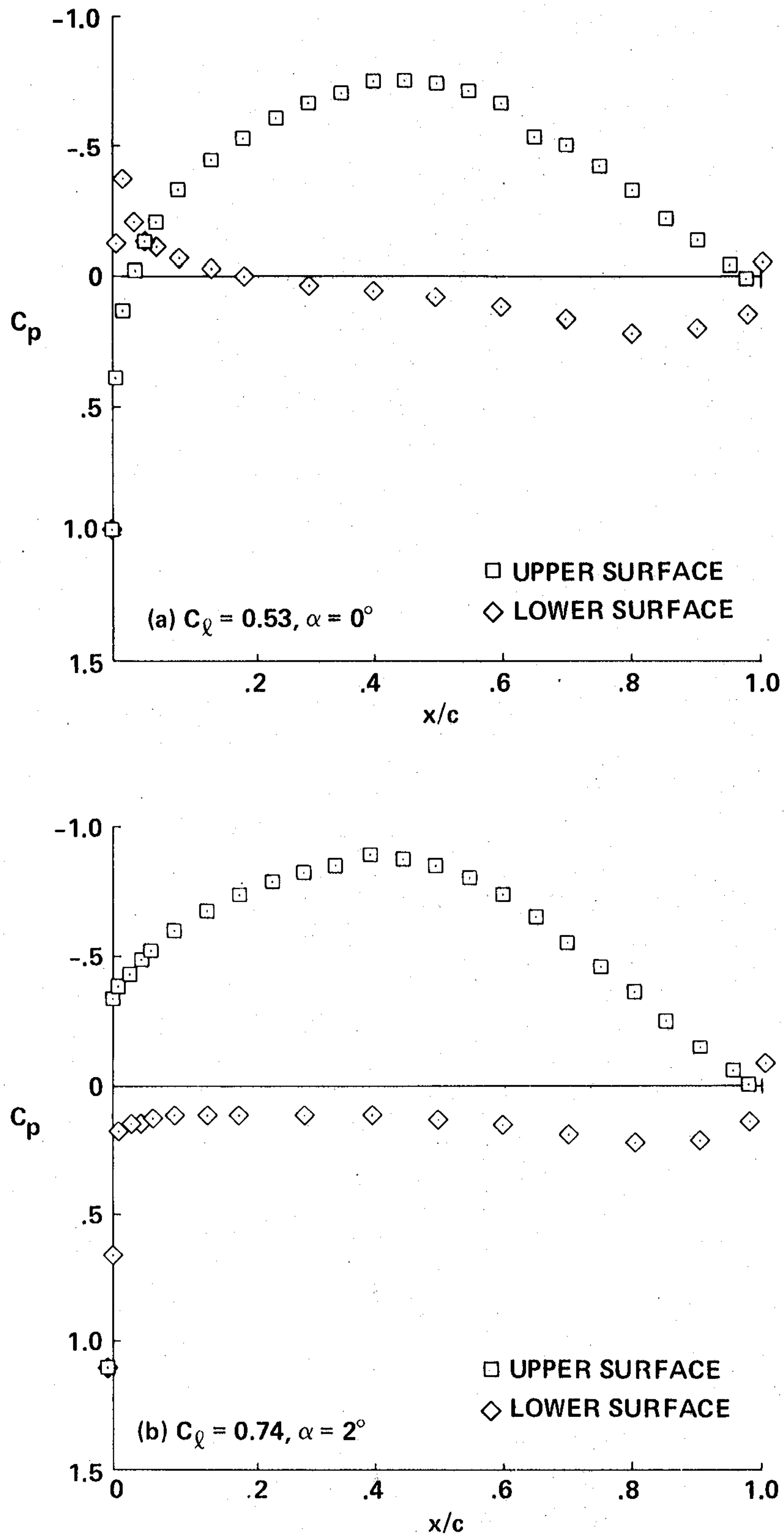
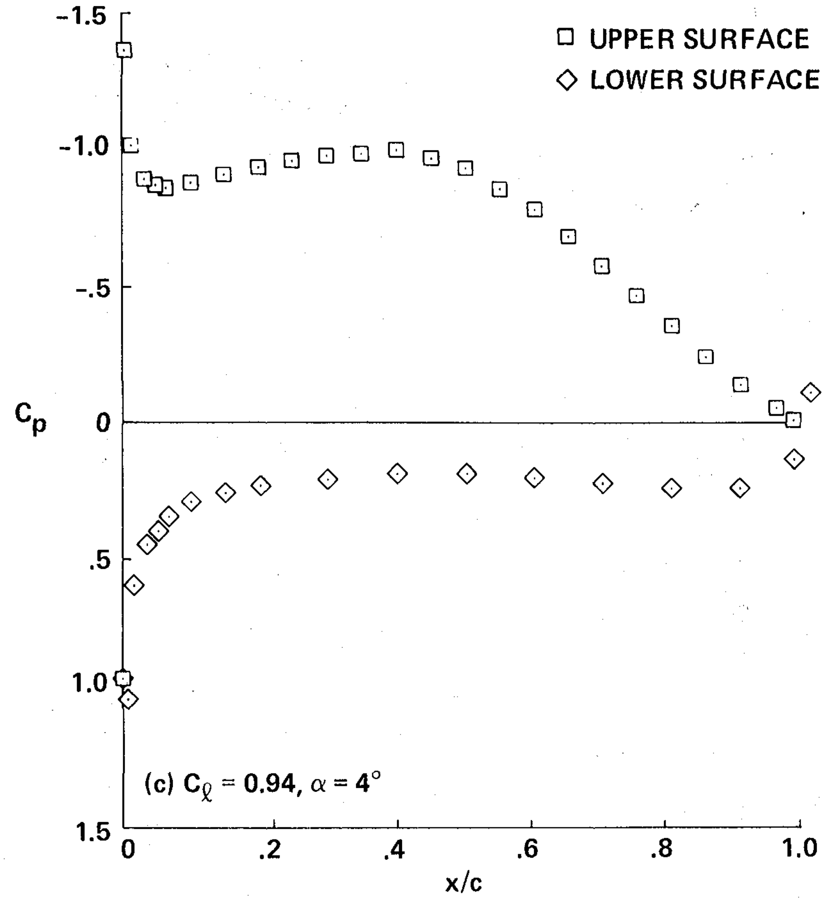


Figure 9.- Pressure distributions for the original airfoil; M = 0.40; Re = 4.3×10^6.



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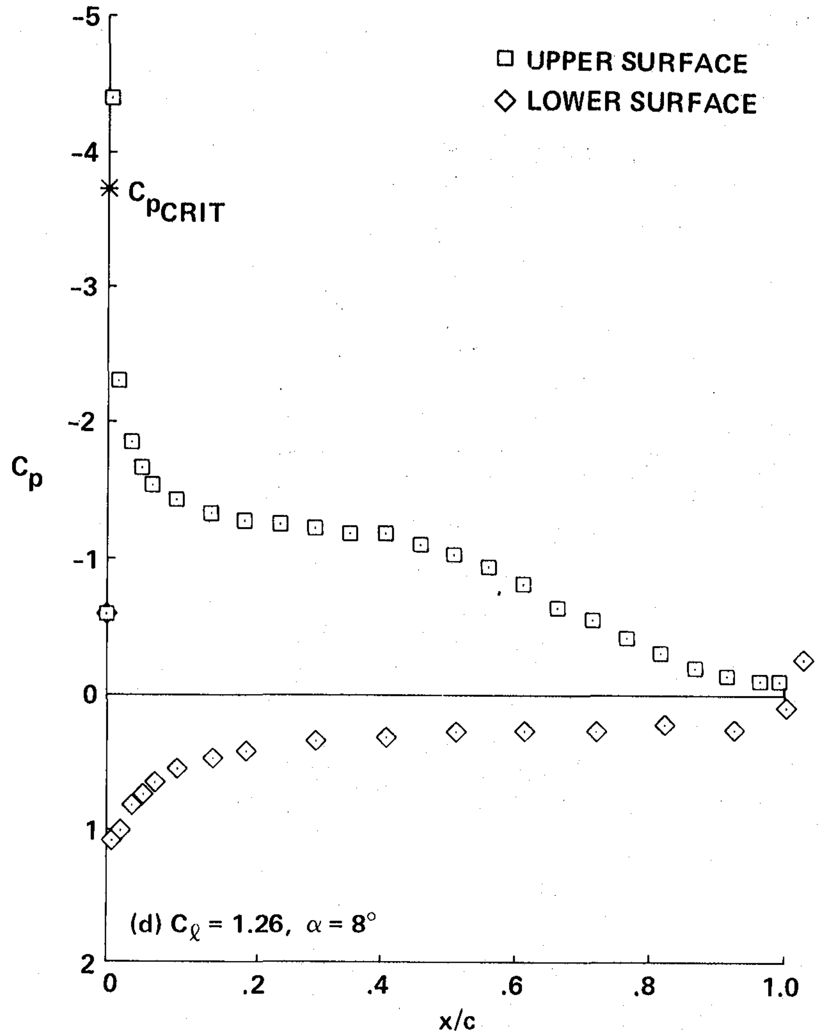

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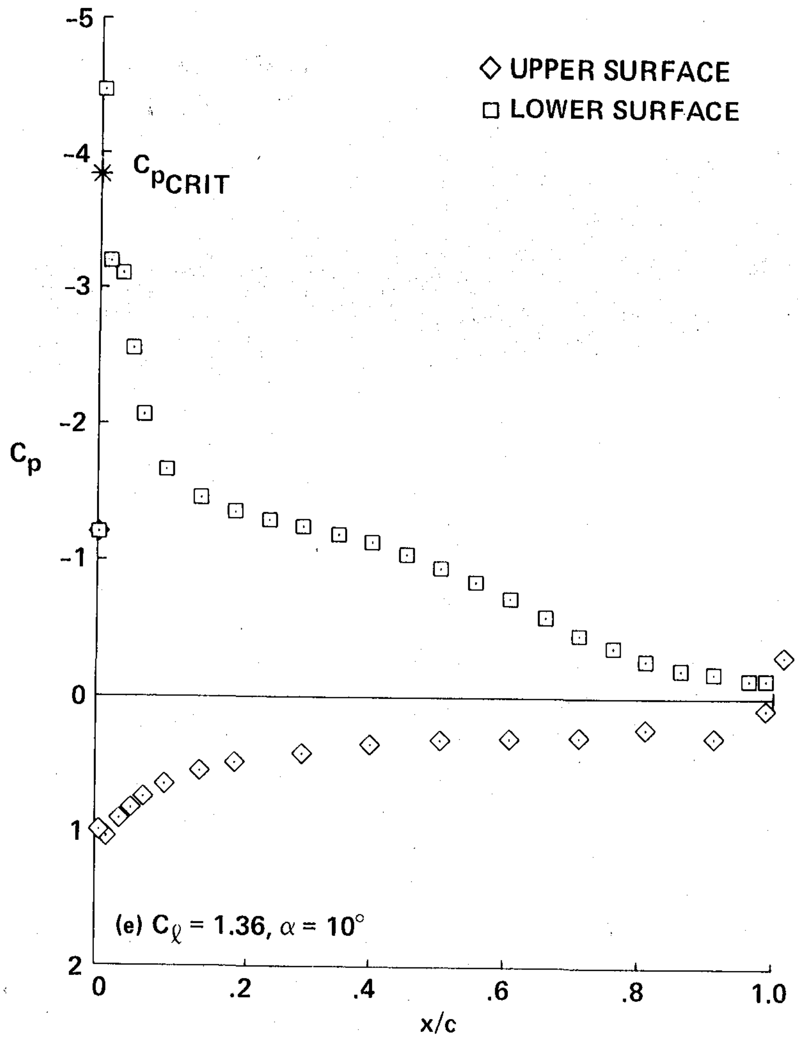

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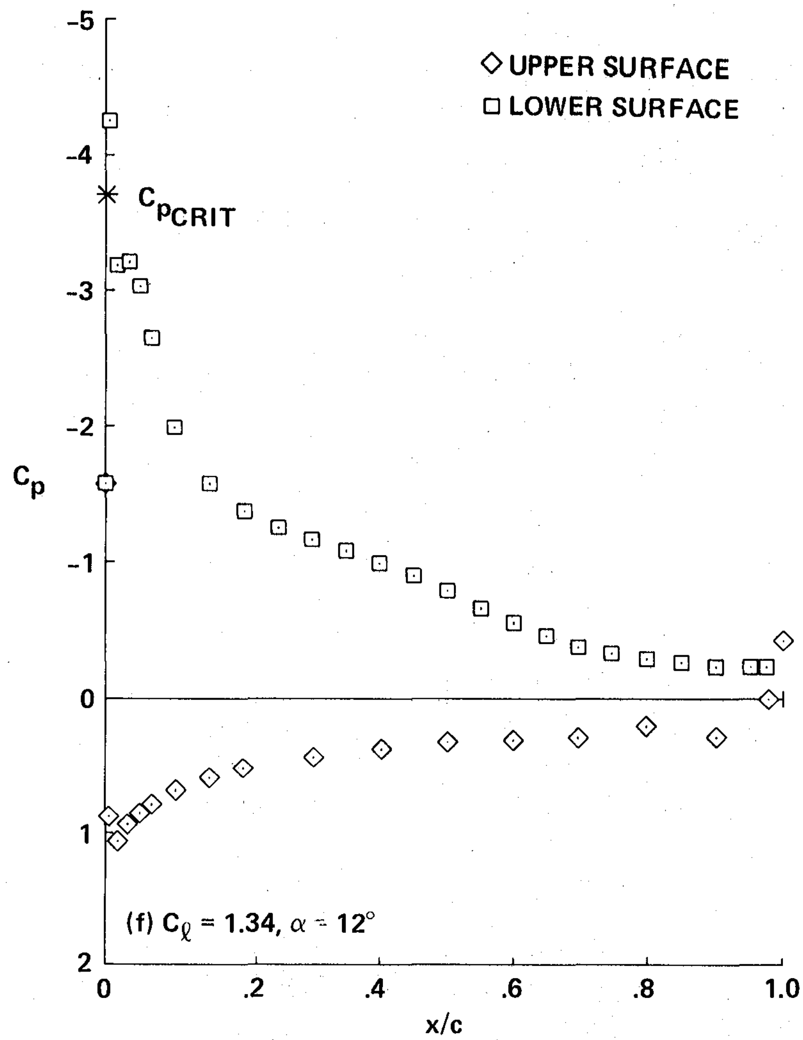

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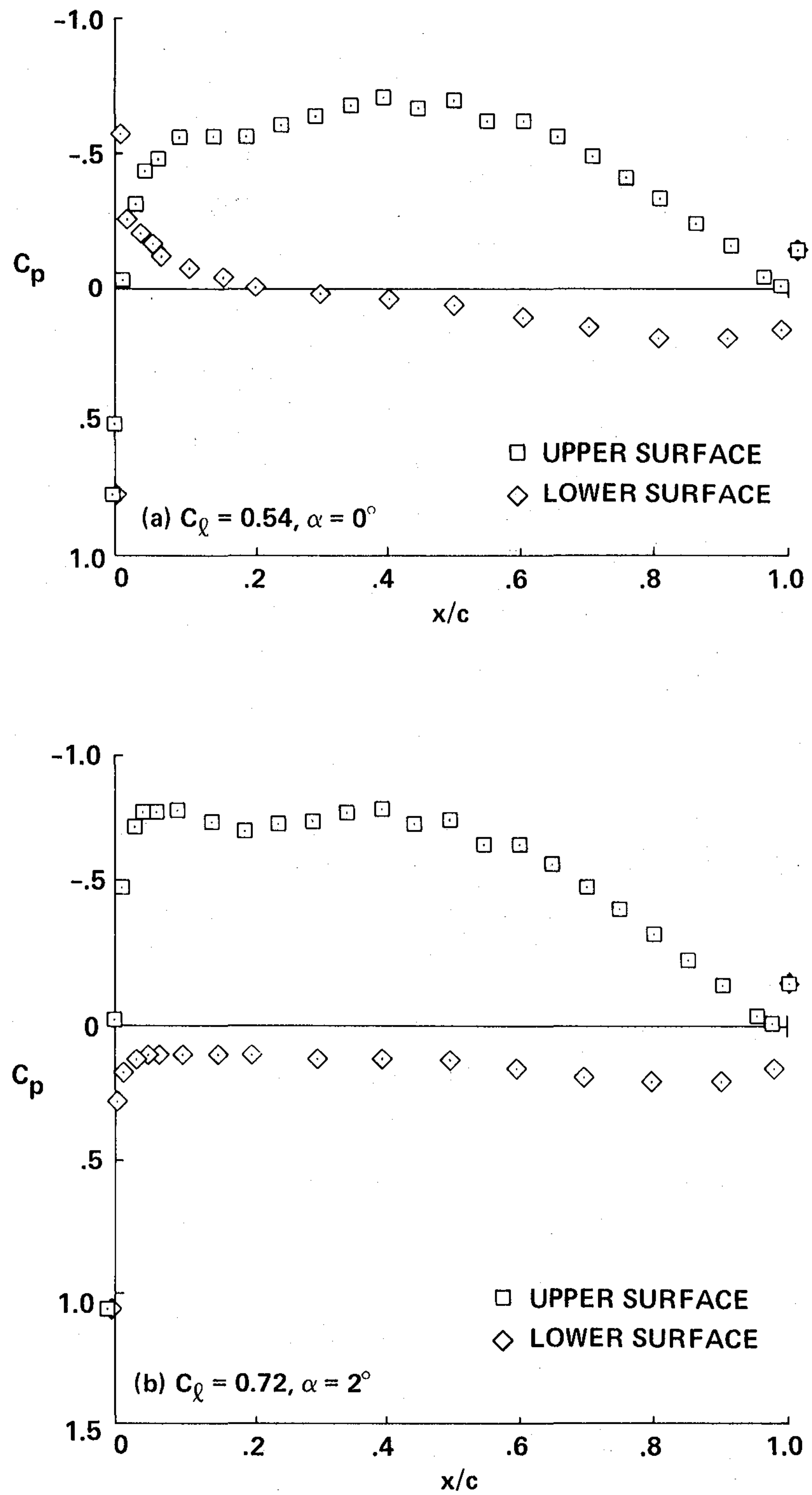


Figure 10.- Pressure distributions for the recontoured airfoil; $M = 0.30$, $Re = 4.2 \times 10^6$.

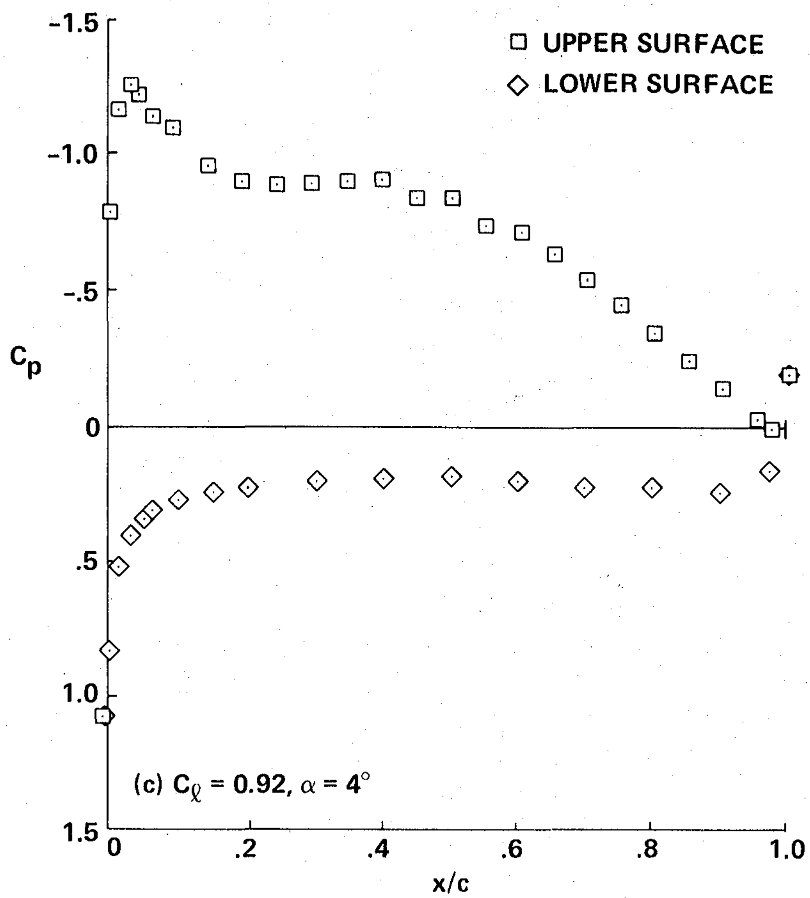
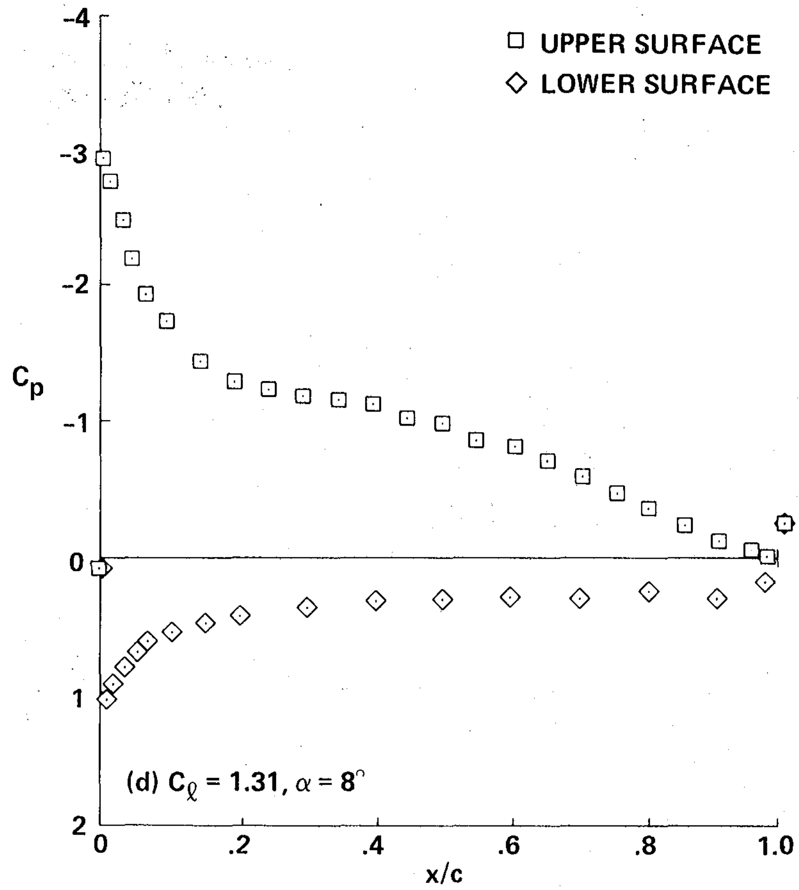


Figure 10.- Continued.



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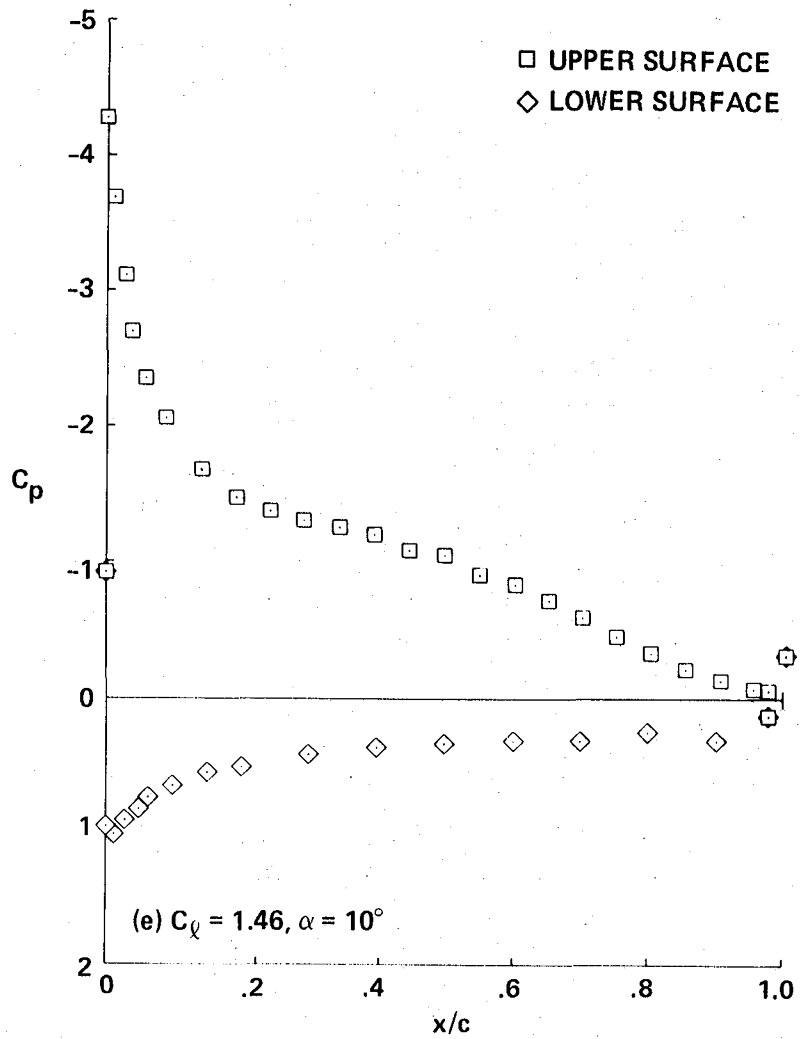

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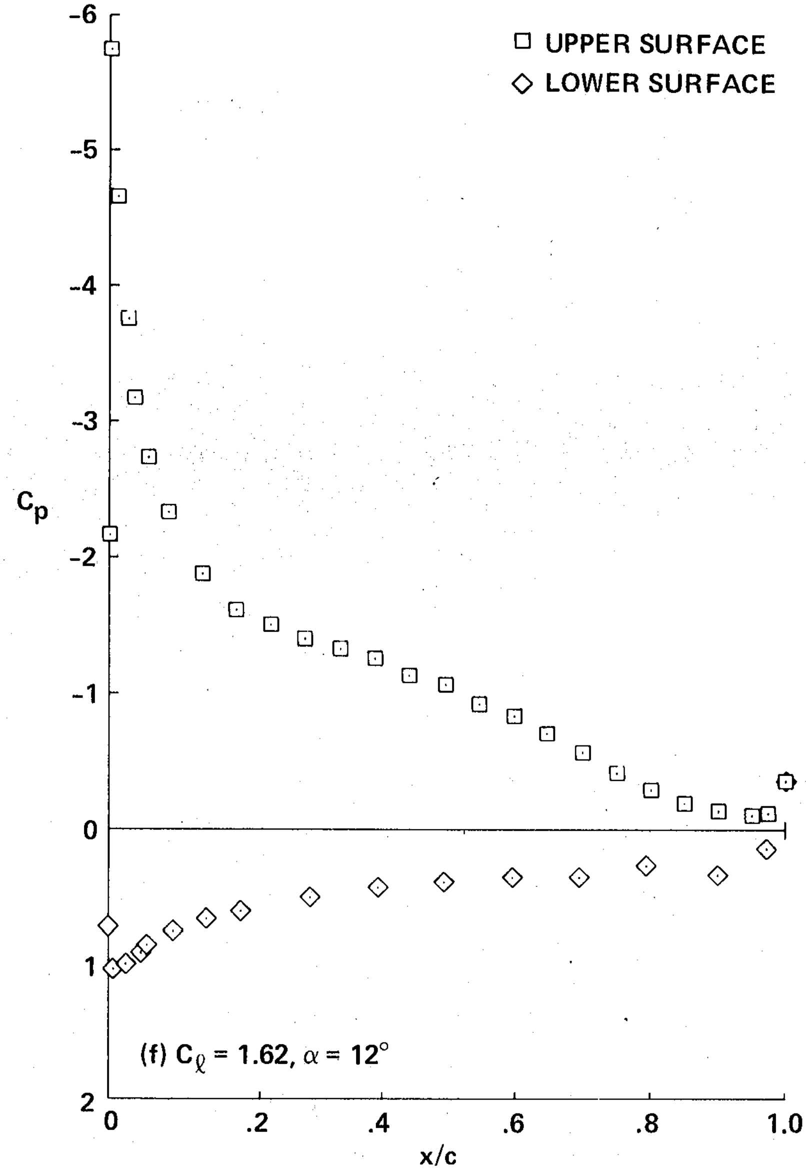

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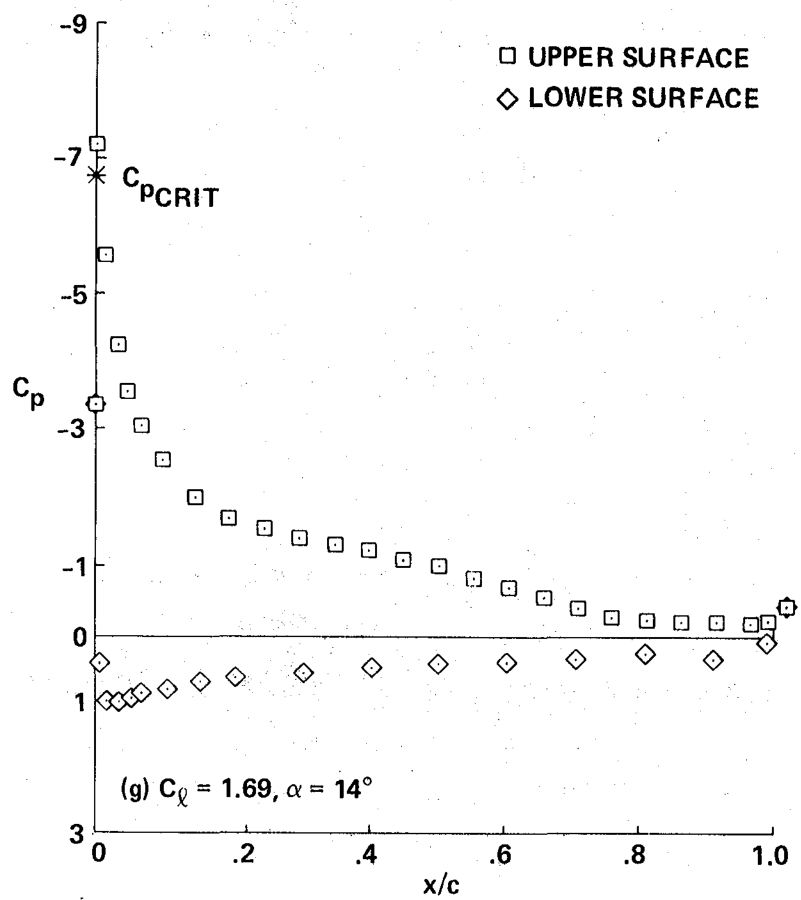

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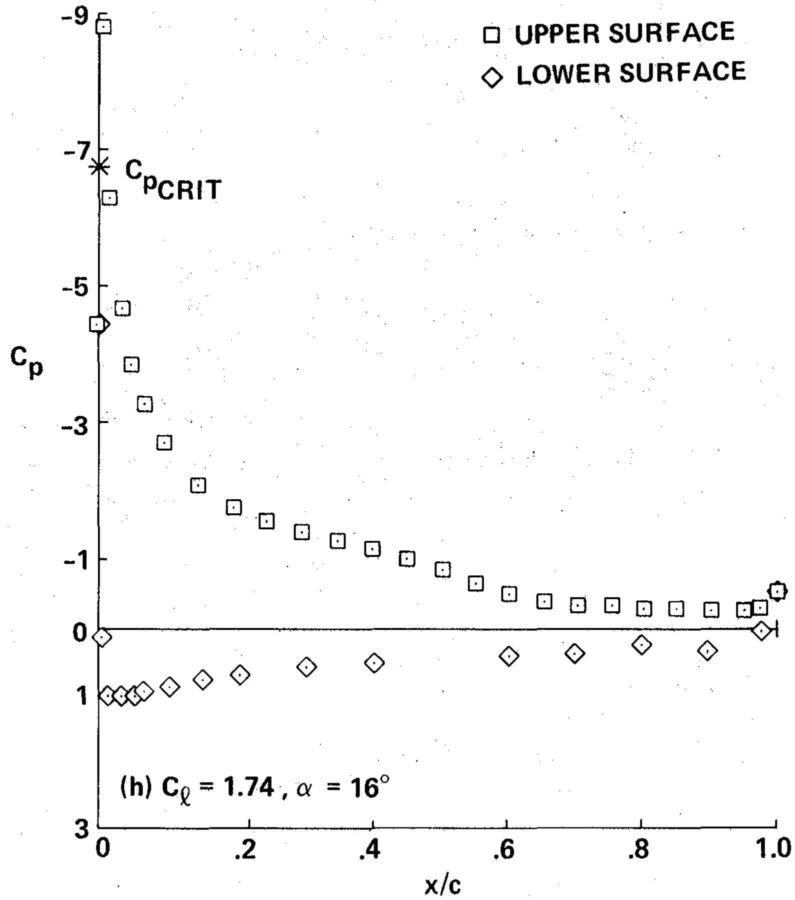

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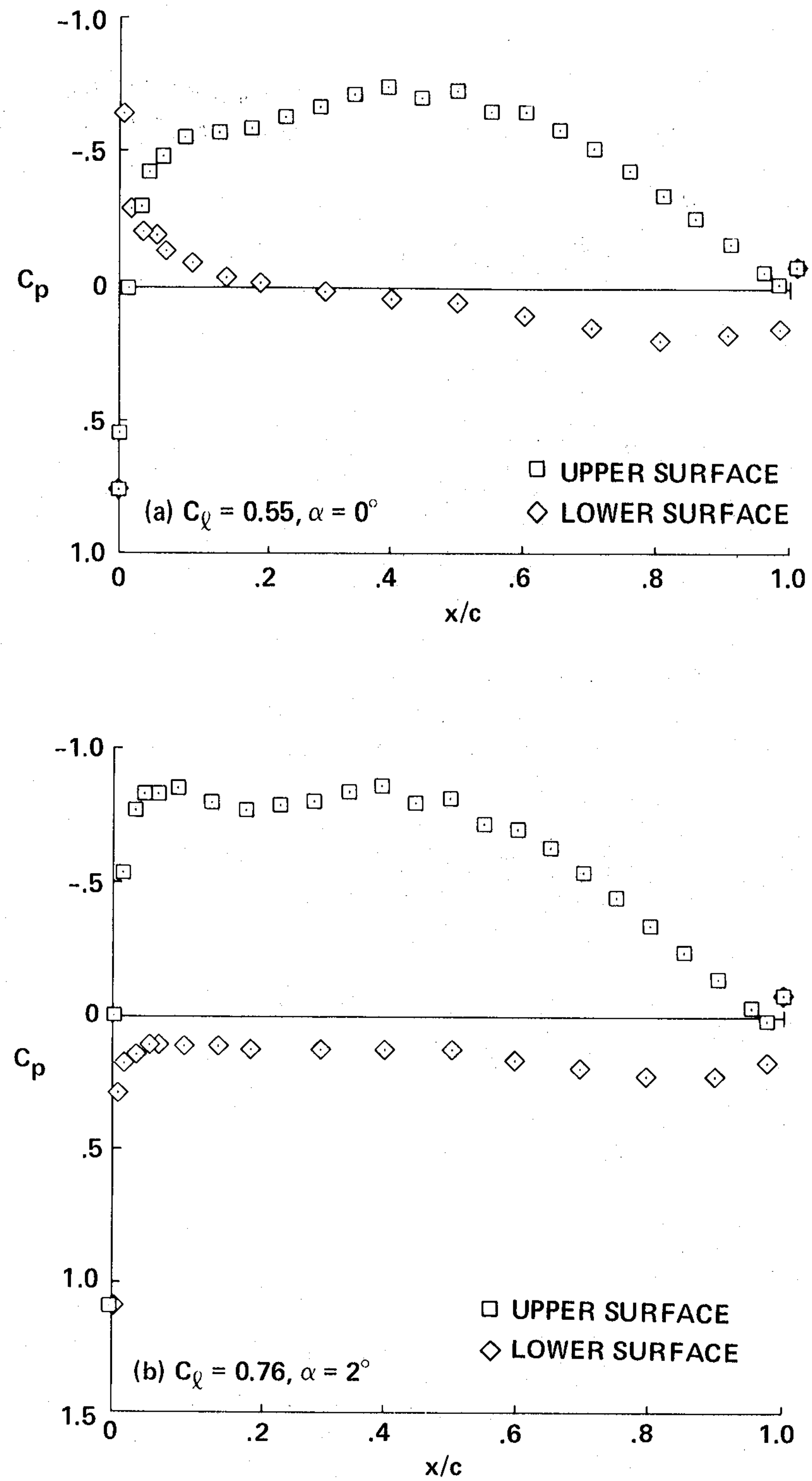


Figure 11.- Pressure distributions for the recontoured airfoil, M = 0.40, Re = 4.3×10^6.

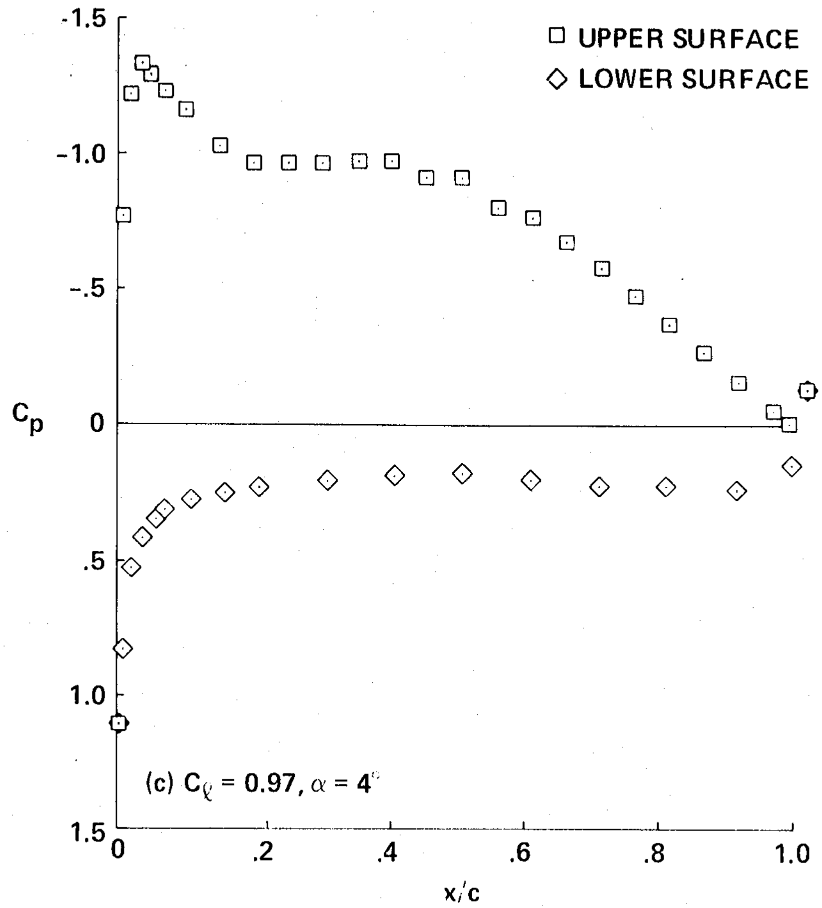
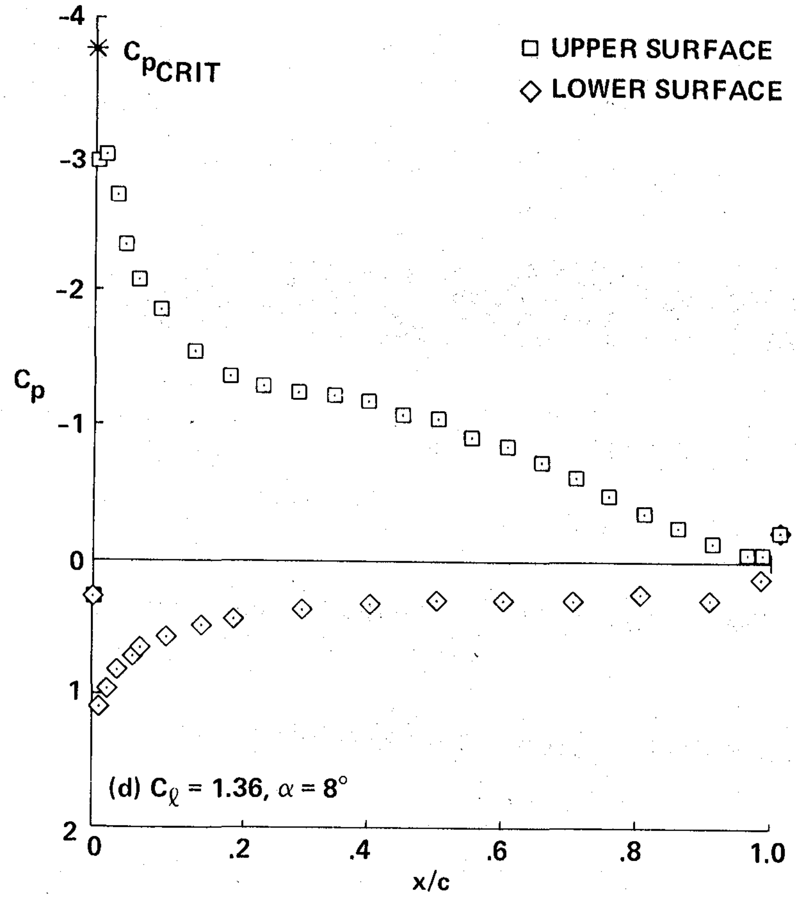


Figure 11.- Continued.



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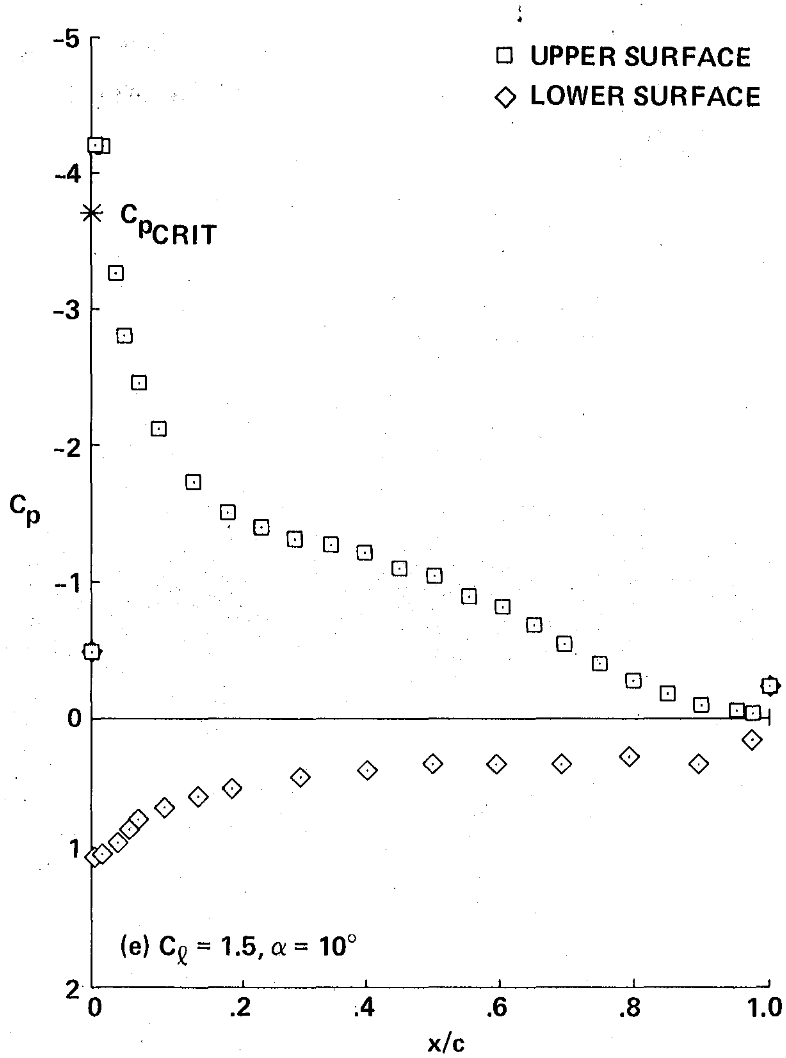

Figure 11.- Continued.

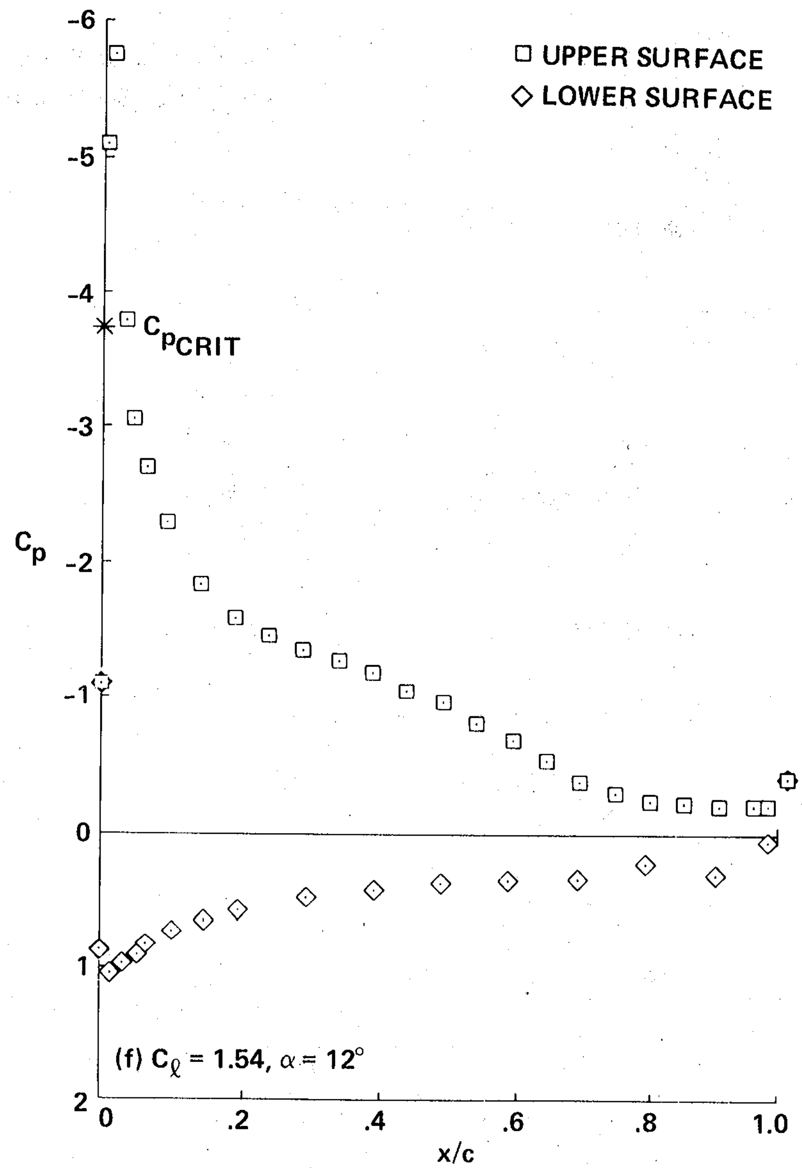

Figure 11.- Continued.

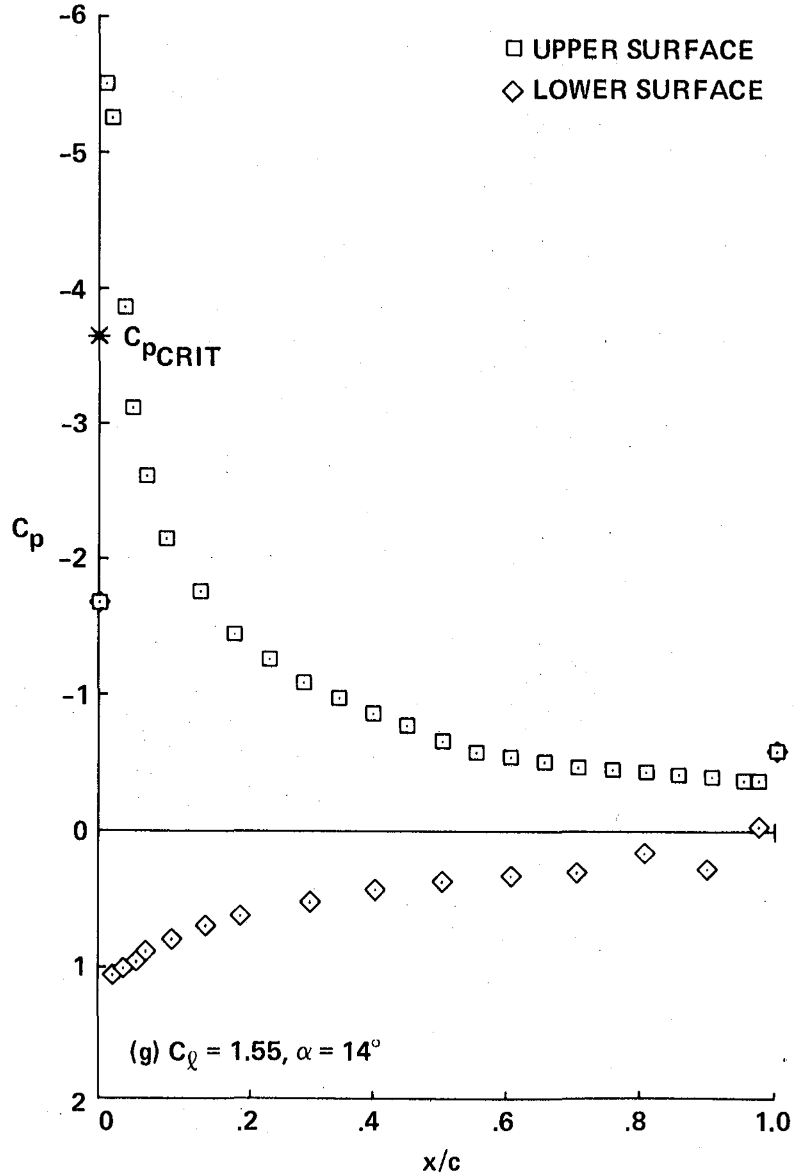

Figure 11.- Continued.

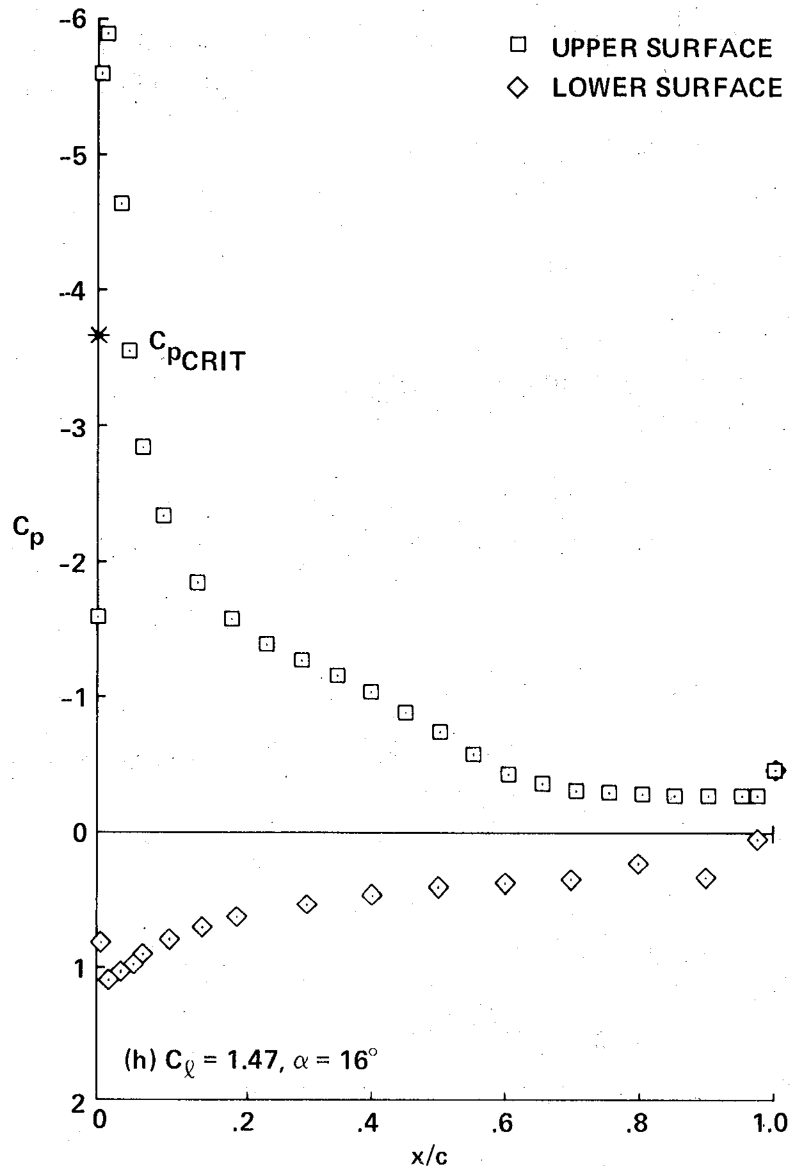

Figure 11.- Concluded.

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16. Abstract

A recontoured upper surface was designed to increase the maximum lift coefficient of a modified NACA 65 (0.82)(9.9) airfoil section which was tested at Mach numbers of 0.3 and 0.4 and Reynolds numbers of 2.3×10^6 and 4.3×10^6. The original 6-series section was tested for comparison with the recontoured section.

The recontoured profile was found to have a higher maximum lift coefficient at all test conditions than the original airfoil. The recontoured airfoil showed less drag and nearly the same pitching moment characteristics as the original 6-series airfoil at all test conditions.

The improvements found for the recontoured airfoil of the present study are similar to those found during previous investigations of recontoured 6-series airfoils with less camber.

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