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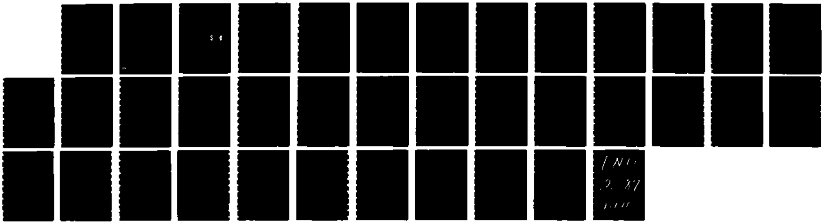

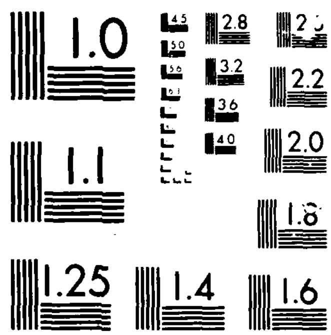
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FURTHER STUDIES ON THE 21% THICK, SUPERCRITICAL NLF AIRFOIL NAE 68-060-21:1

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by

M. Khalid , D.J. Jones
National Aeronautical Establishment

AERONAUTICAL NOTE
NAE-AN-41
NRC NO. 26453

OTTAWA
SEPTEMBER 1986

National Research Council Canada
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FURTHER STUDIES ON THE 21% THICK, SUPERCRITICAL NLF AIRFOIL NAE 68-060-21:1

ÉTUDES SUPPLÉMENTAIRES DU PROFIL NLF SUPERCRITIQUE NAE 68-060-21:1 À ÉPAISSEUR DE 21%

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AERONAUTICAL NOTE
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Laboratoire d'aérodynamique à hautes vitesses

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Acting Director/
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Summary

Further wind tunnel tests have been carried out on the NAE 10" chord supercritical NLF airfoil NAE 68-060-21:1. This airfoil in previous tests showed very low drag levels when free transition was allowed on the model. In the main part of the current investigation, performed at chord Reynolds number of about 7,9 and 13 million, transition was fixed at 7% and 15% on upper and lower surfaces respectively. It is observed that there is a substantial loss of lift under these conditions which appears to be associated with boundary layer thickening on the lower surface causing decambering near the trailing edge.

Also additional tests were carried out under free transition at other Reynolds numbers than those previously used. The same drag bucket behaviour near the design flow conditions was observed.

Résumé

Des essais supplémentaires en soufferie ont été menés avec le profil NFL supercritique NAE 68-060-21:1 à corde de 10 po. Dans les essais antérieurs, ce profil présentait de très faibles traînées quand on réalisait sur la maquette les conditions de transition libre. Dans les travaux principaux de l'étude en cours, effectués avec un nombre de Reynolds à la corde d'environ 7,9 et 13 millions, la transition a été fixée à 7% et 15% respectivement pour l'extrados et l'intrados. On a constaté qu'il se produit une perte substantielle de portance dans ces conditions, qui semble associée à un épaississement de la couche limite sur l'intrados provoquant un décollement près du bord de fuite.

D'autres essais ont été menés en transition libre avec des nombres de Reynolds différents. Le même phénomène de chute de la traînée au voisinage des conditions théoriques d'écoulement a été observé.

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Symbols

Symbol	Definition
c	chord length
C_{D_W}	wake drag
C_L	lift coefficient
C_M	pitching moment about quarter chord, negative nose down
C_p	pressure coefficient
H	shape parameter
M_∞	Mach number (wind tunnel free stream corrected for wall interference)
R_c	Reynolds number based on chord length (10 in. for NAE 68-060-21:1)
t/c	maximum thickness to chord ratio
x/c	relative distance along airfoil chord
α	angle of attack (corrected for wall interference)
δ^*	boundary layer displacement thickness

Subscripts

∞	free stream
p	integrated from airfoil pressures

1.0 Introduction

In the continuing investigation of the NLF airfoils designed and tested jointly by NAE and de Havilland* we present here further studies on the 21% airfoil NAE 68-060-21:1. A previous report [1] has dealt with the case of free transition on this airfoil. It was shown that the airfoil behaved extremely well under this condition and yielded drag levels far below any previously tested airfoil at NAE. In fact the drag levels at supercritical Mach numbers are comparable with drag at low Mach numbers for the NACA 63, 64 and 65 series airfoils (about 50 counts) as shown in Ref. 2. This low drag was accounted for by there being long runs of laminar flow on both upper and lower surfaces.

In a similar study on an NLF 16% airfoil (Ref. 2 and 3), it was shown that this airfoil also displayed excellent drag characteristics. In Ref. 3 a study was made of the effect of fixing transition on the 16% airfoil. This study indicated that $C_L - \alpha$ changed significantly at the lowest Reynolds number tested, $R_c = 8 \times 10^6$, i.e. ΔC_L of about 0.1, with fixed transition giving lower lift. However at the higher chord Reynolds numbers of 14 and 20×10^6 the differences in $C_L - \alpha$ were very small.

In the present study we also find a significant loss of lift due to transition fixing at all Reynolds numbers ranging from 0.2 at 6.8×10^6 to 0.1 at 12.8×10^6. This loss is also indicated theoretically using the BGK [4] code. It seems to be accounted for by the thicker boundary layer in the fixed transition case. This is

*with support from NRC PILP project CA155-1-0655/252 particularly noticeable on the lower surface where the cove region is filled in by the boundary layer thus decambering the trailing edge region and so reducing overall lift.

This report, in addition to investigating fixed transition, also presents further results with free transition at $R_c = 9.2$ and 20.1×10^6. This data supplements earlier data at $R_c = 6.8, 12.8$ and 16.7×10^6. A later section looks at the effect of the pressure holes in causing turbulence and in changing boundary layer characteristics.

2.0 Investigation of Transition Strip Height

Before analysing the fixed transition results we wanted to be sure that the NAE method of transition strip application was not adversely affecting performance due, for instance, to too high a step at the transition location. In order to investigate this we compared the NAE method of application with another method, normally used by de Havilland, and measured the height of the grit roughness. This was done on a flat metal plate to simulate airfoil applications in the wind tunnel.

In the first (NAE) method the strip area (2 mm wide) is sprayed with lacquer from a distance of about two feet. The 320 grit carborundum powder is then blown over the strip area from a sheet of paper to give a coverage of about 10%. In the second method the strip surface is wetted with a single stroke of a clean brush dipped in a mixture of 1/3 lacquer, 1/3 thinner and 1/3 retarder. The carborundum granules are then deposited in the same way as in the first method.

The height of each strip was then measured by running the spherical indicator of a surface gauge with a sensitivity of 0.0005 in., along the lengths of the strips. The strip from the NAE method was from 0 to 0.0005 in thickness compared to 0.001 to 0.0015 for the second (brushing) method. Thus it seems that the NAE method of transition fixing is quite acceptable. It is also well in line with established practice, see Ref. 5.

The transition strips were applied at 7% chord on the upper surface and at 15% chord on the lower surface using 320 carborundum grit.

3.0 Discussion of Results

3.1 $C_L - \alpha$ and $C_M - \alpha$

In Figs. 1a and 1b we show typical $C_L - \alpha$ and $C_M - \alpha$ curves for $R_c = 6.75\times10^6$ and $M_\infty = 0.68$, 0.70 and 0.6. The difference in lift and pitching moment between free and fixed transition is seen to be quite substantial. For instance the lift difference is about 0.2, for $M_\infty = 0.68$ and 0.70 over most of the α range with $\frac{\partial C_L}{\partial \alpha}$ remaining fairly constant in both cases at about 0.17. Also the pitching moment magnitude is much reduced when the transition strip is applied. This loss of lift is similar to the 0.1 loss in lift on a 16% t/c NLF airfoil at $R_c = 8\times10^6$ [3]. However at $R_c = 14\times10^6$ there was no significant loss in lift for the 16% foil.

The explanation seems to be that the growth of the tripped turbulent boundary layer in the adverse pressure gradient region aft of

50% chord has the effect of decambering the airfoil. This effect is reflected in the pressure distributions presented in Figs. 2a and 2b. Note in particular the smaller pressure gradient aft of 60% chord on the lower surface for the 'tripped' case compared to the 'free' case. In the free transition case the flow on the lower surface is probably laminar up to 40% chord and the turbulent boundary layer will be much thinner and so decamber the airfoil to a lesser degree. Looking at Fig. 3 we can see that 60% chord on the lower surface is just after a cove region has been entered; it is here where the large thickening of the boundary layer occurs.

This large difference in C_L - α is also noticed theoretically. Calculations using the BGK code [4] with Green's lag entrainment boundary layer method indicates a loss of lift of about 0.3 (Fig. 4a) which is somewhat bigger than the experimental difference. Transition in the 'free' case occurred at the pressure minima. Figure 4a also shows the shape parameter H in the 'fixed' case which is used to indicate separation and H = 2.5 is usually taken as the cut off point for separated flow. It can be seen that H on the lower surface increases rapidly at about 60% chord rising to a value of about 2.3 at which value it stays fairly constant to 90% chord. This region of high H is also the region where the boundary layer growth is most pronounced, thus inducing a decambering effect on the airfoil. This in turn reduces the overall lift as well as the pitching moment. On Fig. 4b we show the displacement thickness δ^* versus distance along the foil. It can be seen that the decambering effect will be much larger in the fixed transition case than for free transition. This seems to be the key factor in accounting for the loss of lift.

3.2 Reynolds Number Effect on C_L -α

It can be seen from Fig. 5a that the Reynolds number effect on C_L - α is very small in the free transition case indicating that the boundary layer growth is not significantly different at the various Reynolds numbers (except, unexplainably, at $R_c = 16.7\times10^6$). On the other hand, with fixed transition, Fig. 5b shows a substantial difference in lift at constant α, with an increase of about 0.05 as the chord Reynolds number increases from 6.8 to 9.2 million and from 9.2 to 12.8 million. This behaviour indicates that the boundary layer is getting thicker as expected with decreasing Reynolds number. Pressure plots (Fig. 6) substantiate this as the pressure gradients are smaller aft of 60% on the lower surface for the lower Reynolds number.

The same behaviour of increased lift with higher Reynolds number is observed theoretically. Figure 7 shows the difference in pressure distribution and the corresponding difference in lift. This amounts to about 0.07 which is very close to the experimental difference.

In the free transition theoretical case, to compare to the experiment of Fig. 5a, we were unable to produce the same difference in lift (about zero except for $R_c = 16.7\times10^6$) for various Reynolds numbers. In fact theoretically the lift increased from 0.74 to 0.80 for $M_\infty = 0.68$ and R_c = 6.8 and 12.8×10^6 respectively with $\alpha = 0°$.

3.3 Pressure Distribution at Different Spanwise Locations

Note that the free transition pressure distributions shown in the previous figures do not seem to be affected by the turbulence [illegible] of the pressure holes themselves in that the [illegible] shows for instance much larger aft lift than in the transition fixed case. Although the line of pressure holes creates a turbulent strip within an otherwise predominantly laminar flow, its effect on the boundary layer behaviour must be negligible. In order to observe differences in pressures, if any, in the turbulent strip caused by the pressure holes (at y = -1.75 inches, see Fig. 8) and pressures elsewhere on the body, an extra set of upper and lower surface tappings were placed at spanwise location y = +1.75 inches. This second set was placed aft of 60% chord and thus was preceded by almost completely laminar flow. Hence we expected to see some differences in pressure readings. Our observations however were inconclusive. For instance Fig. 9a ($M_\infty = 0.68$, $R_c = 12.6 \times 10^6$, $C_{L_p} = 0.599$) shows a trend of the sort of behaviour we had expected with more aft end lift indicated for the section preceded by laminar flow. However Fig. 9b ($M_\infty = 0.68$, $R_c = 9.3 \times 10^6$, $C_{L_p} = 0.603$) shows almost perfect agreement especially on the lower surface while Fig. 9c ($M_\infty = 0.68$, $R_c = 6.8 \times 10$, $C_{L_p} = 0.590$) shows less aft lift.

As can be seen these pressure differences at the two spanwise locations are quite small and indicate to the authors that the full line of pressure tappings gives a good representation of pressures in the laminar part of the flow. This would explain the good matching of pressure integrated lift to balance lift. Note however that although the pressure distribution and hence local lift are not affected by the pressure holes the drag measured directly behind a line of pressure holes is distinctly higher than drag measurements taken behind a clean part of the airfoil (see Ref. 1).

This small effect on the local boundary layer growth by the tappings must be due to 'side relief' from the laminar regions on each side of the turbulent strip in contrast to the 'tripped' case where there is no 'side relief'.

3.4 Effect of Transition on Drag

As expected, the drag levels for the same lift are much higher with fixed transition than with free transition. As shown in Fig. 10 the typical increase is about 80 drag counts.

We show on Figs. 11a and 11b the drag levels for a large range of Reynolds numbers. These include new data from recent tests (April 86) for R_c = 9.2 and 20.1 million with free transition which supplement the earlier data mentioned in Ref. 1.

Figure 12 shows the present transition free and transition fixed data for $C_L = 0.6$ plotted as C_{D_W} versus t/c. Also shown are the data for a number of other airfoils tested in the NAE 2D facility. The integers adjacent to symbols for the accessory data correspond to Mach numbers. The transition fixed data appears consistent with other airfoil data giving drag values about 30 drag counts above Hoerner's low speed values [6].

4.0 Conclusions

It has been demonstrated that fixing transition at 7% and 15% chord on the upper and lower surfaces respectively has a significant detrimental effect on the performance of the NLF airfoil

NAE 68-060-21:1. Lift, pitching moment and drag are all significantly altered by this fixing of transition.

The drag level with fixed transition appears quite consistent with that of other (free transition) airfoils tested at NAE. With free transition on the 21% remarkably low drag values are obtained near the design conditions as already noted in previous work (Ref. 1).

5.0 References

1. Jones, D.J., Khalid, M. Analysis of Experimental Data for a 21% Thick Natural Laminar Flow Airfoil, NAE 68-060-21:1. National Research Council Report NAE-AN-34, Oct. 1985.

2. Eggleston, B., Jones, D.J., Poole, R.J.D., Khalid, M. Thick Supercritical Airfoils with Low Drag and NLF Capability. ICAS Proceedings, Sept. 1986 (to be published).

3. Eggleston, B. A Review of Tests of Thick Low Drag Supercritical Airfoil. de Havilland of Canada Report DHC-PILP-85-2. (Company Confidential).

4. Bauer, F., Garabedian, P. and Korn, D. Supercritical Wing Sections III. Lecture Notes in Economics and Mathematical Systems No. 150. Springer-Verlag 1977.

5. Braslow A.L. and Knox E.C. Simplified Method for Determination of Critical Height of Distributed Roughness Particles for Boundary Layer Transition at Mach Numbers from 0 to 5. NACA TN-4363, Sept. 1958.

6. Hoerner, S.F. Fluid Dynamic Drag. 1965.

SYM	RUN	M_∞	$R_c \times 10^{-6}$	TRANSITION
□	29754	0.681	6.73	FIXED
⬡	29785	0.681	6.75	FIXED*
▼	28391	0.680	6.75	FREE
⊙	29754	0.700	6.75	FIXED
△	28392	0.700	6.74	FREE

* TO CHECK REPEATABILITY WITH 29754

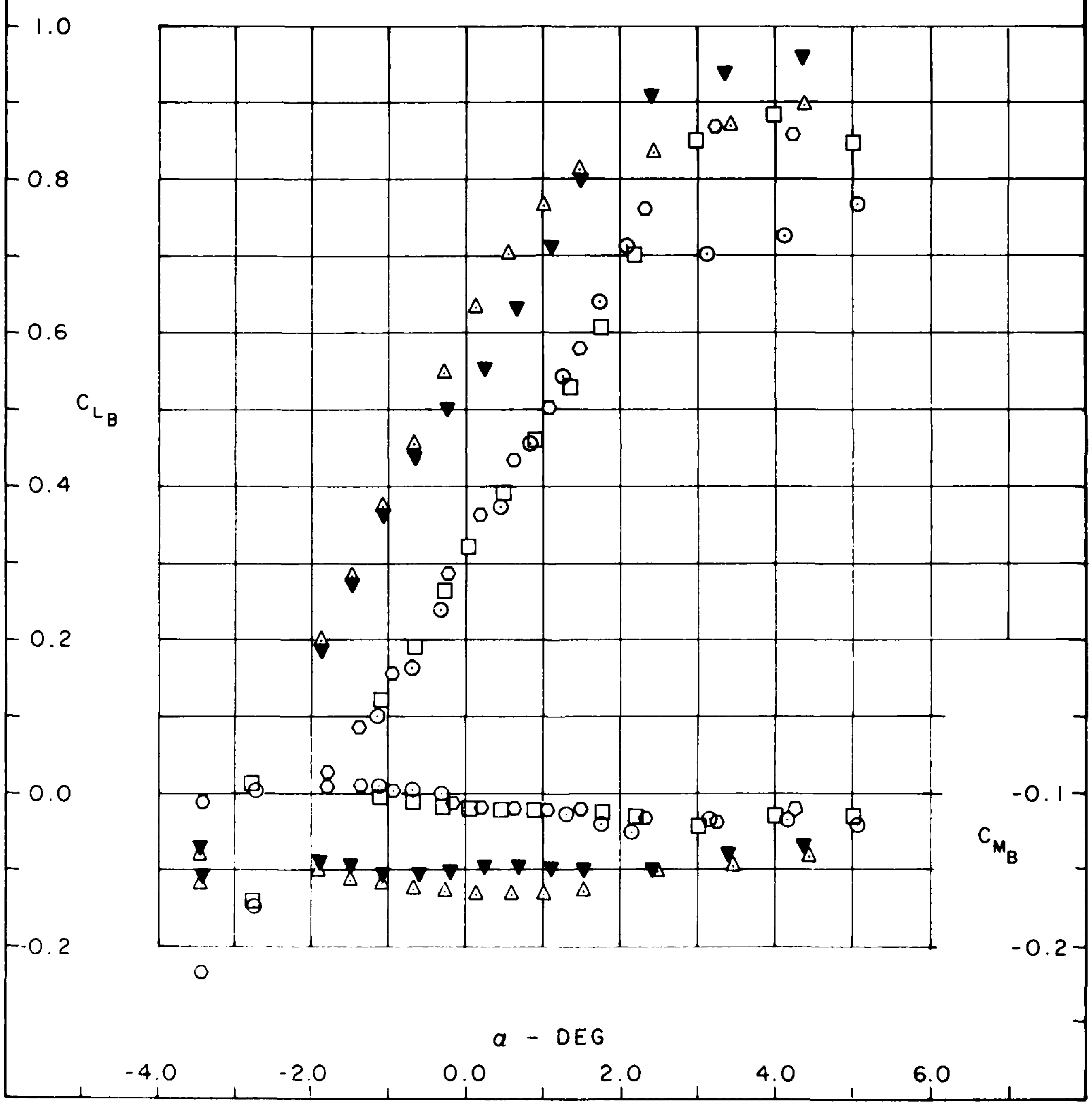

FIG. 1a: COMPARISON OF $C_L - \alpha$ AND $C_M - \alpha$ FOR FIXED AND FREE TRANSITION

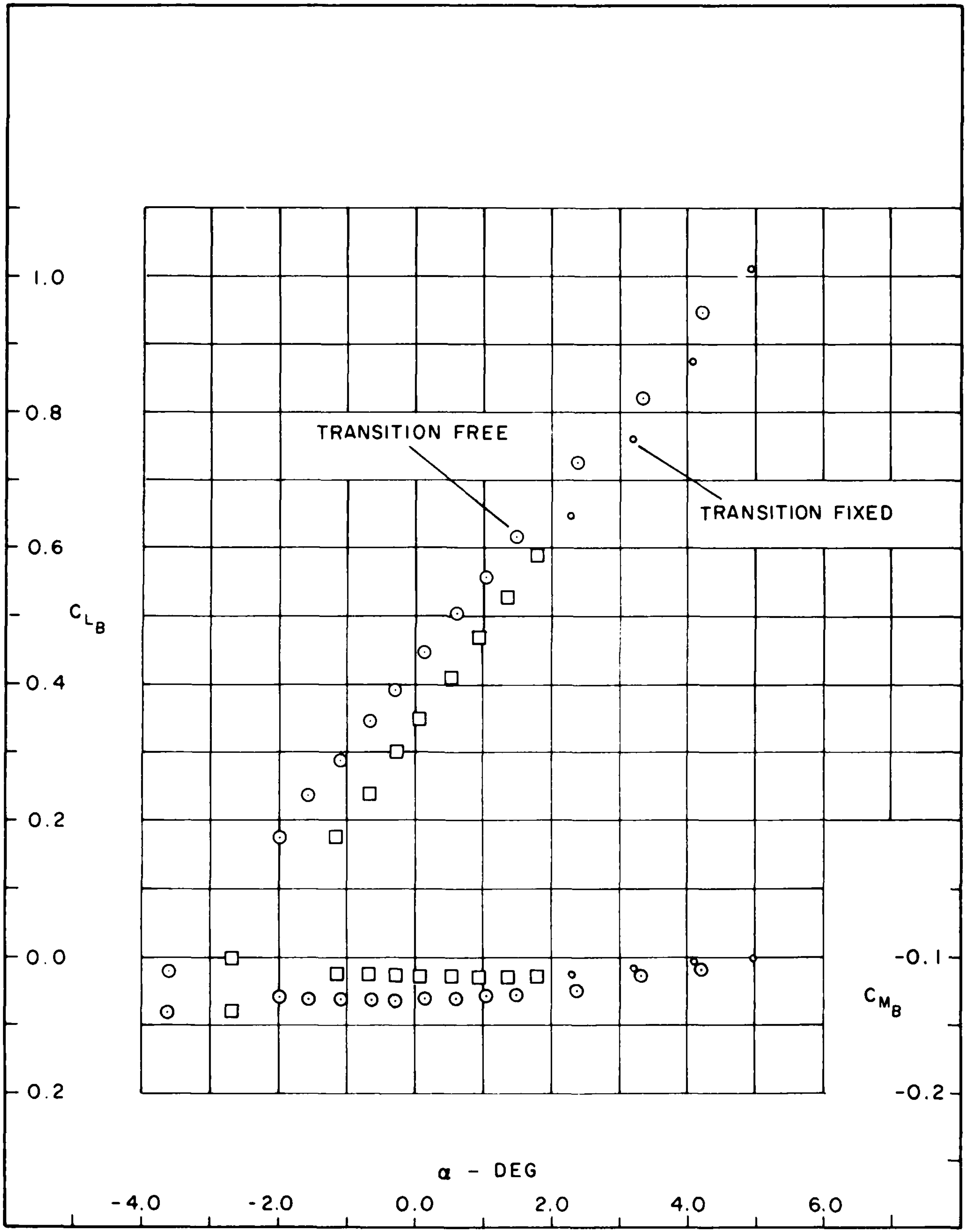

FIG. 1b: COMPARISON OF $C_L - \alpha$ AND $C_M - \alpha$ AT $M_\infty = 0.60$, $R_c = 6.75 \times 10^6$

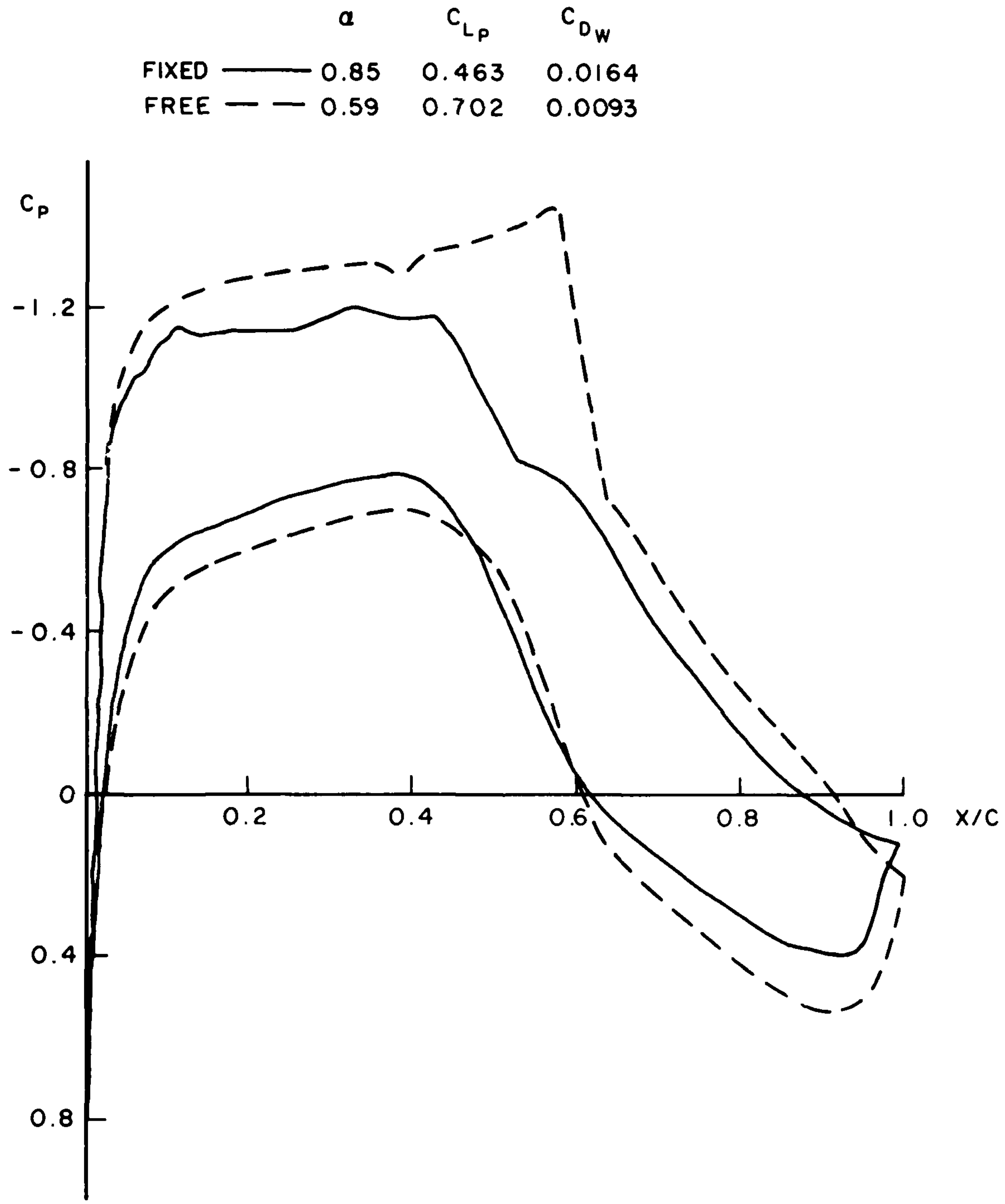

FIG. 2a: PRESSURE DISTRIBUTIONS FOR FREE AND FIXED TRANSITION AT $M_\infty = 0.7$, $R_c = 6.8 \times 10^6$

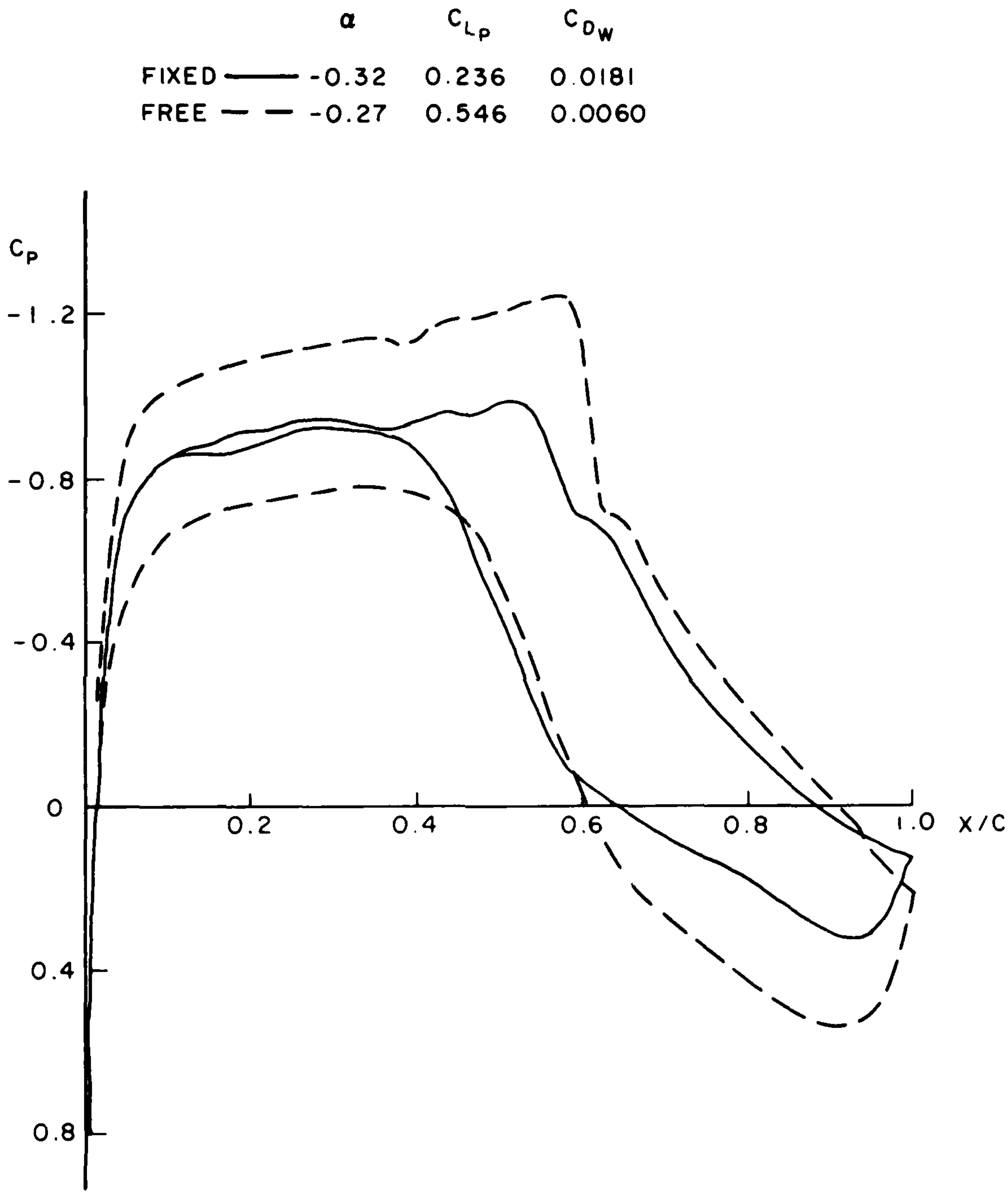

FIG. 2b: PRESSURE DISTRIBUTIONS FOR FREE AND FIXED TRANSITION AT $M_\infty = 0.7$, $R_c = 6.8 \times 10^6$

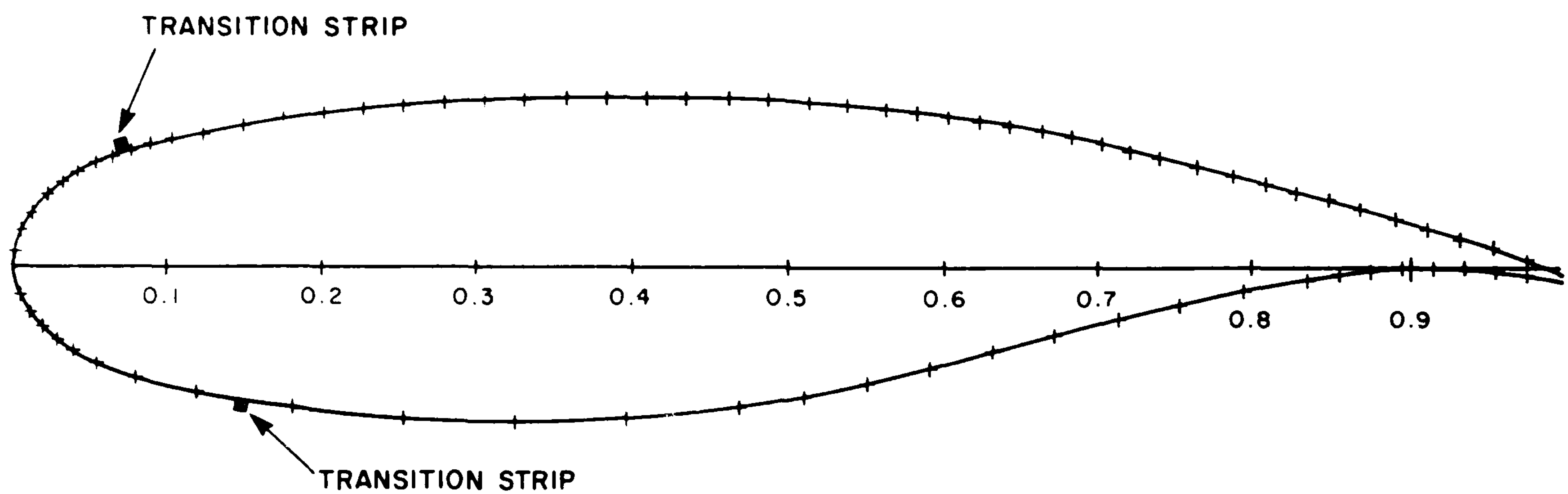

FIG. 3: A SKETCH OF THE 21% t/c AIRFOIL NAE 68-060-21:1

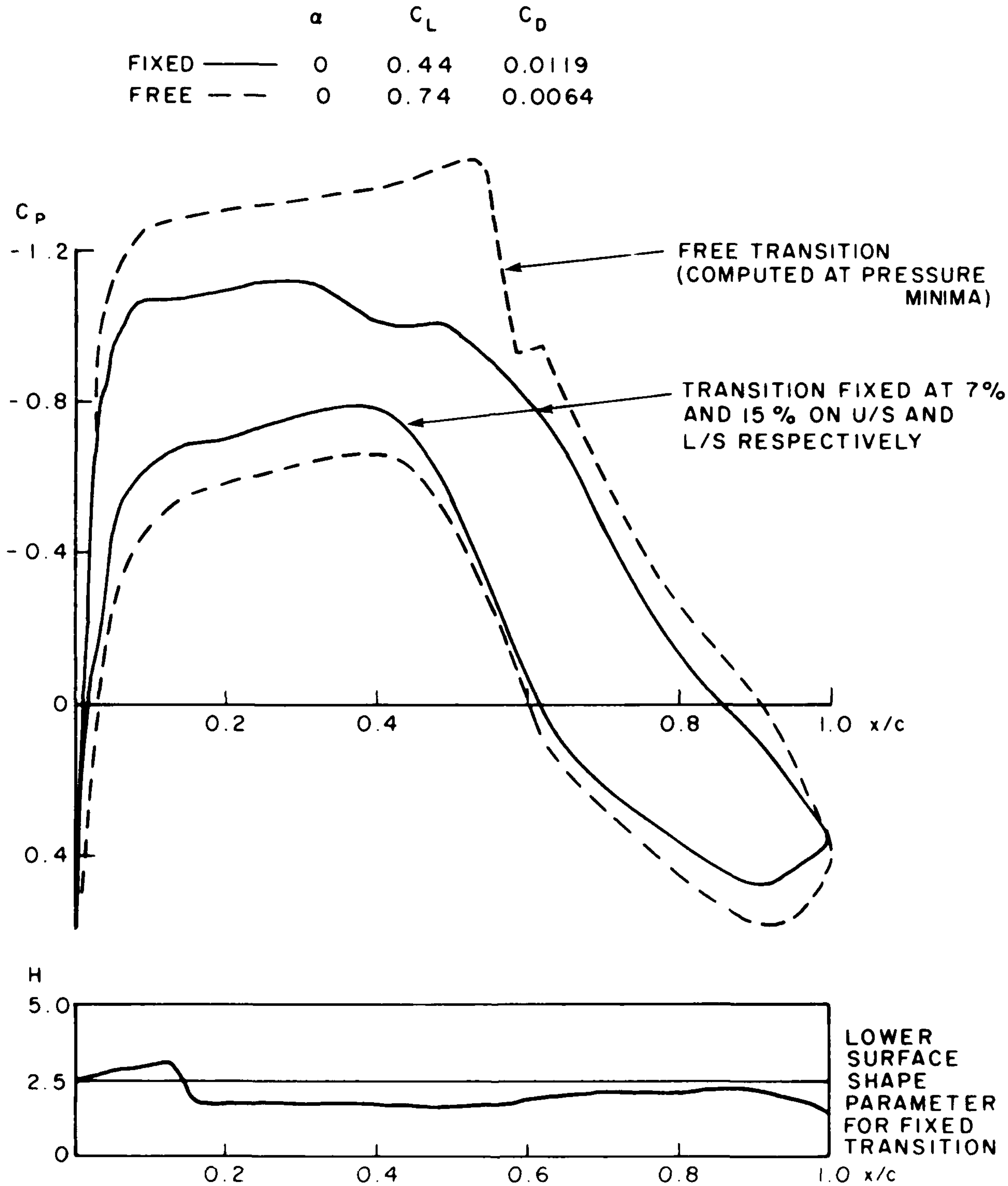

FIG. 4a: BGK COMPUTATIONS TO COMPARE FIXED AND FREE TRANSITION
M_∞ = 0.68, R_c = 6.8 × 10^6

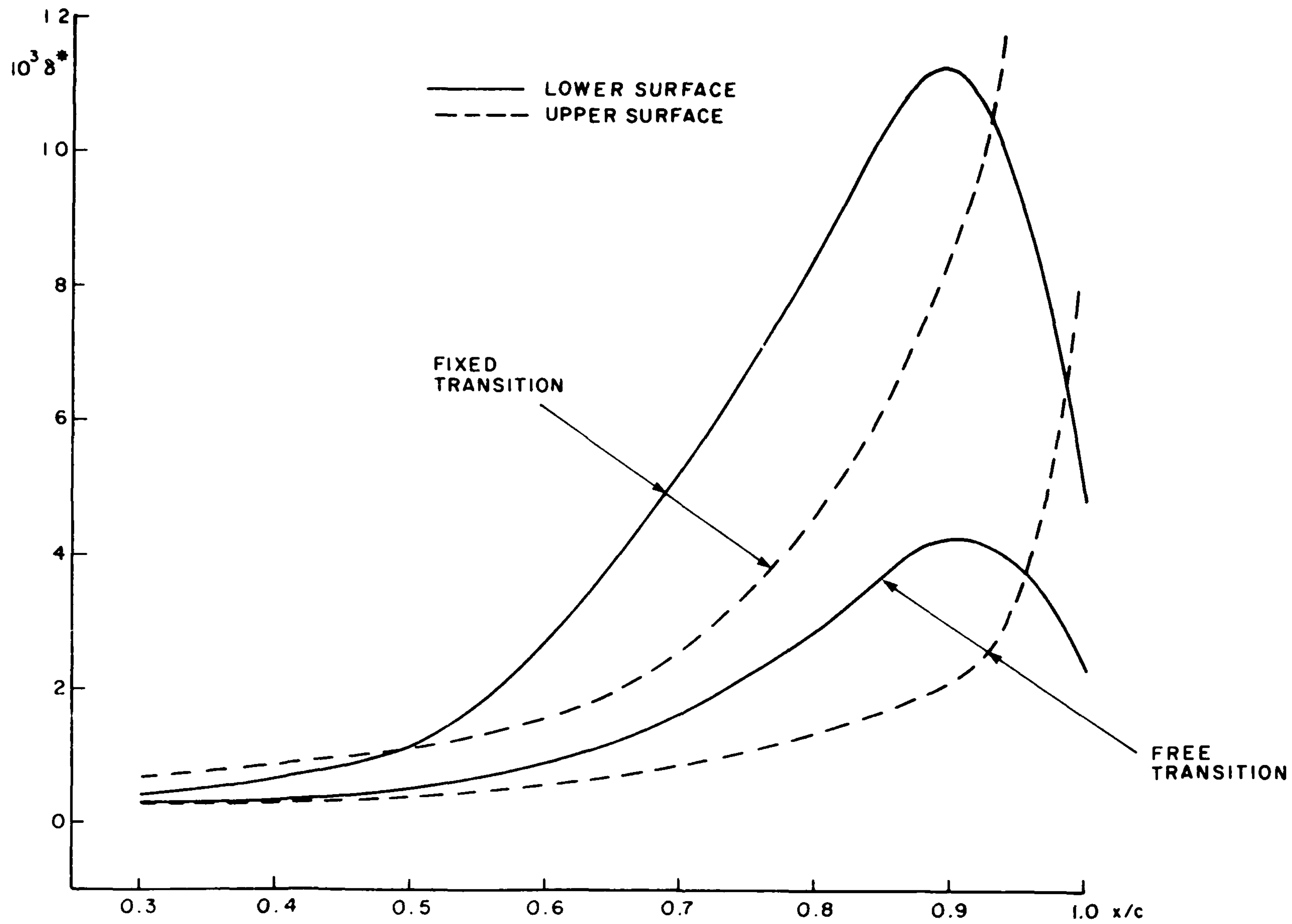

FIG. 4b: BGK CALCULATION OF δ^* VERSUS x/c. $M_\infty = 0.68$, $R_c = 6.8 \times 10^6$, $\alpha = 0°$

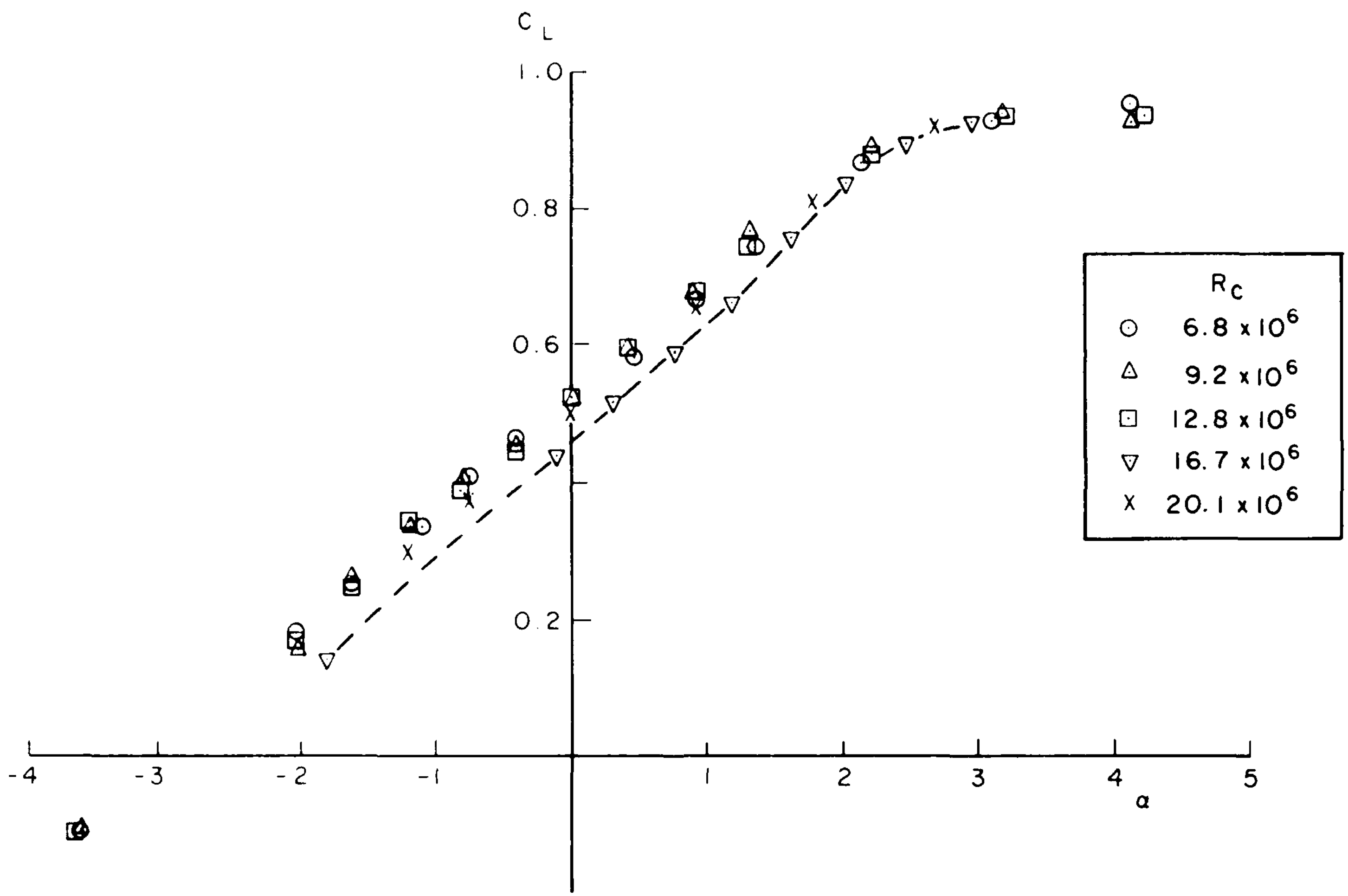

FIG. 5a: C_L - α WITH FREE TRANSITION. M_∞ = 0.68

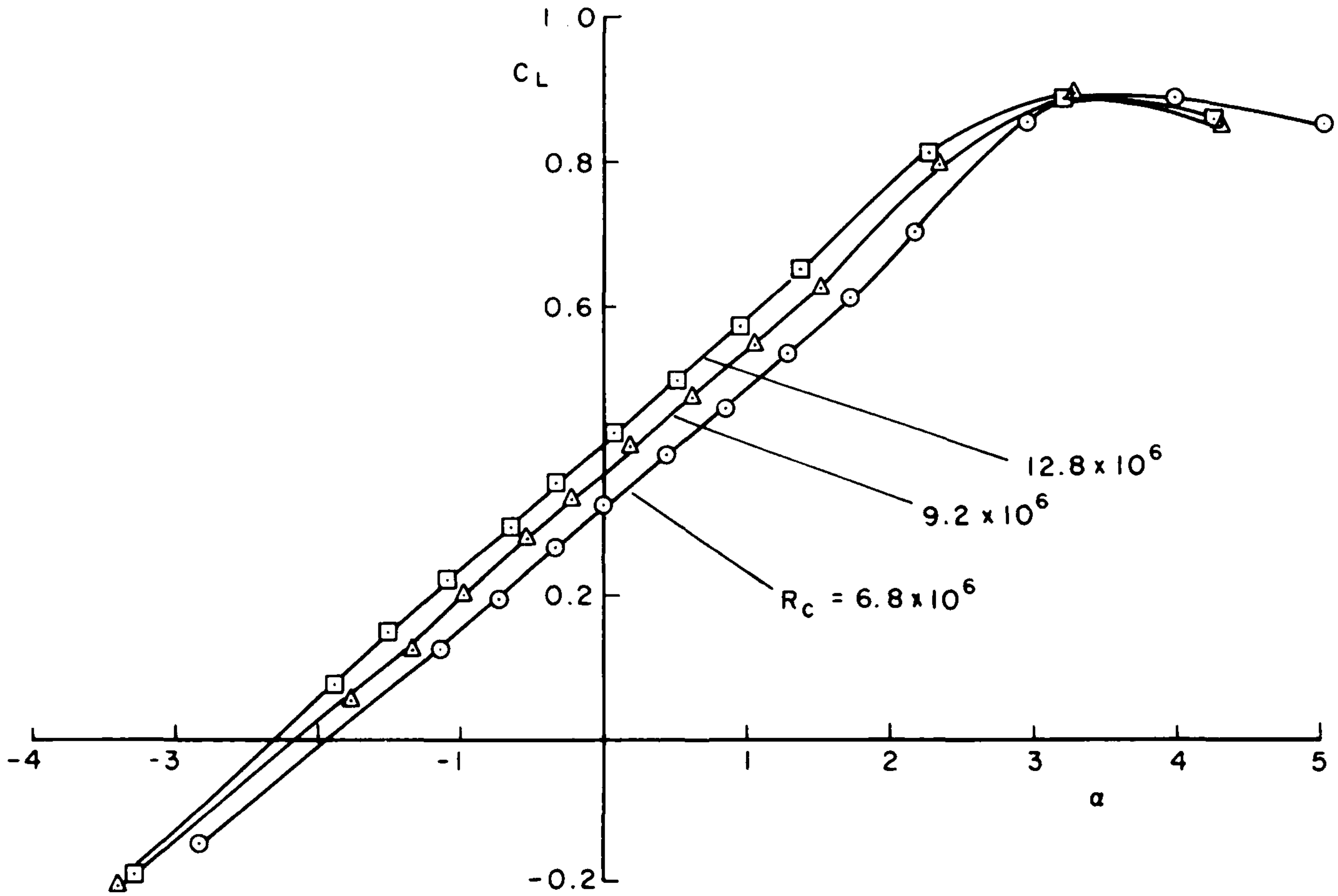

FIG. 5b: $C_L - \alpha$ WITH FIXED TRANSITION. M_∞ = 0.68

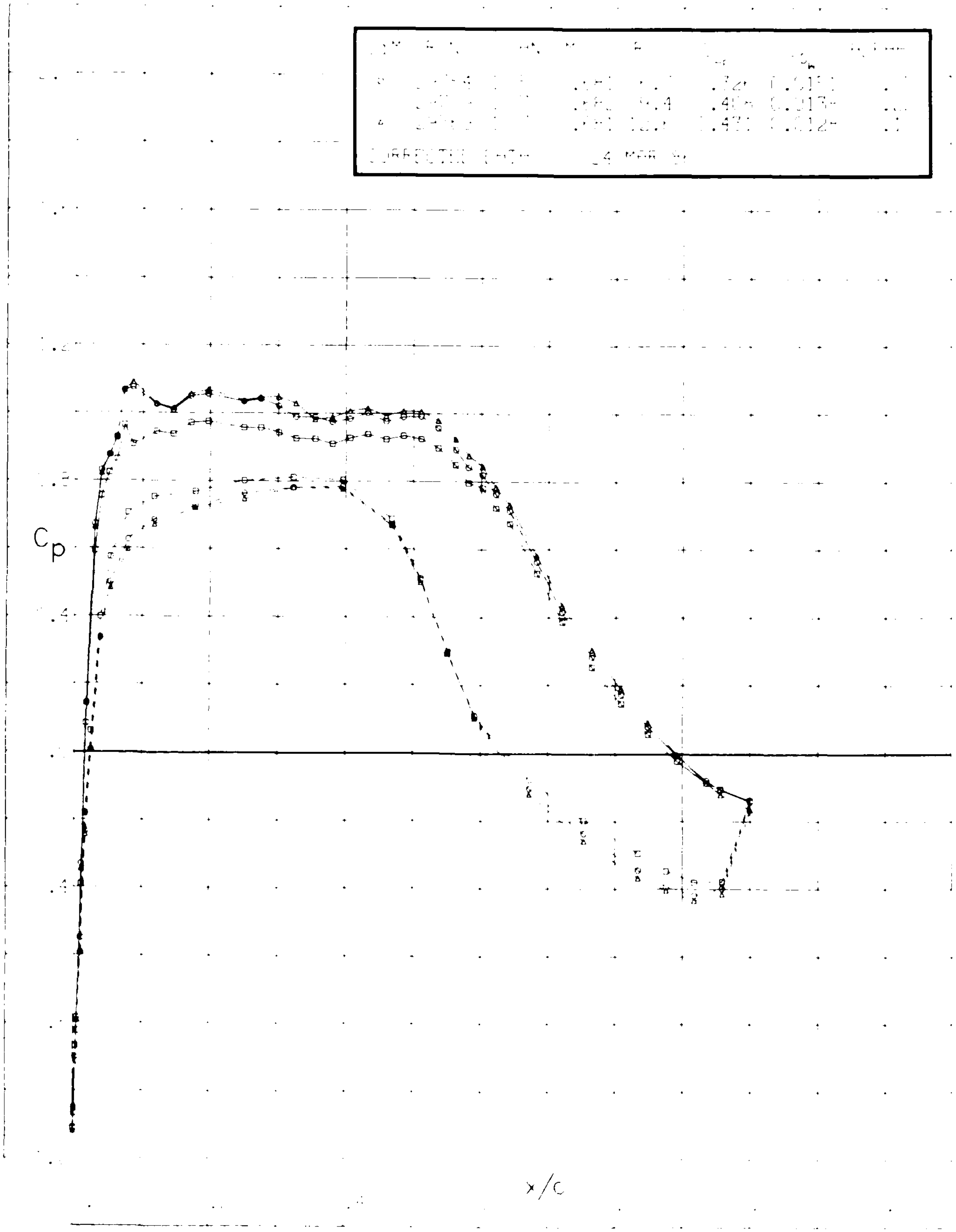

FIG. 6: EFFECT OF REYNOLDS NUMBER ON C_p WITH FIXED TRANSITION

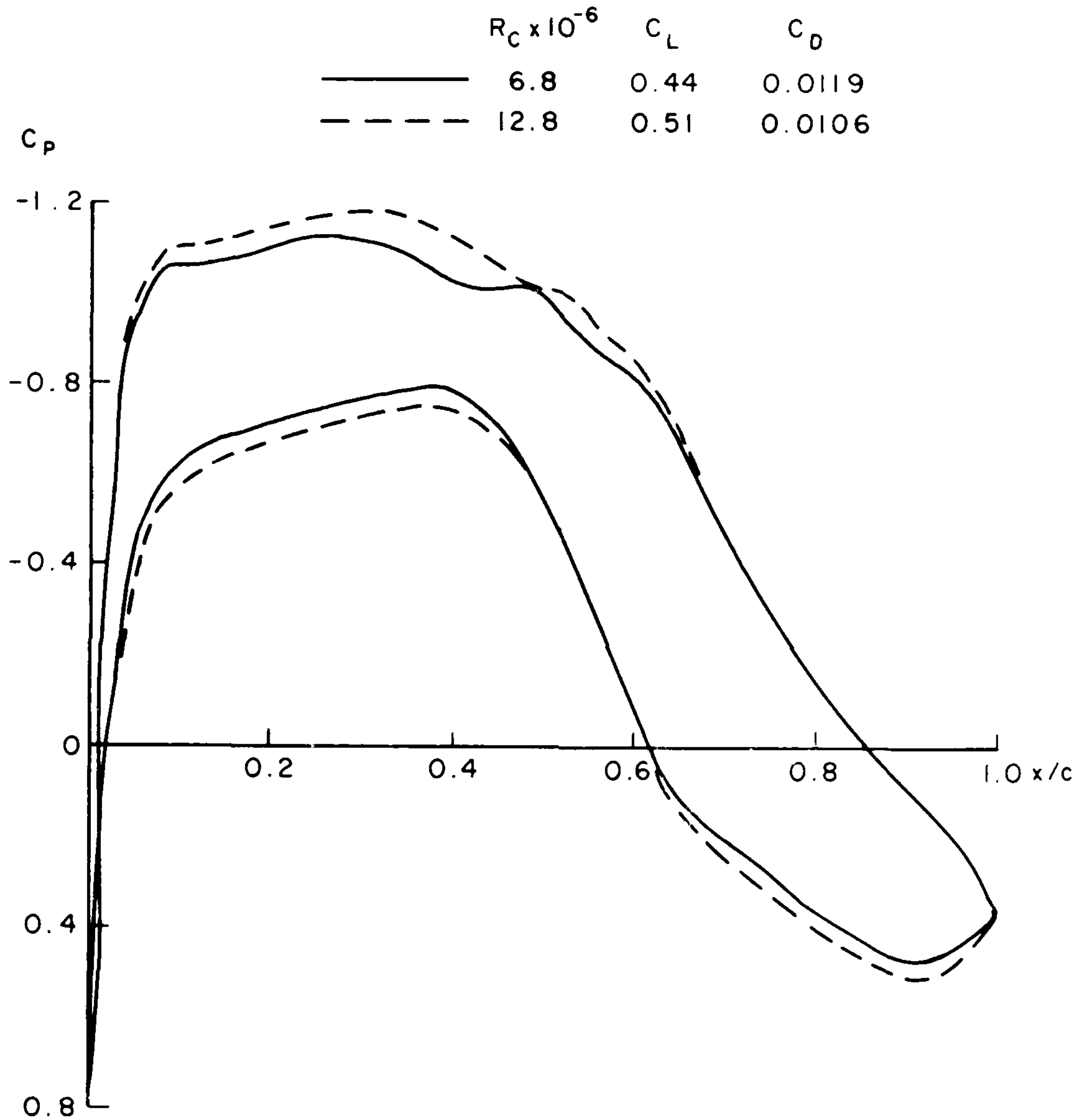

FIG. 7: BGK COMPUTATIONS TO SHOW REYNOLDS NUMBER EFFECT WHEN TRANSITION FIXED. $M_\infty = 0.68, \alpha = 0°$

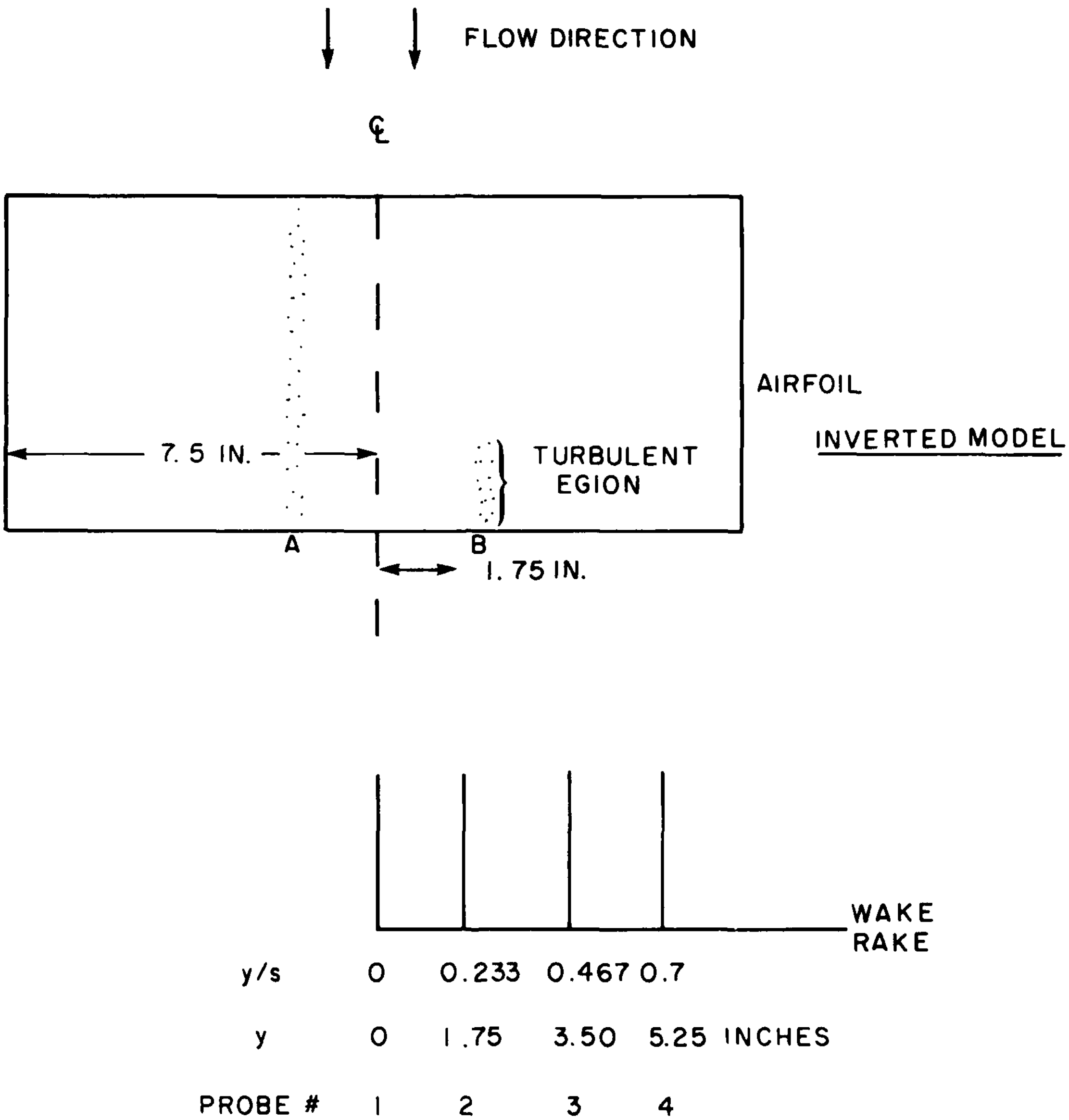

FIG. 8: THE TWO SPANWISE LOCATIONS OF PRESSURE TAPPINGS

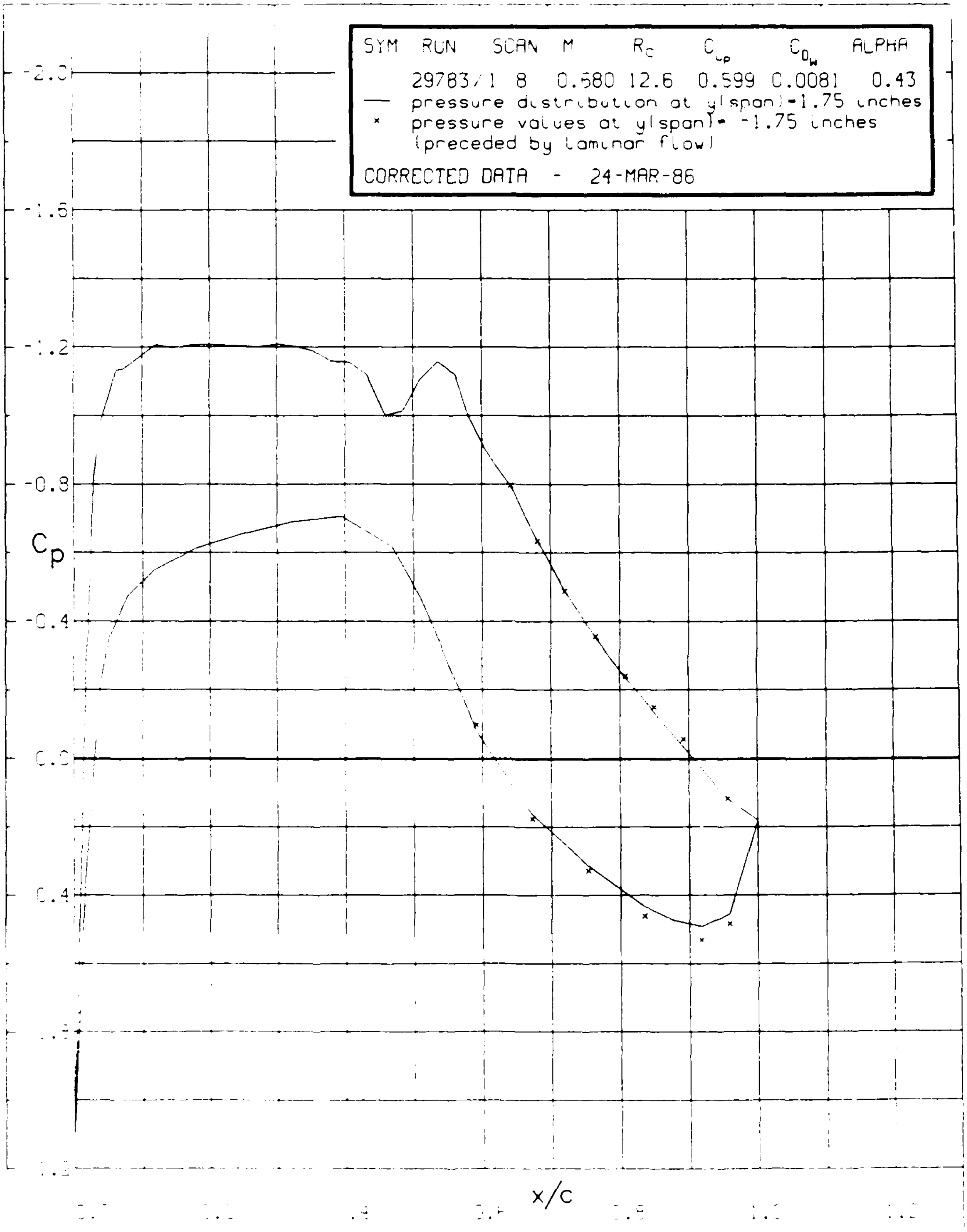

FIG. 9a: PRESSURE VARIATION AT TWO SPANWISE LOCATIONS
$M_\infty = 0.68$, $R_c = 12.6 \times 10^6$

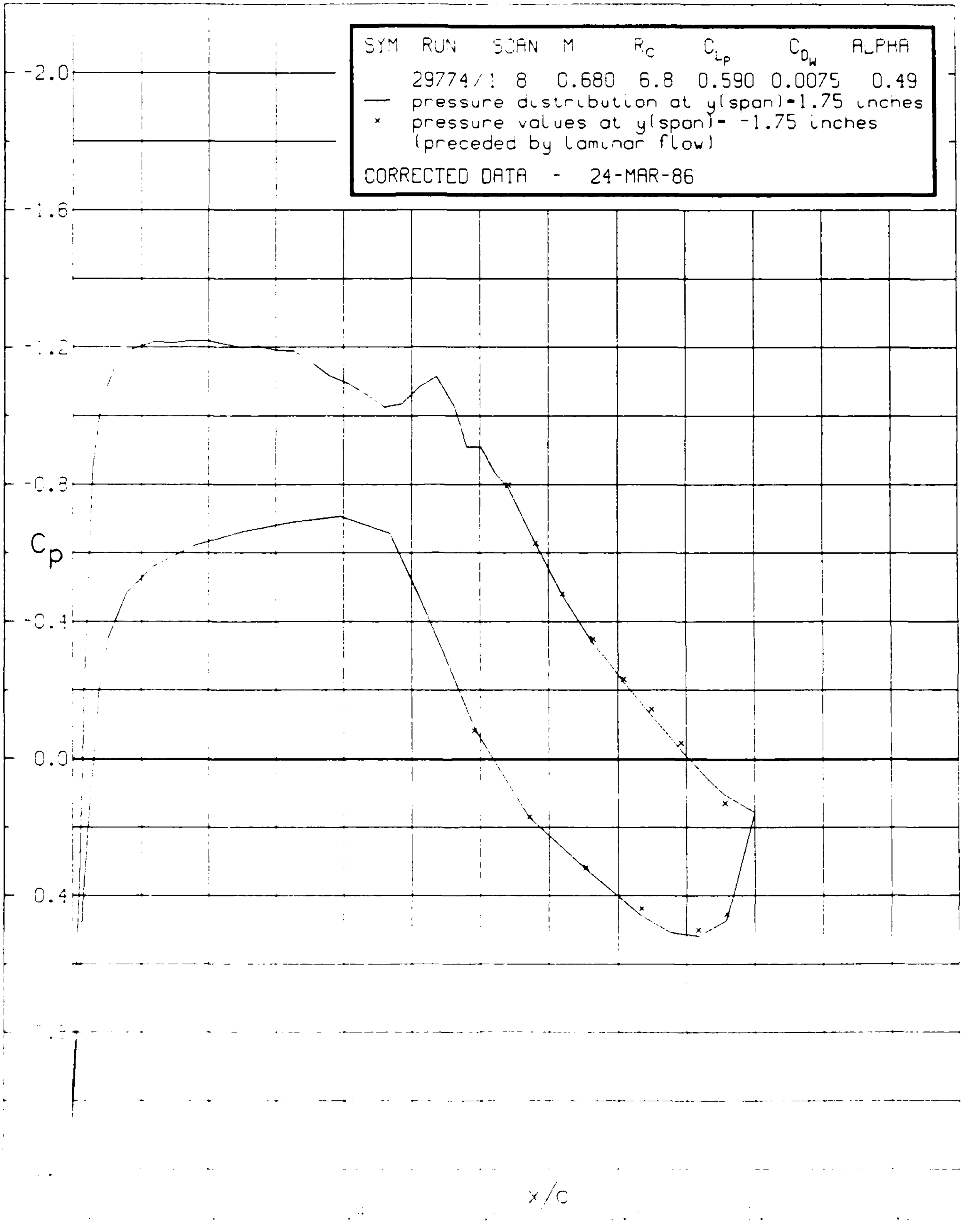

FIG. 9b: PRESSURE VARIATION AT TWO SPANWISE LOCATIONS
$M_\infty = 0.68, R_c = 9.3 \times 10^6$

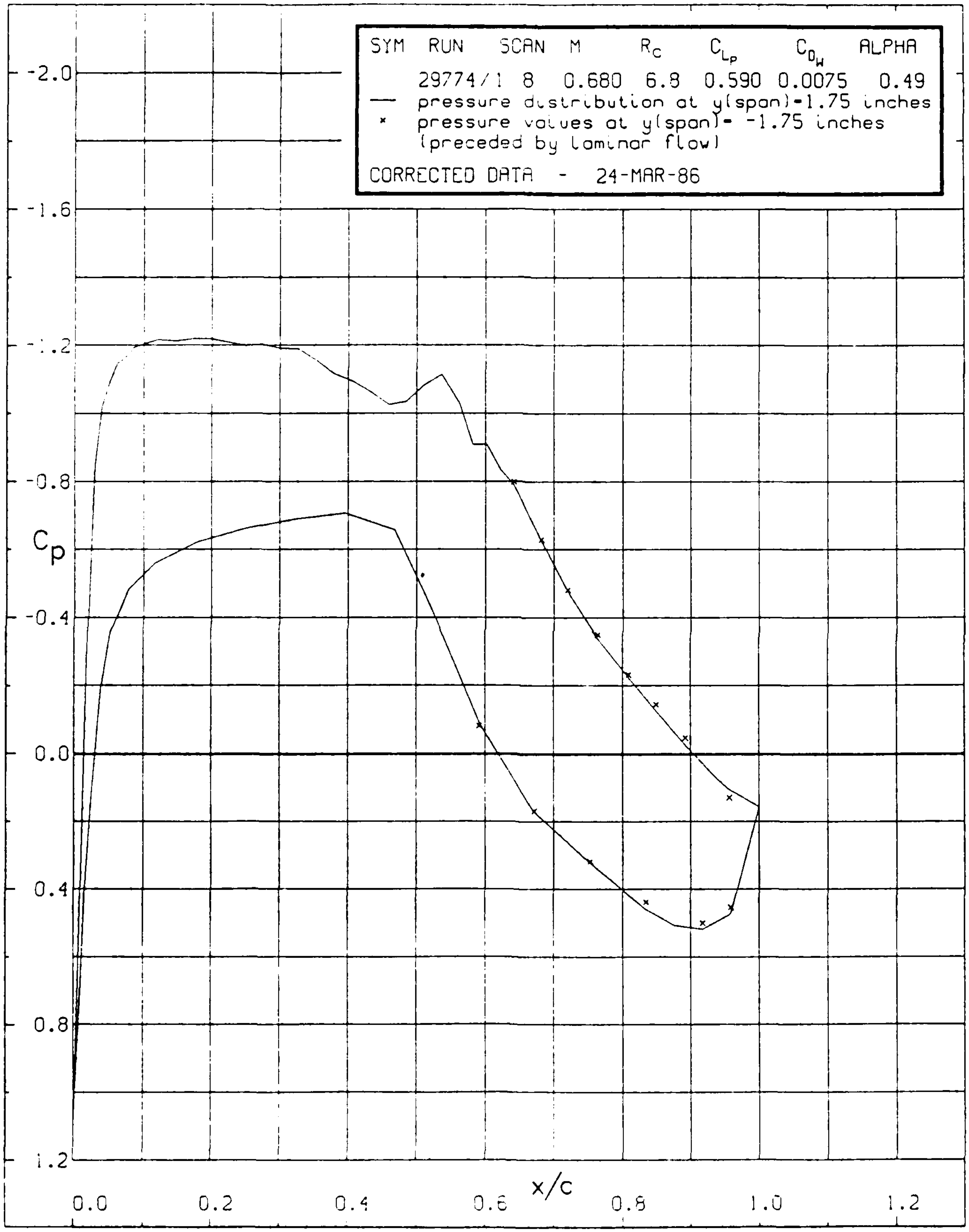

FIG. 9c: PRESSURE VARIATION AT TWO SPANWISE LOCATIONS
$M_\infty = 0.68$, $R_c = 6.8 \times 10^6$

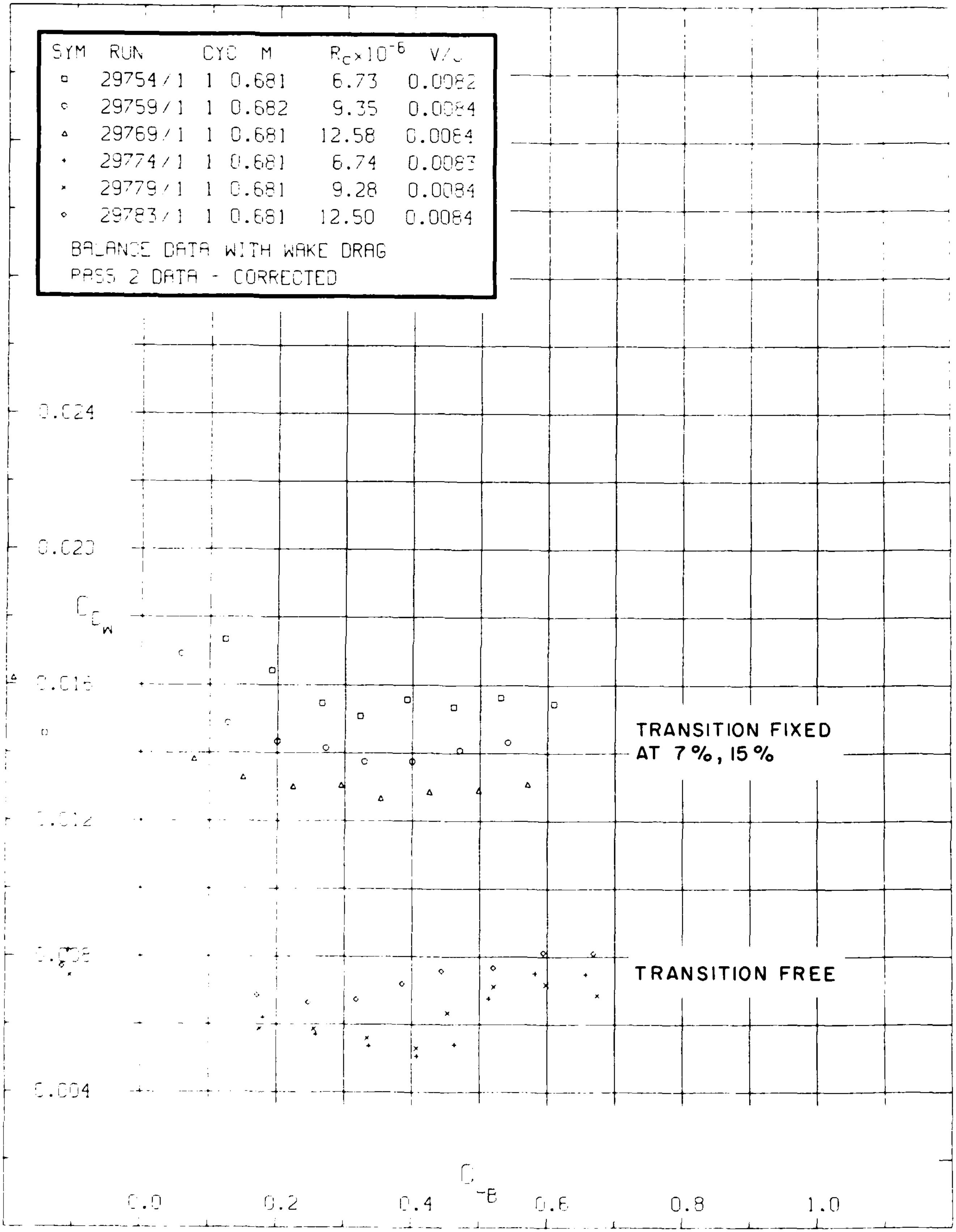

FIG. 10: EFFECT OF TRANSITION ON DRAG VALUES

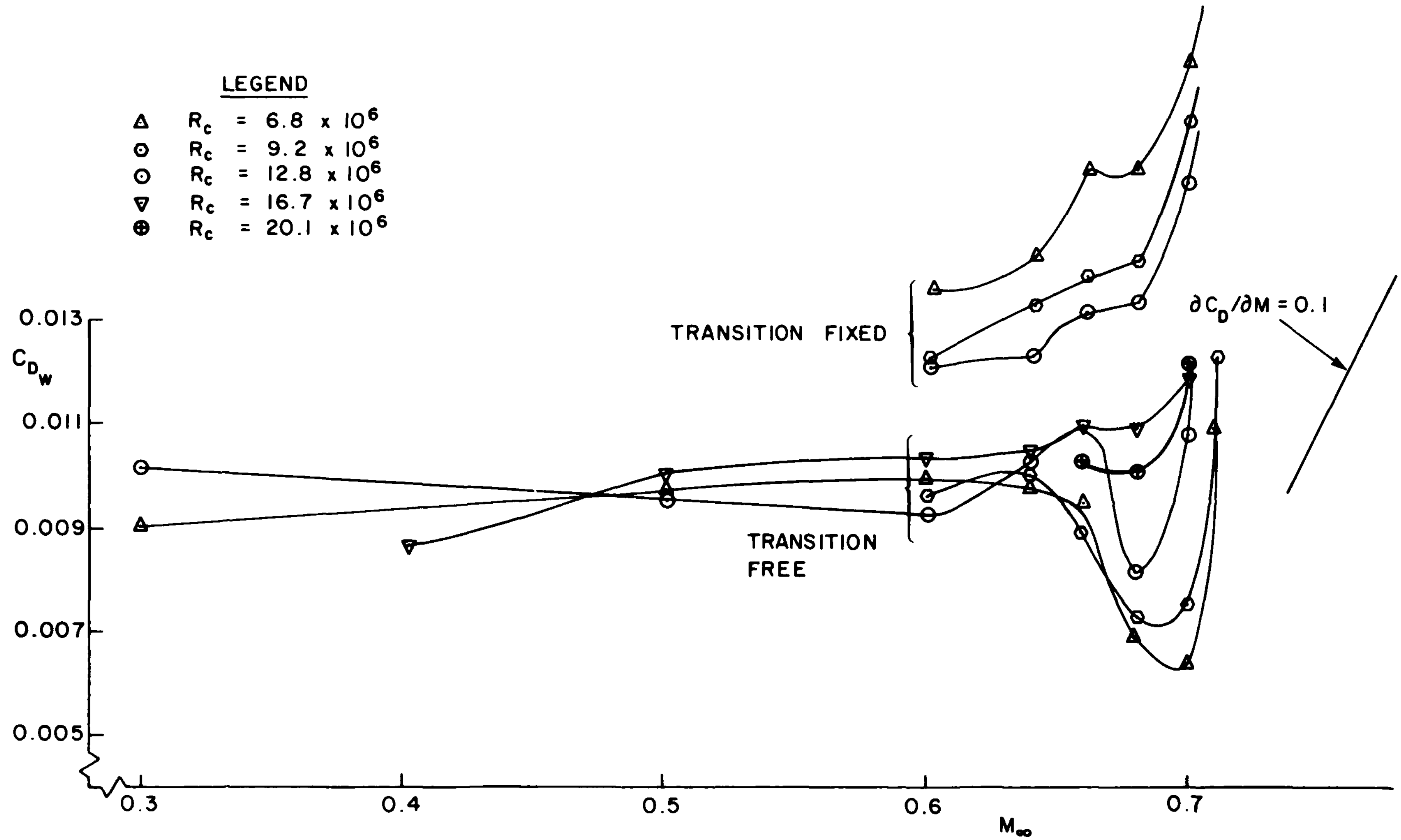

FIG. 11a: C_{D_W} VERSUS M_∞ FOR C_L = 0.6

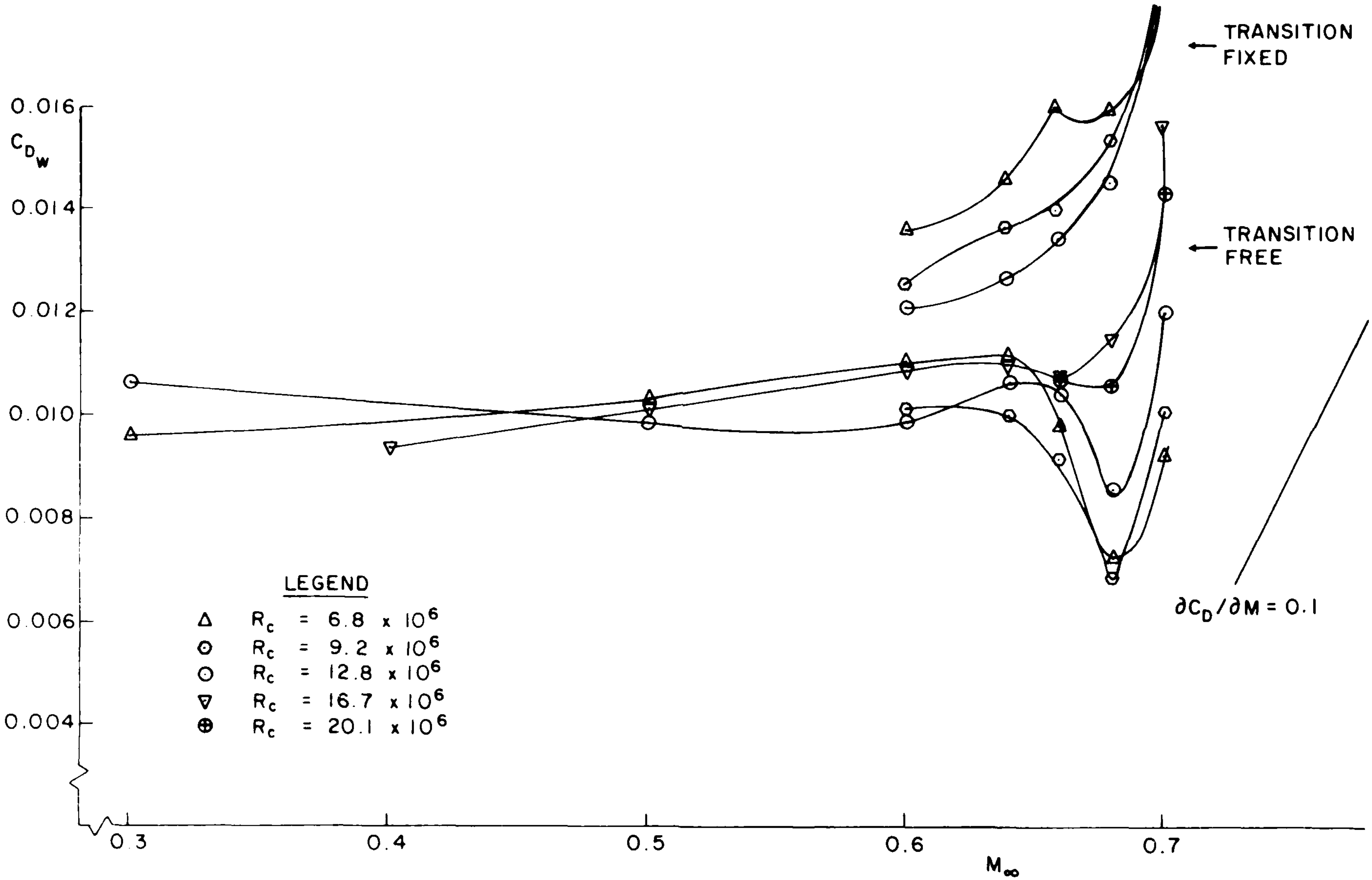

FIG. 11b: C_{DW} VERSUS M_∞ FOR C_L = 0.7

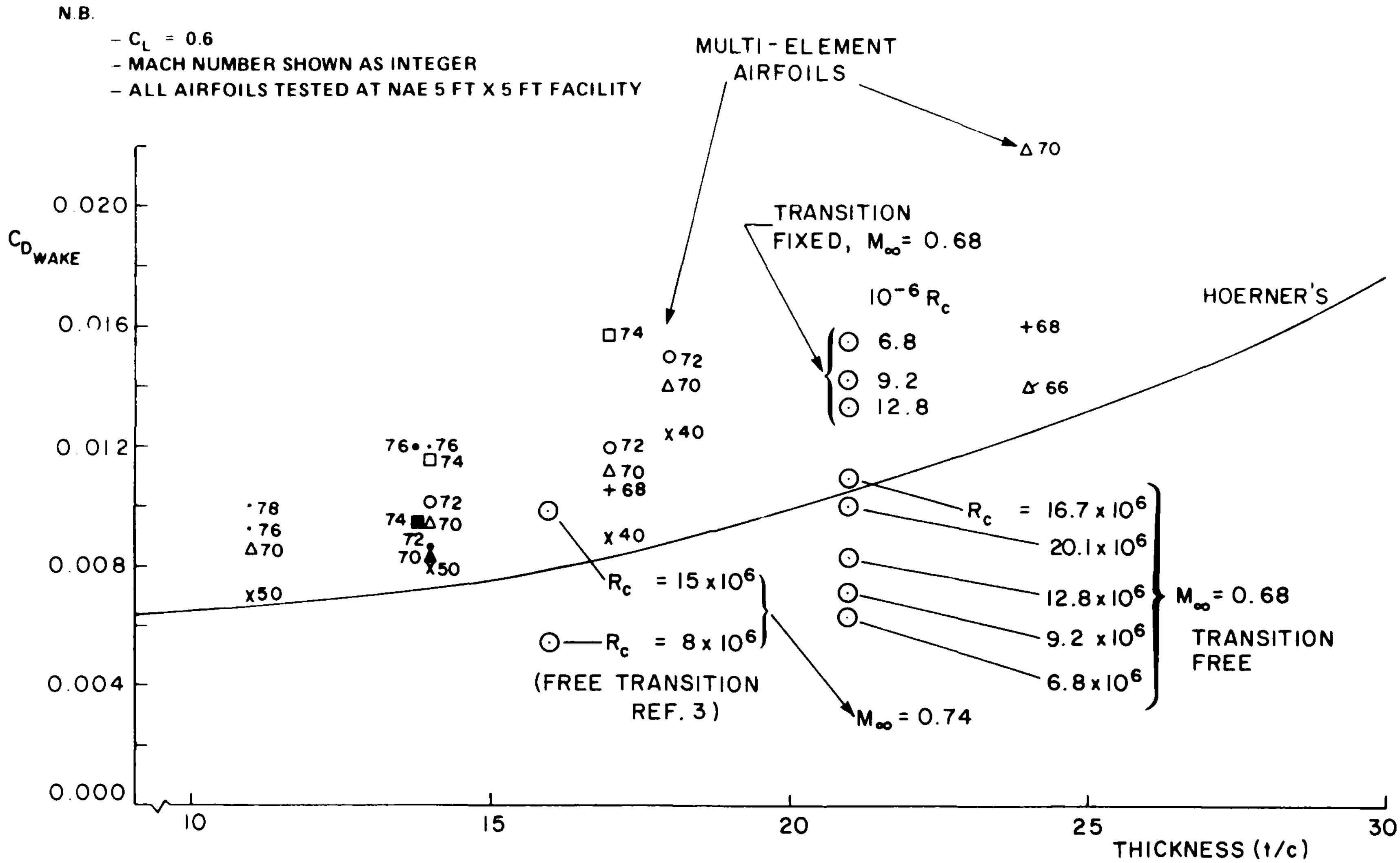

FIG. 12: DRAG COMPARISONS WITH OTHER AIRFOILS

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Aeronautical Note

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DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

1. Aerofoils (supersonic)
2. Aerofoils - drag
3. Aerofoils - Reynolds number effects
4. Aerofoils - test results

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SUMMARY/SOMMAIRE

Further wind tunnel tests have been carried out on the NAE 10" chord supercritical NLF airfoil NAE 68-060-21:1. This airfoil in previous tests showed very low drag levels when free transition was allowed on the model. In the main part of the current investigation, performed at chord Reynolds number of about 7,9 and 13 million, transition was fixed at 7% and 15% on upper and lower surfaces respectively. It is observed that there is a substantial loss of lift under these conditions which appears to be associated with boundary layer thickening on the lower surface causing decambering near the trailing edge.

Also additional tests were carried out under free transition at other Reynolds numbers than those previously used. The same drag bucket behaviour near the design flow conditions was observed.

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