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TESTS ON A CAST 7 TWO-DIMENSIONAL AIRFOIL
IN A SELF-STREAMLINING TEST SECTION

FOR REFERENCE

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UTTL: Tests on a CAST 7 two-dimensional airfoil in a streamlining test section

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ABS: A unique opportunity has arisen to test one and the same airfoil model of CAST-7 section in two wind tunnels having adaptive walled test sections. The tunnels are very similar in terms of size and the available range of test conditions, but differ principally in their wall setting algorithms. Detailed data from the tests of the model in the Southampton tunnel, are included with comparisons between various sources of data indicating that both adaptive walled test sections provide low interference test conditions.

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1. Introduction

The acceptance of flexible walled test sections for two-dimensional testing at transonic speeds relies upon two main factors, the speed with which adaptation is achieved and the reliance that can be placed on the achievement of zero or low levels of flexible wall interference. The former is satisfied by the use of predictive methods for computing the required wall contours coupled with a sensible choice of test sequences and rapid-acting wall setting mechanisms. The latter factor requires those who are developing the new test sections to produce bodies of data lending support to the argument that interference-free conditions have indeed been achieved. This report covers work which has been carried out aimed at adding in a unique way to that body of data.

Resulting from the activities of the Garteur group[1] there had been manufactured a series of airfoils of the same CAST 7 section of various sizes for testing in several wind tunnels. One of these models, of 100mm chord, was tested at the Technical University of Berlin in their 150mm flexible walled test section. The same model has now been tested in the 6-inch (152-4mm) flexible walled test section at the University of Southampton, allowing comparisons to be made for the first time of transonic data for essentially the same sized test sections, speeds and model, but using different wall-setting algorithms. The algorithms are analytically based. We could expect the data comparisons to show up errors which may be introduced by weaknesses in the algorithms.

Further, the Garteur group had accumulated a considerable body of experimental data covering bands of Mach and Reynolds numbers and angles of attack, which could be used for comparative purposes to raise confidence. However this data, while for the CAST 7 section, was taken with several different models and could therefore include the effects of manufacturing differences in addition to the usual differences which occur from tunnel to tunnel.

This report details the test data taken in the transonic self-streamlining wind tunnel (TSWT) at the University of Southampton, and

includes relevant comparisons with Technical University of Berlin (TUB) data and other sources including another flexible walled test section.

2. TSWT Test Data

2.1 The Test Section and Tunnel

This is shown in schematic form on Figure 1. The test section is 6 inches square at the upstream end, with parallel rigid sidewalls throughout, pierced to carry the model. The flexible top and bottom walls are anchored at their upstream ends and adjusted in contour by twenty motor-driven screw jacks on each, distributed unevenly as shown on the figure. The data used in predicting the contours for interference-free flow comprises merely the static pressure distributions along the flexible walls, and the tunnel reference Mach number[2].

The wind tunnel is induced-flow, driven by dried compressed air through an injector downstream of the test section. Mach number may be varied continuously from low subsonic to low supersonic by adjustments to driving air pressure and wall contour.

2.2 Test Conditions

The model was tested through a range of angles of attack from -2° to $+3\frac{1}{2}^{\circ}$ at its design Mach number of 0.76, and through a range of Mach number from 0.3 to 0.82 at the angle of attack giving the design C_L (0.52) at the design Mach number. The stagnation conditions in this tunnel are atmospheric.

Reference Mach number is determined from stagnation pressure and a reference static hole at the beginning of the test section at mid-height on a sidewall. The length of test section has been chosen so that the disturbance induced by the model in the streamwise component of flow at the reference hole is negligible. Further, by placing the model symmetrically in the test section the effects of the induced upwash at both ends of the test section largely cancel[2]. These features, coupled

with the streamlining of the walls, eliminate any need to apply corrections to the test data to account for top and bottom wall interference or length truncation.

2.3 The Model

This was manufactured (by the Aircraft Research Association, Bedford) for the TUB tunnel with a chord of 10cm and span of 15cm. Make-up pieces were manufactured to adapt the span to suit the fractionally larger TSWT. The model carried static pressure tappings around roughly the mid-span at the streamwise coordinates given on Figure 2. Endplates were fitted to the model to reduce the effects of the test section sidewall boundary layers, and transition bands were applied near to the leading edges of these and the airfoil. The test section height-to-chord ratio at 1.52 is much lower than normal for conventional two-dimensional testing.

No attempt was made to accurately align the model angular reference with the test section flow and therefore the quoted angles of attack are merely nominal. However some care was taken in measuring the changes in angle of attack which are judged to be accurate to 0.1 degree.

2.4 Streamlining

The process begins by first running a test at a Mach number below that which chokes the test section with the walls straight, even if the resultant Mach number is below that ultimately intended. The first movements of the walls towards streamlines, that is the first iteration, has a profound effect on the choking Mach number, in our experience raising it to a value above the range of interest in most two-dimensional testing of transport aircraft sections. From hereon in a test program choking is no longer a problem, the test sequence proceeding from one set of streamlines for one combination of model attitude and Mach number, to other combinations and streamlines. The walls need never be, and usually are not, re-set to straight during a test program.

The effects of this procedure on the Mach number distributions along the flexible walls are illustrated on Figure 3. The figure shows for each flexible wall the Mach number at the wall derived from a measurement of static pressure at each of the indicated jack positions. Nineteen jacks are shown. The furthest downstream, the twentieth, does not carry a pressure tapping and therefore is not shown. The first run with the model present at a nominal zero angle of attack and with straight walls was at an indicated reference Mach number of about 0.7. The maximum wall Mach number was 0.91 and occurred on the top wall. As the walls were far from streamlines (and of course unventilated) the model would be suffering severe interference effects. Model data, which is normally taken at this stage only for interest, will be seen to show substantial supercritical flow. The test section is close to choking.

The initial aim was to streamline at this attitude and Mach 0.76. The streamlining cycle proceeded through several iterations during which the reference Mach number was quickly raised to the desired value. Plotted also on Figure 3 are the wall Mach number distributions after wall streamlining. The peak Mach number is reduced to about 0.86 despite the increase in reference Mach number from 0.7 to 0.76, indicated a reduction in blockage. In fact the residual wall interferences were reduced by the effects of streamlining to the usual low levels indicated by the normal[3] measures.

The streamwise location of the model is indicated on Figure 3. Another effect of streamlining is in the data for the region downstream. As has been seen from the earliest days[4] the walls automatically adapt to the blockage caused by the wake. In this case the Mach number downstream of the model in the case of straight walls asymtotes to a value well above the reference, whereas when streamlined the Mach number in this region is essentially the same as the reference, as must be the case in free air conditions.

The effects on the airfoil pressure distribution of streamlining the walls are shown on Figure 4. With the walls straight and at Mach 0.706 there is a strong upper-surface shock at about 65% chord. Another feature is the slightly negative pressure coefficient (about -0.1) at

the trailing edge. While localised re-accelerations of the flow can occur it is unlikely that this occurred at 80% chord on the upper surface and therefore this point is assumed a stray.

After streamlining and despite the increase in reference Mach number the recompression shock is almost eliminated and the trailing edge pressure coefficient is raised to about 0.1.

Figure 5 shows sets of streamlined wall contours for the angle of attack sweep including the case just discussed, in the form of displacements of the wall from their aerodynamically straight positions. Aerodynamically straight contours are those which give constant Mach number throughout the test section[5] when empty and run at the Mach and Reynolds numbers of interest. The displacements on Figure 5 follow a fairly systematic pattern. In the upstream reaches of the test section the upwash induced by lift is quite evident and not insignificant even at the furthermost upstream jack more than four chords distant, a point which cannot be ignored because of the wall loading which it induces as mentioned in Section 2.1.

One could infer, from the bunching together of the contours in the upstream region at angles of attack above about 2°, an approximate constancy of circulation and only modest changes of lift. This is confirmed by the measurements of lift as will be seen.

The wall streamlines part around the model to accommodate its thickness and move almost together again downstream at the lower angles of attack. The shock-induced thickening of the wake at higher angles leaves both walls moved somewhat outward, eliminating wake blockage.

The corresponding wall Mach number distributions are shown on Figures 6 and 7. To avoid too much confusion Figure 6 covers the whole length of test section for a limited number of cases, while Figure 7 covers just the region around the model for all cases in the sweep but with an expanded length-scale. At the highest angles of attack it is seen that the channel over the airfoil is nearly choked whereas that under the model is somewhat below the reference Mach number. The

ripples in Mach number evident on Figure 6 particularly for the lower surface up to station 15 inches and beyond station 30 inches exhibit a certain amount of self-consistency and almost certainly represent imperfections in the streamlining procedures either with the model present, or in the earlier streamlining of the empty test section[5].

The model was installed and pressure checked, the data files on its shape and orifice coordinates were created and the test carried out all inside five days. Contributing to this was the rate with which the test section adapted to streamlines, the rate depending strongly on the required number of iterations for each test condition. This number increases with the severity of the change in test conditions between one streamlining cycle to the next. A test program can be chosen to minimise tunnel run time based on the general rules that in two-dimensional testing minimum iteration is required if a Mach sweep is carried out at constant angle of attack, followed by a small change in angle and a further Mach sweep. This arises because generally the changes in wall contours with test conditions are less in the case of a Mach sweep except in a sensitive range of Mach number, and of course are small if the movement of the model is small. Experience during these tests illustrates the point:

average number of iterations when:

- angle of attack changed through intervals between $\frac{1}{2}^{o}$ and 1° at constant Mach number - 2.0 iterations/cycle

- Mach number is changed through intervals between .02 and .05 at constant angle of attack - 1.67 iterations/cycle.

Examples of large changes include straight-walls-to-streamlines (6 iterations), change of angle of attack from $+3.5^{o}$ to -1° (4 iterations), change of Mach number from 0.76 to 0.82 (6 iterations) and from 0.6 to 0.3 (3 iterations).

2.5 Model Data

Airfoil pressure distributions were taken at all stages in the test program, but are reproduced here (aside from that on Figure 4) only for the cases where the walls were streamlined and the model therefore free from top and bottom wall interference. No corrections have been applied. The pressure distributions and force and moment coefficients derived from the pressures are shown on Figure Sets 8 and 9 for both sweeps. Figure 10 summarises the force and moment coefficient data. The lift curve slope, derived by least-squares fitting a straight line through the -2° to $+2^{o}$ data is 0.168 per degree. The maximum lift coefficient is 0.748. The Mach sweep taken at the angle of attack giving the design lift coefficient of 0.52 at Mach 0.76, is summarised on Figure 11. C_{MLE} is the pitching moment coefficient about the leading edge.

Figure 12 is a photograph of the test section with the near wall partially removed revealing the model and end-plate, and parts of the two flexible walls. It is a double exposure taken after the tests were complete showing two pairs of wall contours re-set using the recorded data files: straight walls and walls streamlined for this angle of attack, 3.5 degrees. The bottom wall has moved very little under the trailing edge, but upward slightly under the leading edge. In the field of view the top wall has moved upward everywhere during streamlining, peaking at a displacement of about 0.4 inches between jacks 10 and 11.

Figure 13 is a photograph of the model after its removal from the test section revealing a fault which developed during the tests. A fine powder has adhered to the surfaces particularly aft of the transition strips. This was caused by a failure in the air drying plant which resulted in the release of Silica gel into the airstream. The deposit is seen to be fairly uniform over the central 80% of the span aft of the transition strip, and in fact was very fine although no measurements were made of particle size. The consequences are discussed later.

3. Comparisons with other Sources of Data

3.1 General Comparisons

The principal source of data used for comparison is the interim report by the Garteur group[1], in which test data from seven wind tunnels is presented uncorrected and corrected. Comparisons are made where appropriate with data taken at roughly the same Reynolds number as covered by the current work. A limited set of pressure distributions is included[1] for the design conditions and a chord Reynolds number of about $2.5.10^6$. The agreement between this data set and the corresponding condition which is shown on Figure 8(c) in this report is very good, in terms of shock position and the levels of pressure coefficient on each surface including the trailing edge. The lift curve slope (Figure 10) agrees with the other sources at low values of C_L (say below about 0.4) but most of the data in reference 1 shows steepening of the slope at $C_L \approx 0.6$.

The data on Figure 15 of reference 1 showing the lift divergence at the angle of attack giving the design C_L at $M = 0.76$ is reproduced here on Figure 14, along with the data from TSWT which is seen to lie very satisfactorily within the main body of data.

Maximum lift coefficient is expected to be sensitive to errors in Mach number[1]. Data is presented on Figure 15, separated into corrected and uncorrected groups for conventional tunnels and adaptive tunnels. Despite the high level of scatter the data does exhibit trends as indicated by two trend lines, the upper corresponding approximately to the trend in corrected and adaptive tunnel data, the lower corresponding to the uncorrected data. The adaptive tunnel data, including that for the ONERA T2 tunnel, is seen to lie close to the trend in corrected data.

The point on Figure 15 identified as TKG is a measurement[1] on the same airfoil as used at TUB and Southampton. The TKG facility (at DFVLR) has a conventional slotted test section with a depth of 98cm compared with the model chord of 10cm. The data point is uncorrected,

but it is likely that interferences would be small with this model/tunnel combination. The close agreement between these three data points is encouraging.

3.2 Repeat Tests at TUB

Following the discovery of the release of silica gel in TSWT the airfoil was returned to TUB and re-tested in the identical condition to expose any consequent changes in performance. None of significance were found. The testing did however provide a further source of comparative data. There were some conditions giving a very close match of Mach number and lift coefficient between the two sources of data. The airfoil pressure distributions for these conditions are shown on Figure 16. In the light of disagreements that are sometimes seen between sources of data on the same model, the agreement on Figure 16 can only be described as good.

4. Discussion

The aim of this report has been to present another body of data on an airfoil section tested in an adaptive tunnel together with relevant comparisons with data from other tunnels, but in particular to show the agreement between two adaptive tunnels where the principal differences lie in the streamlining algorithms. The general agreement between the two adaptive tunnels and between them and conventional tunnels supports the view that two-dimensional data from flexible walled adaptive tunnels is reliable: top and bottom wall interference is being eliminated by wall streamlining. The supporting evidence is in Figures 14-16 where the Southampton and TUB data lie very close and are in reasonable agreement with data from other sources.

There are no indications that the different streamlining algorithms are themselves introducing significant differences in model data.

5. References

1. Elsenaar, A., and Stanewsky, E. A report of a Garteur action group on "Two-dimensional transonic testing methods". Paper nr.5, AGARD-CP-335, May 1982.

2. Judd, M., Wolf, S.W.D., and Goodyer, M.J. Analytical Work in Support of the Design and Operation of Two Dimensional Self Streamlining Test Sections - Semiannual Progress Report, Oct. 1975 - Mar. 1976. NASA CR-145019, July 1976.

3. Goodyer, M.J., and Wolf, S.W.D. Development of a Self-Streamlining Flexible Walled Transonic Test Section. AIAA Journal, Vol.20, No.2, Feb. 1982, pp.227-234.

4. Goodyer, M.J. The Self Streamlining Wind Tunnel. NASA TM-X-72699, Aug. 1975.

5. Wolf, S.W.D., Goodyer, M.J., and Cook, I.D. Streamlining the Walls of an Empty Two-Dimensional Flexible-Walled Test Section - Progress Report. NASA CR-165936, May 1982.

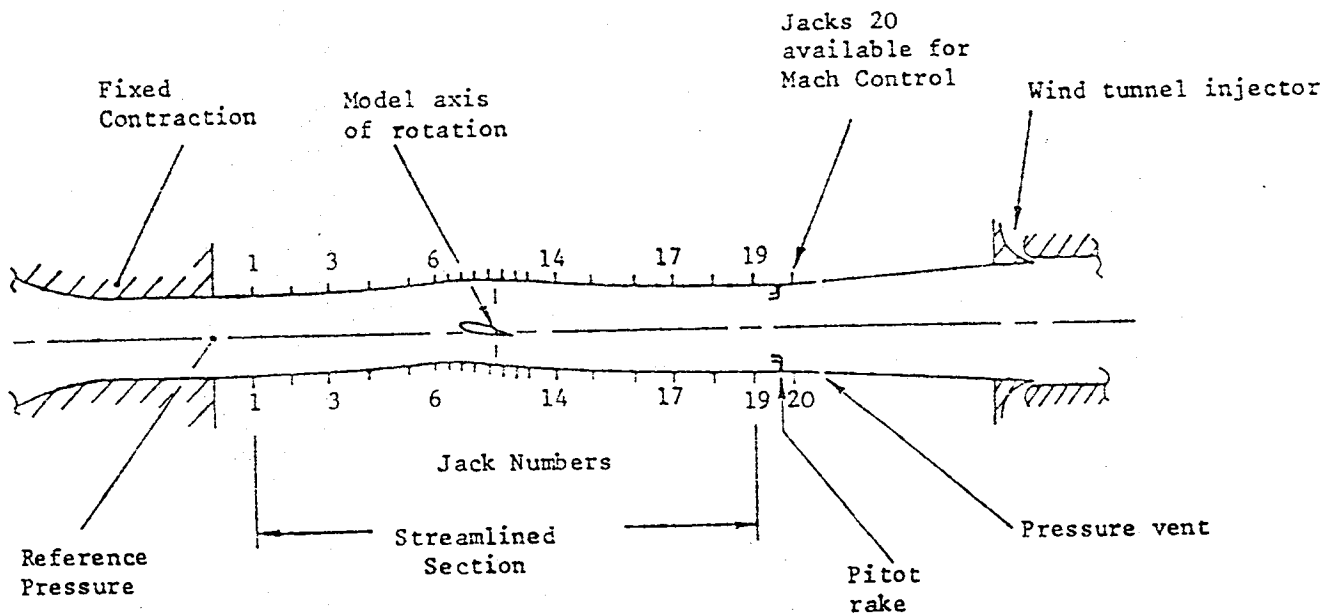
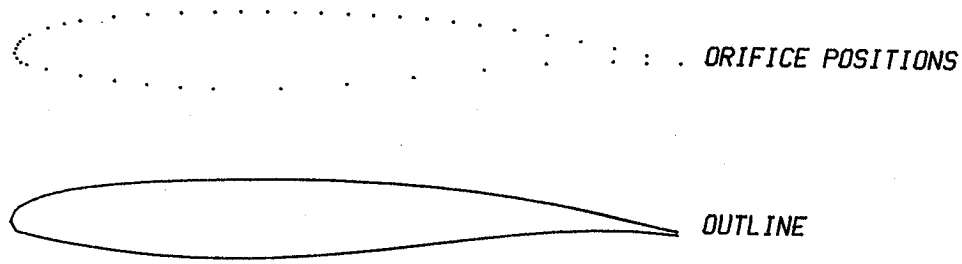


Figure 1. Schematic Layout of Transonic Self-Streamlining Wind Tunnel



Orifice Streamwise Positions

Upper Surface % Chord	Lower Surface % Chord
0.00	0.00
0.25	0.41
0.56	1.02
0.96	1.93
1.40	4.87
2.31	10.05
5.03	15.15
7.51	19.95
9.93	25.00
14.85	29.95
19.93	40.03
24.95	49.93
30.00	59.98
33.86	70.62
37.82	79.89
41.99	89.86
45.90	94.86
49.96	100.00
53.79	
57.83	
61.89	
65.90	
69.93	
75.04	
79.96	
84.99	
90.04	
94.86	
100.00	

Figure 2. The CAST 7 model in outline, with pressure orifice chordwise stations.

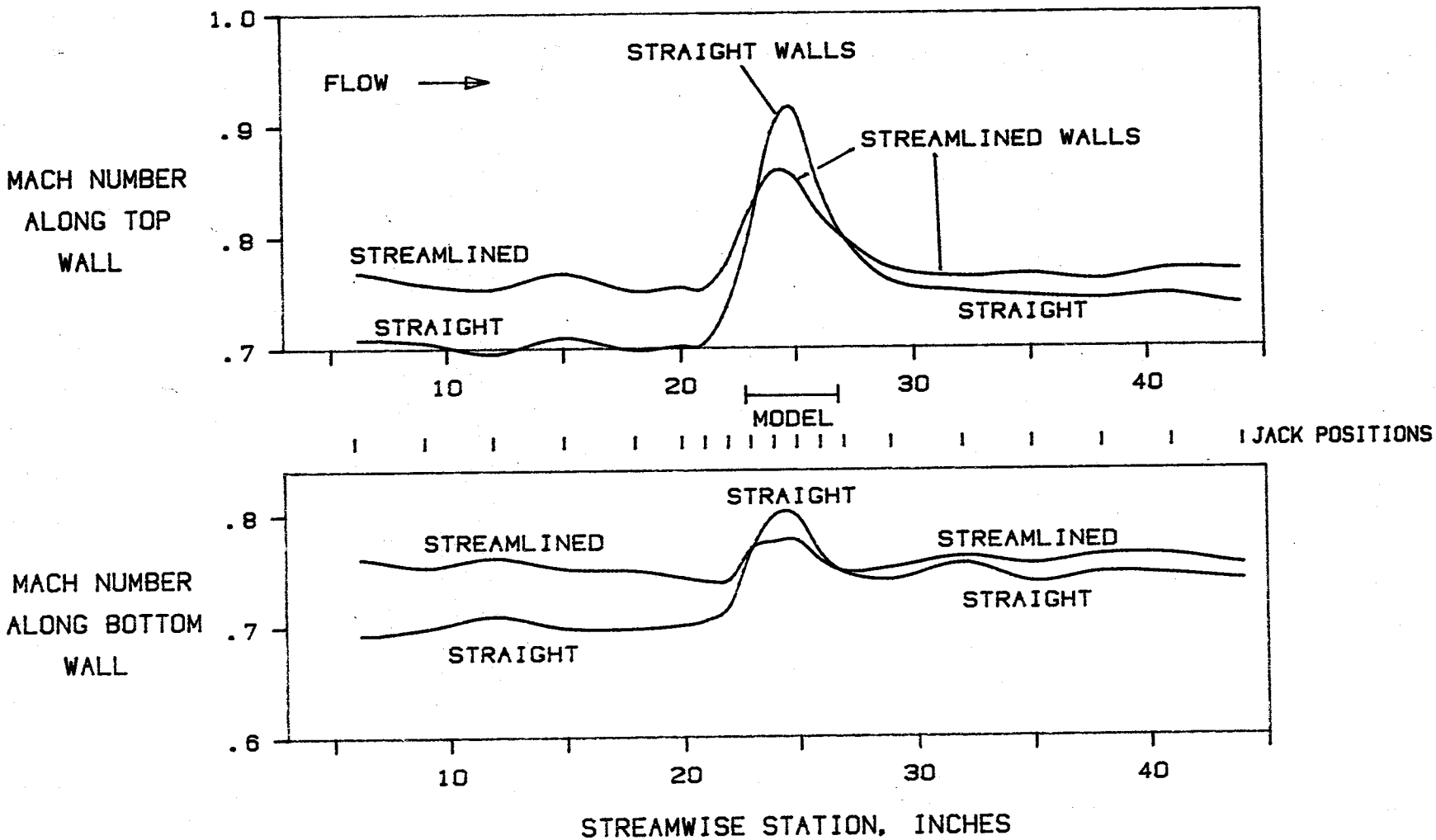


FIG 3. TRANSONIC MEASUREMENTS WITH CAST 7 AT ZERO A-O-A. DISTRIBUTIONS OF MACH NUMBER ALONG CERTERLINES OF STRAIGHT AND STREAMLINED WALLS.

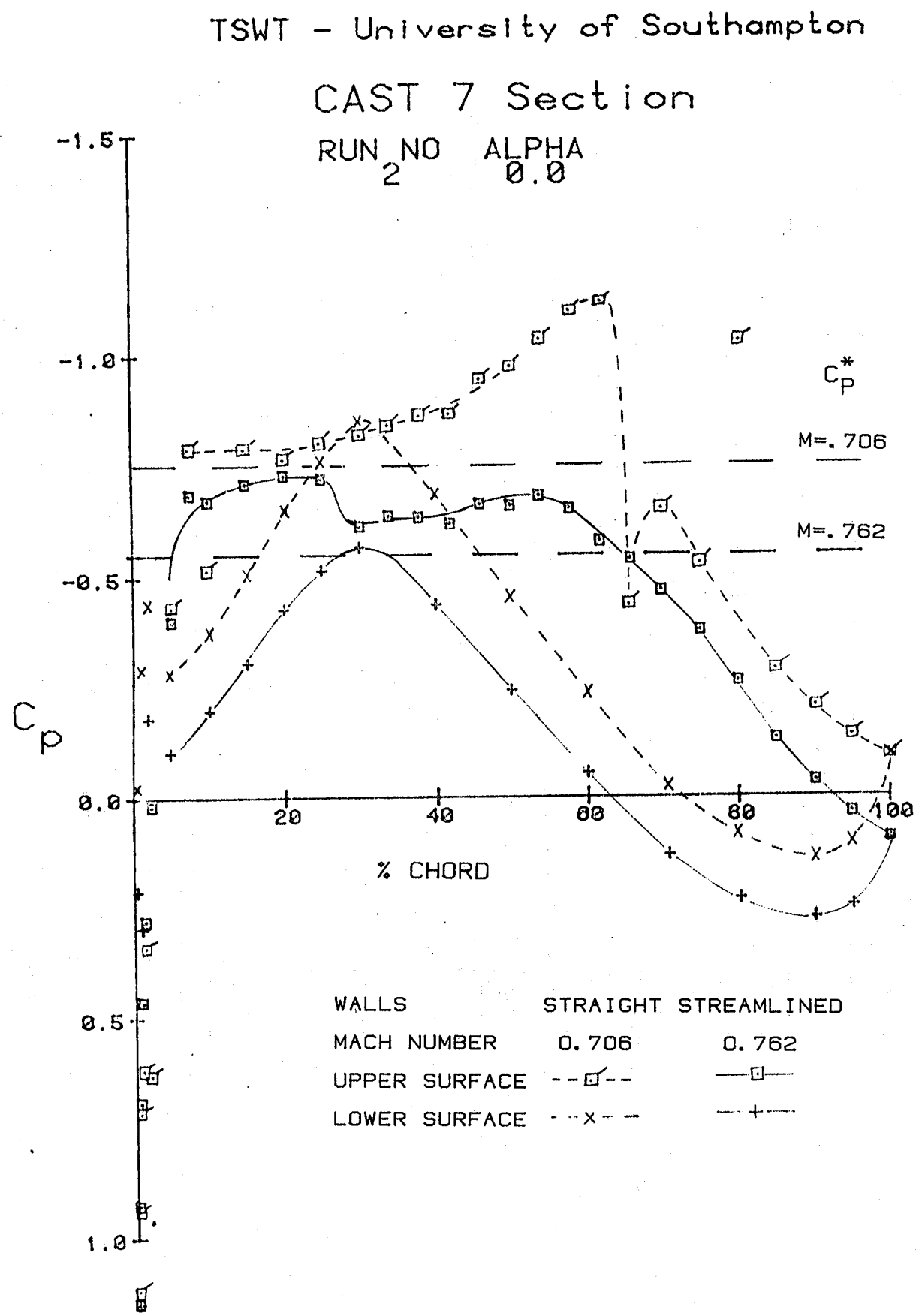


FIG 4. SECTION PRESSURE DISTRIBUTIONS WITH THE INITIAL STRAIGHT WALLS AND THE SUBSEQUENT STREAMLINED WALLS RUN AT A HIGHER REFERENCE MACH NUMBER.

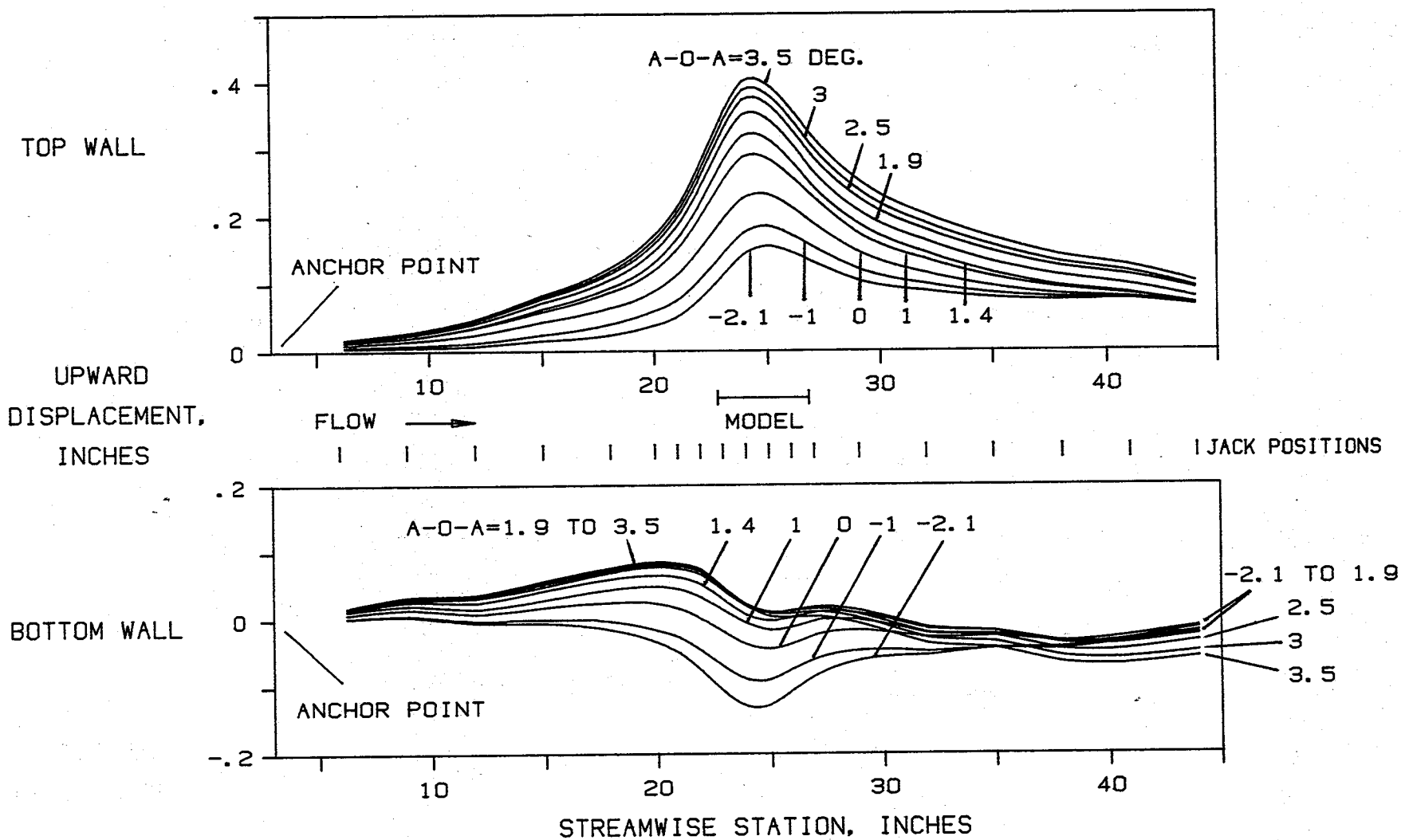


FIG 5. TRANSONIC MEASUREMENTS WITH CAST 7. DISPLACEMENTS OF WALLS FROM THEIR AERODYNAMICALLY STRAIGHT CONTOURS. WALLS ARE STREAMLINED AT MACH 0.76

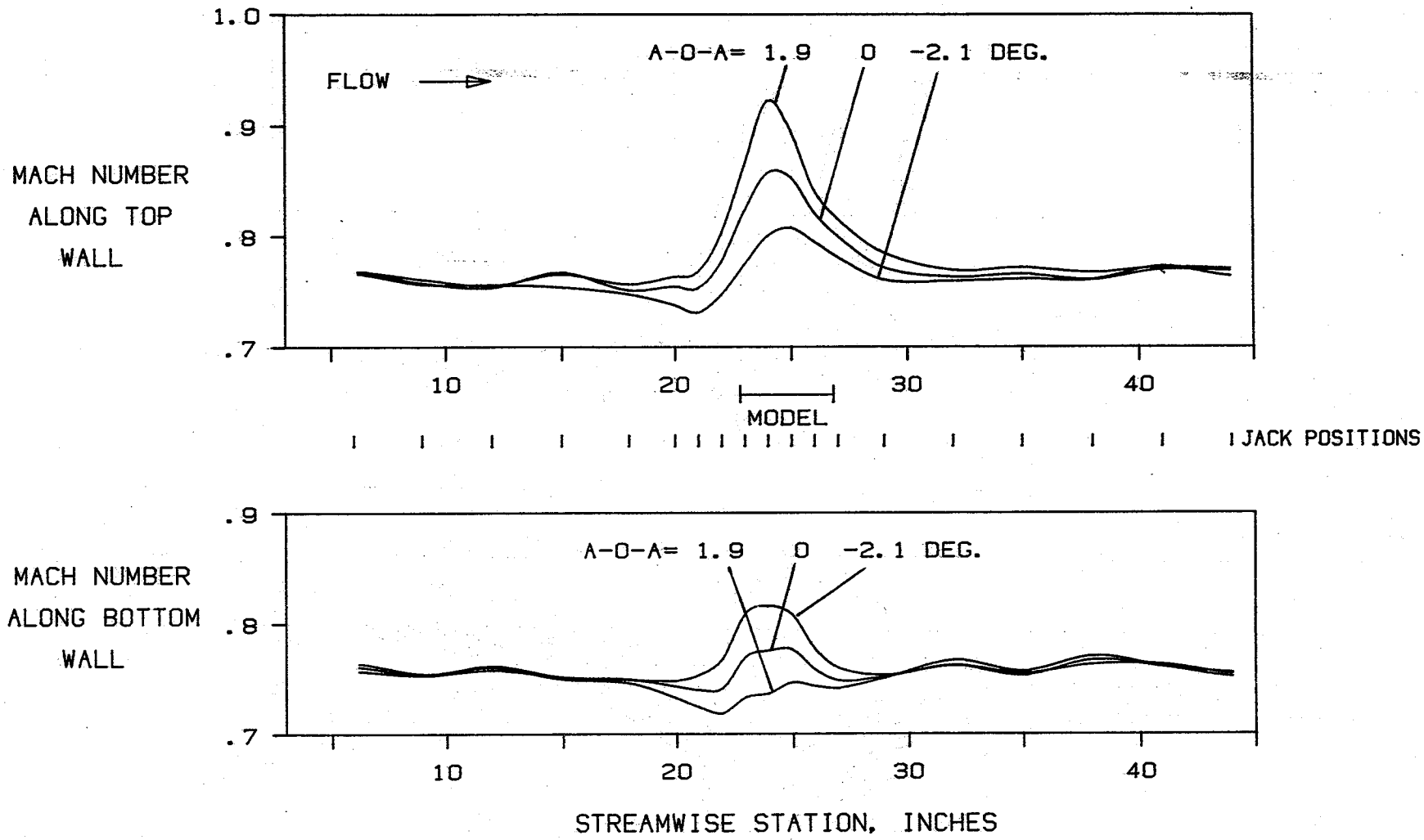


FIG 6. TRANSONIC MEASUREMENTS WITH CAST 7. DISTRIBUTIONS OF MACH NUMBER ALONG CERTERLINES OF WALLS. WALLS ARE STREAMLINED AT MACH 0.76

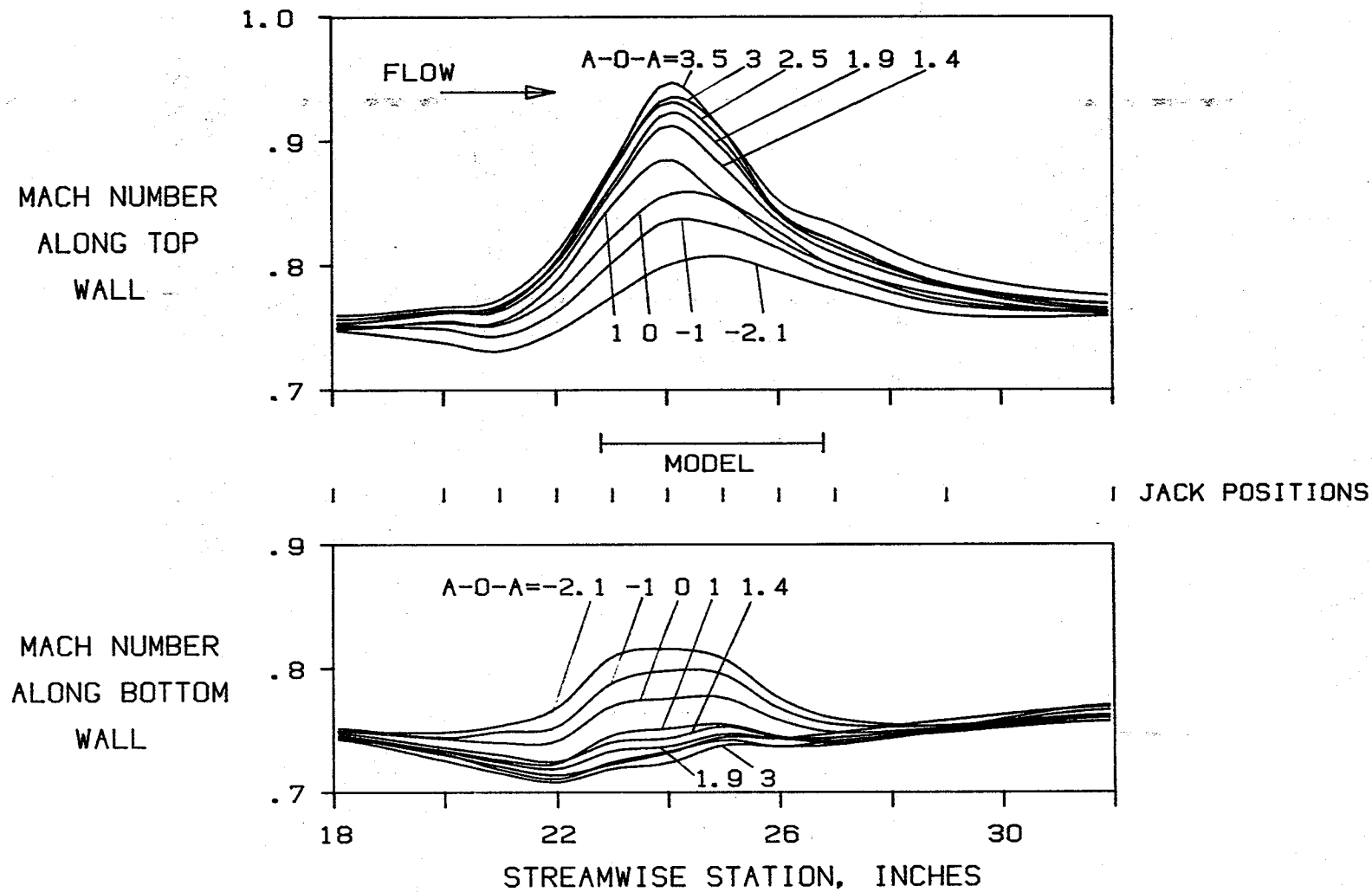


FIG 7. TRANSONIC MEASUREMENTS WITH CAST 7. DISTRIBUTIONS OF MACH NUMBER ALONG THE CERTERLINES OF THE STREAMLINED FLEXIBLE WALLS IN THE REGION OF THE MODEL. MACH 0.76.

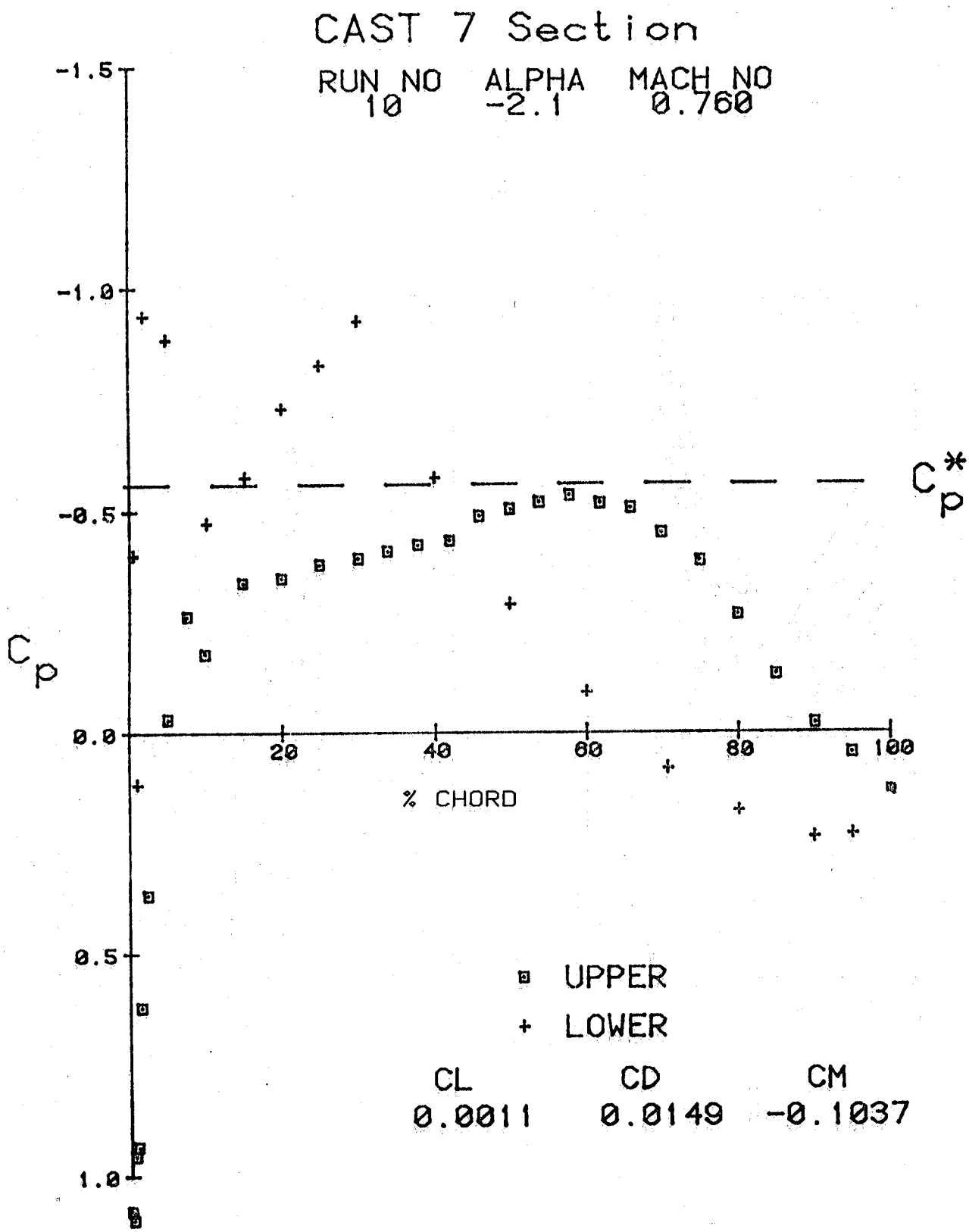


Figure 8. Airfoil pressure distributions at nominal Mach 0.76, streamlined walls.
(a) angle of attack = -2.1°

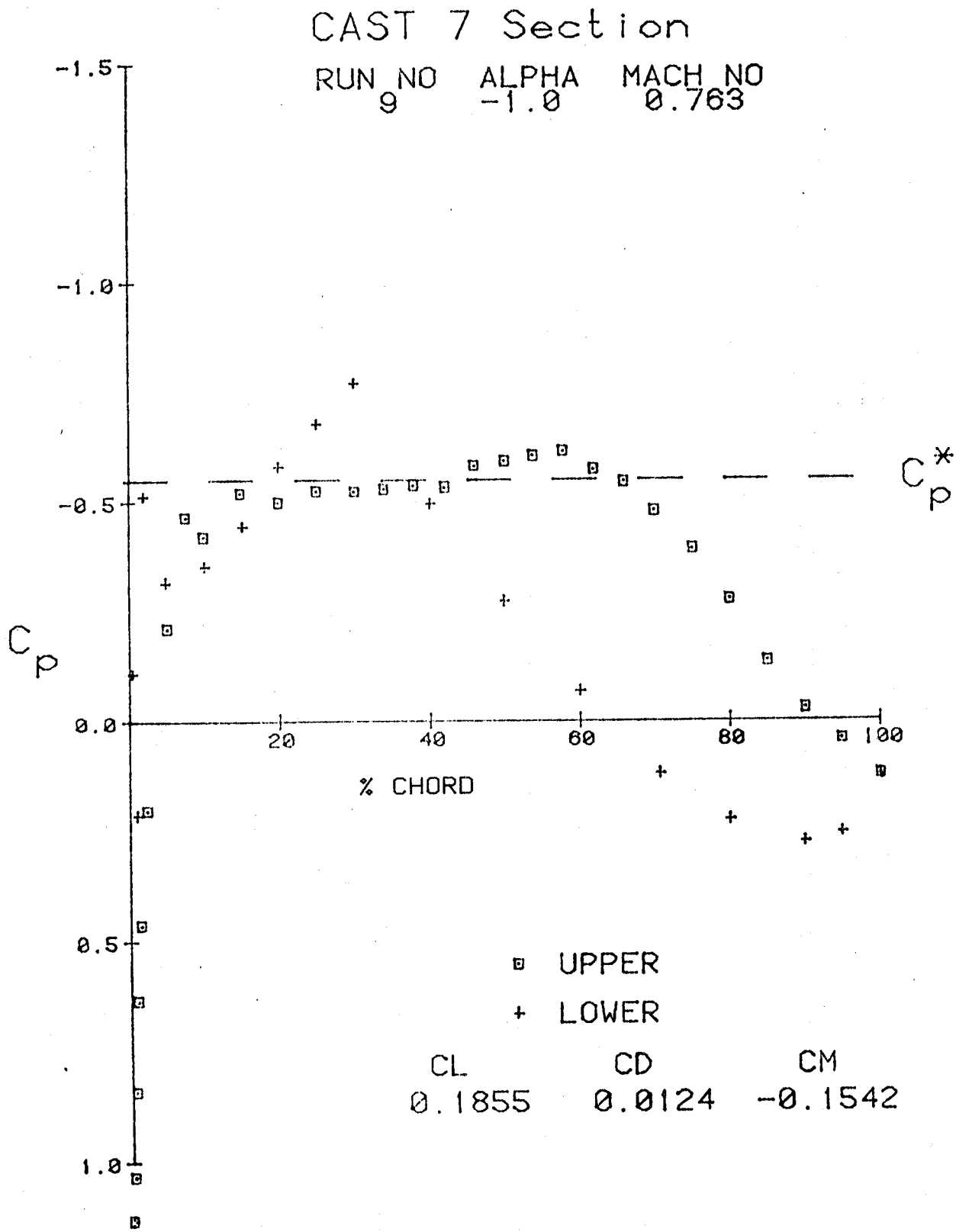


Figure 8(b). Angle of attack = -1.0°

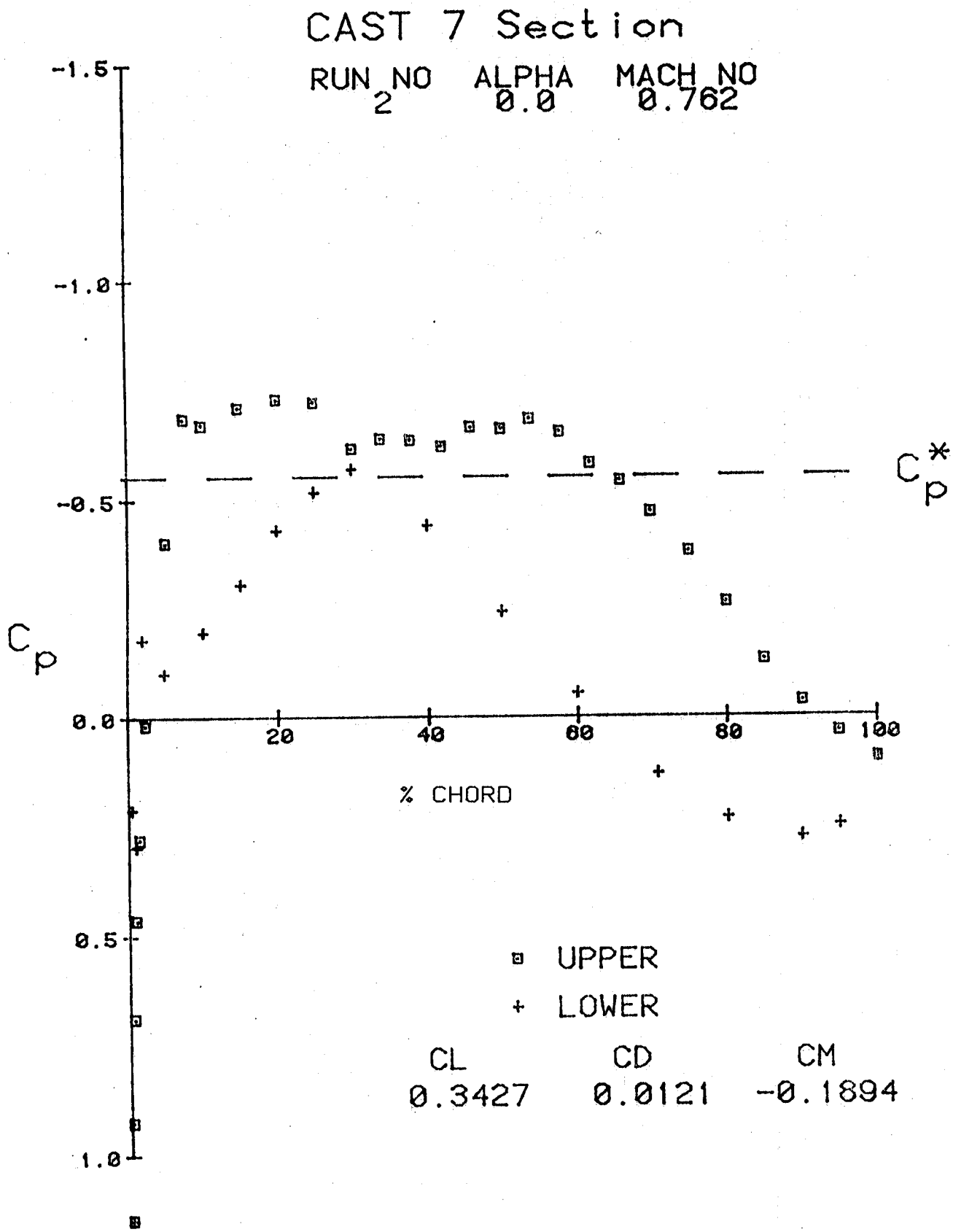


Figure 8(c). Angle of attack = zero

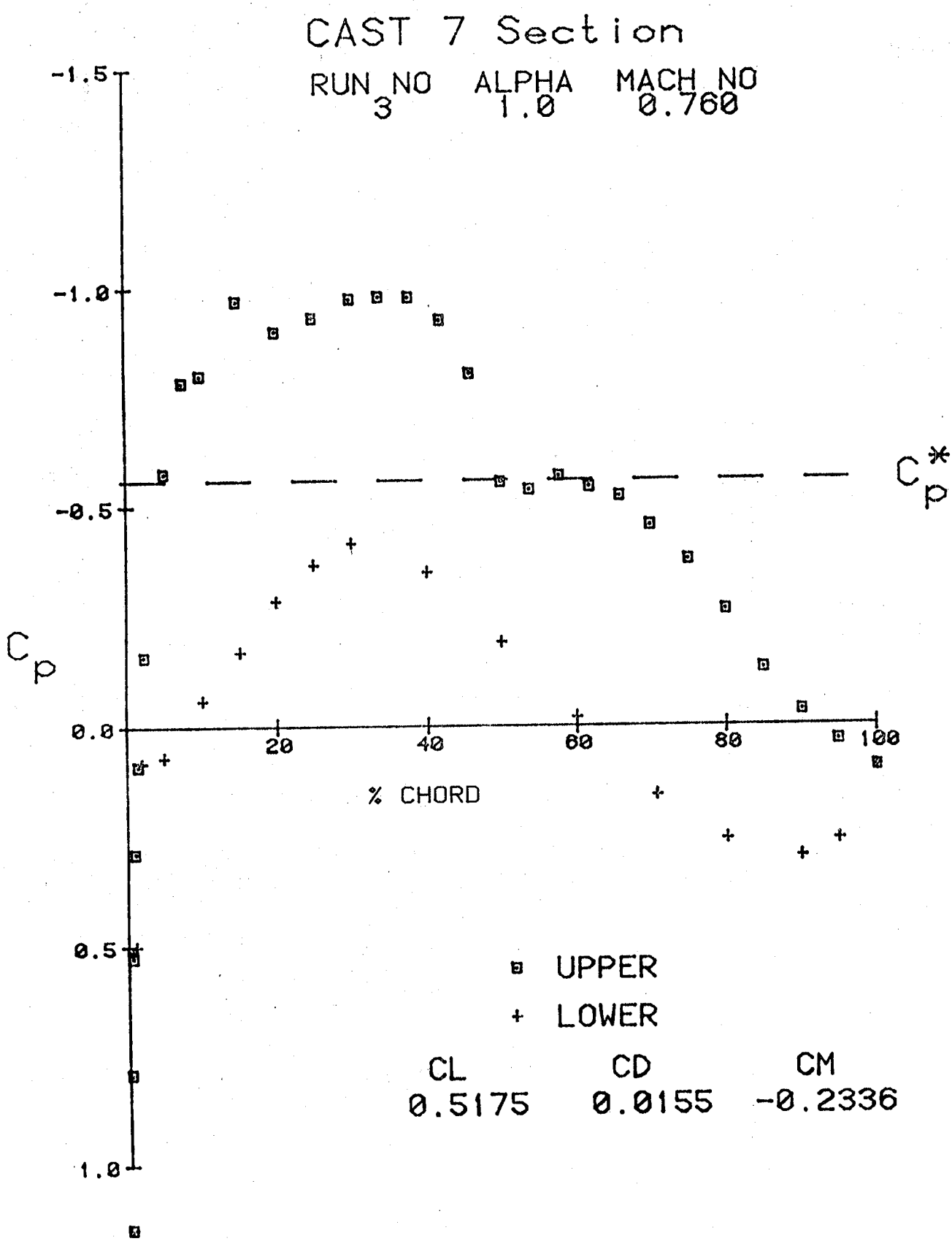


Figure 8(d). Angle of attack = 1.0°

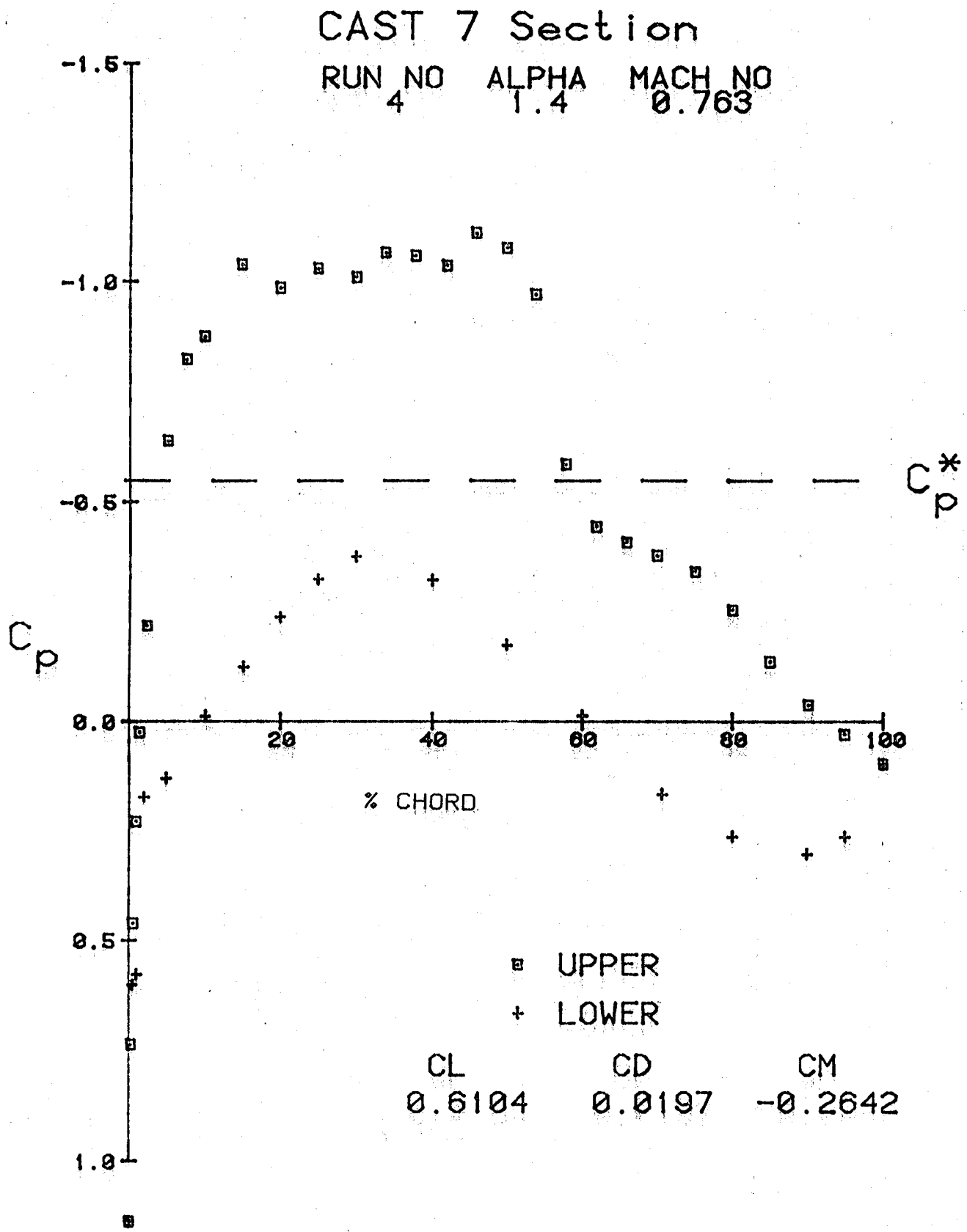


Figure 8(e). Angle of attack = 1.4^{o}

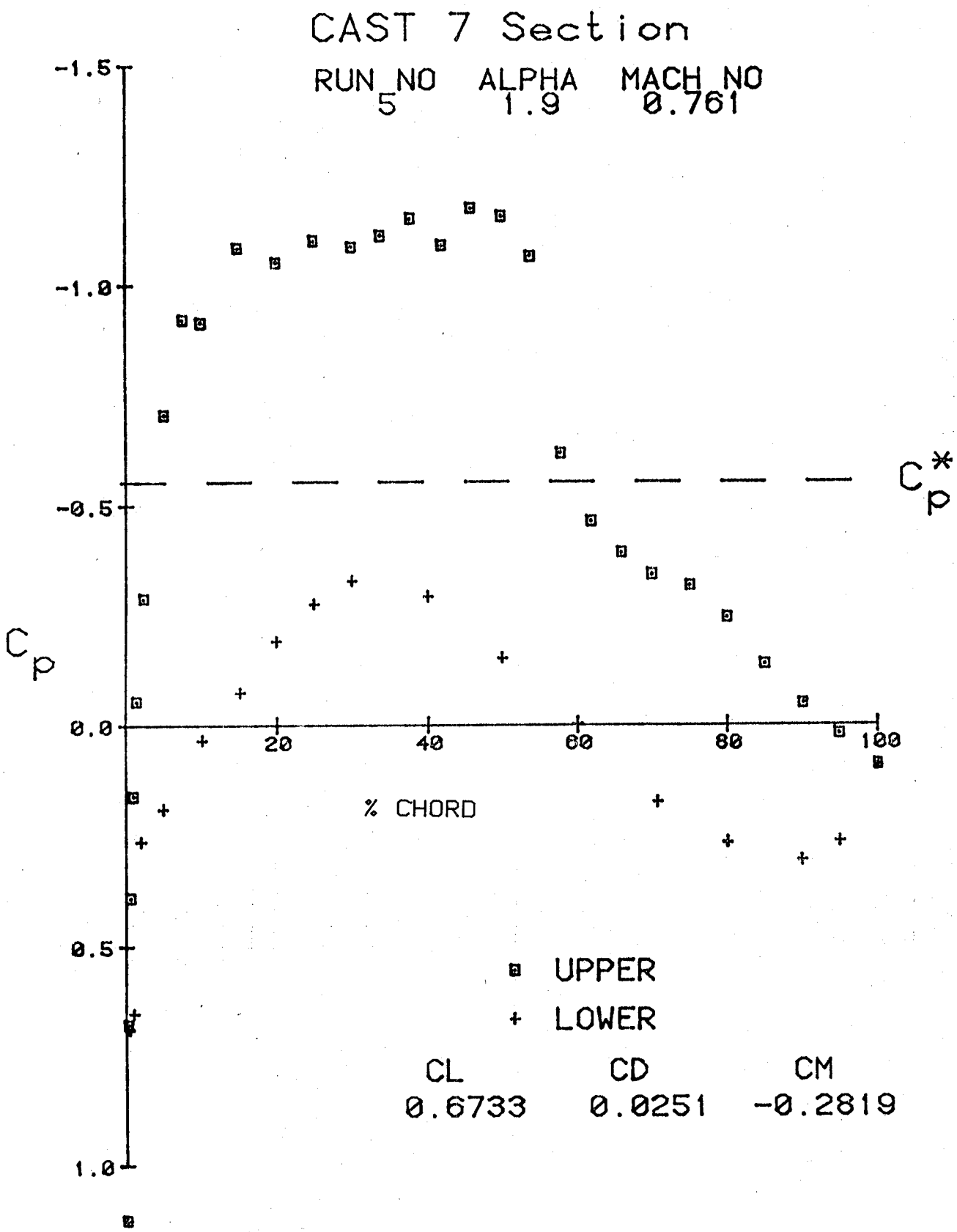


Figure 8(f). Angle of attack = 1.9°

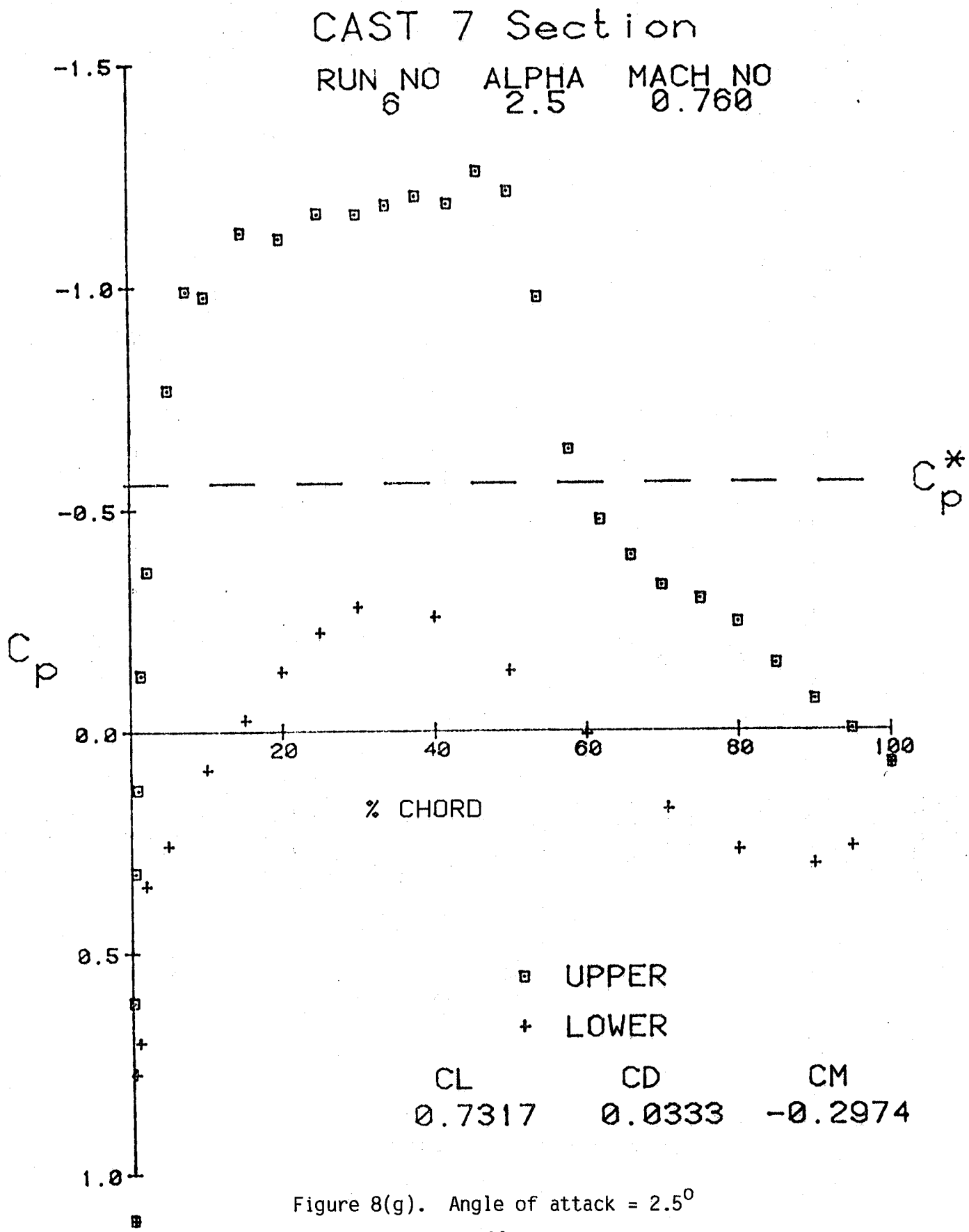


Figure 8(g). Angle of attack = 2.5°

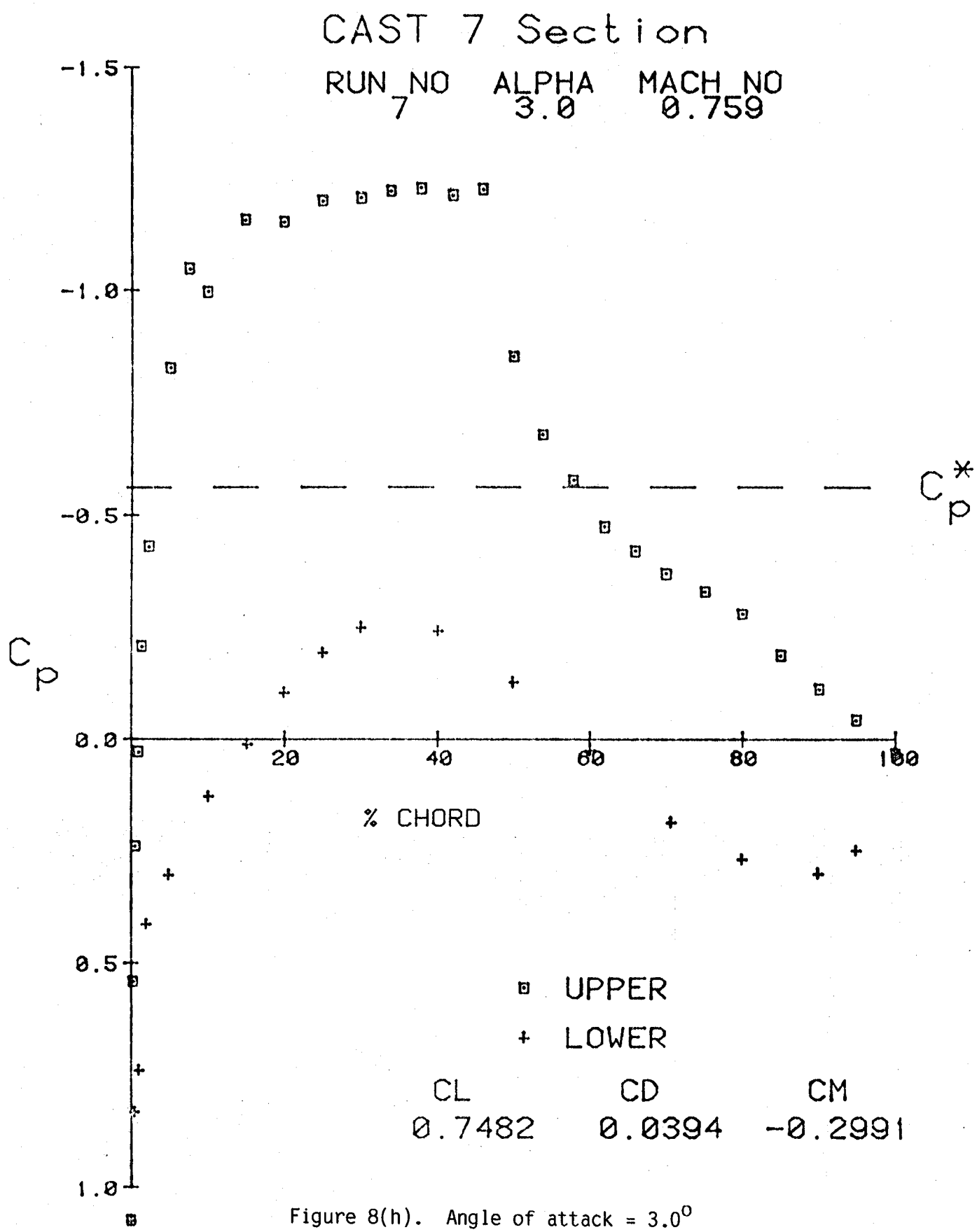


Figure 8(h). Angle of attack = 3.0^{o}

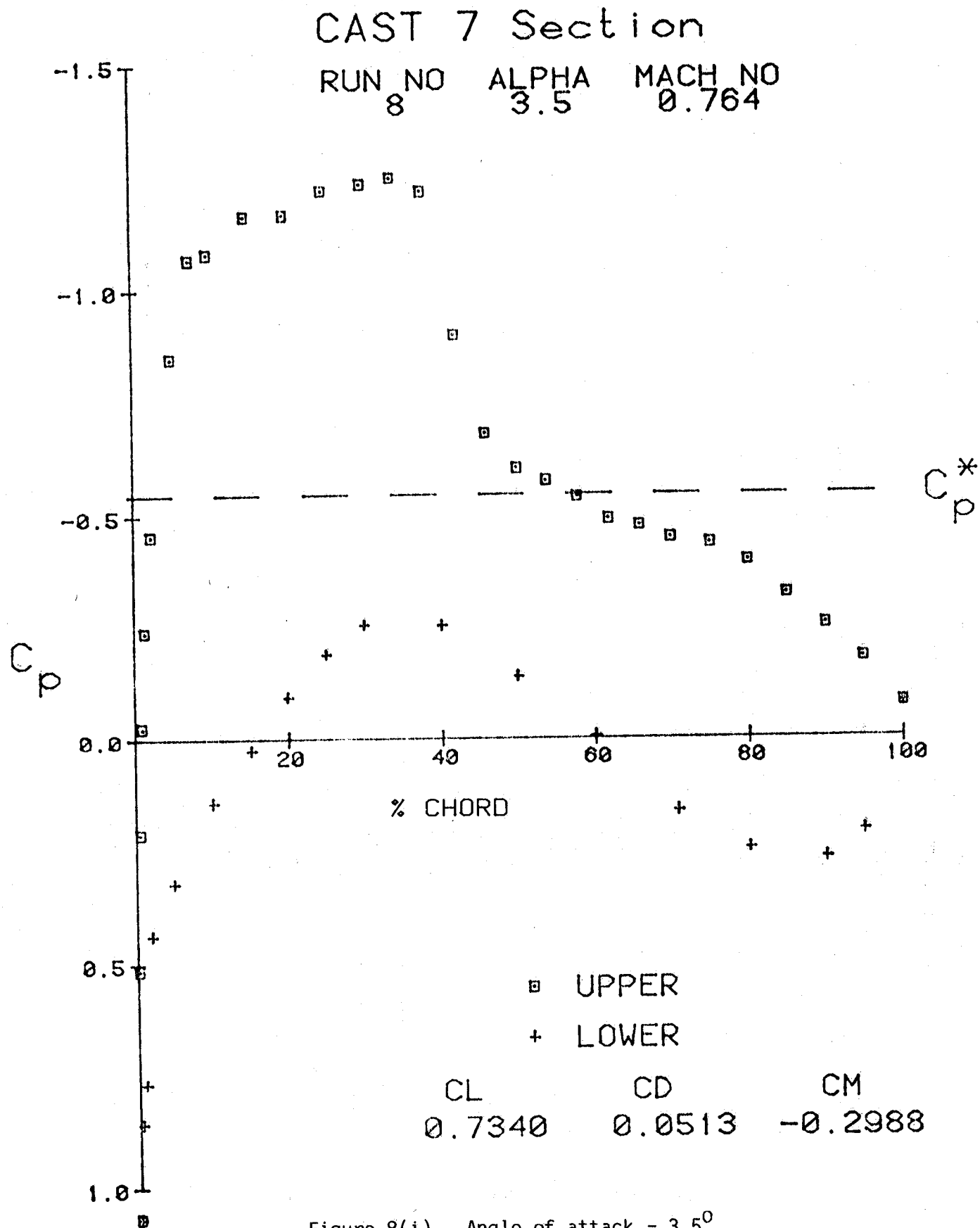
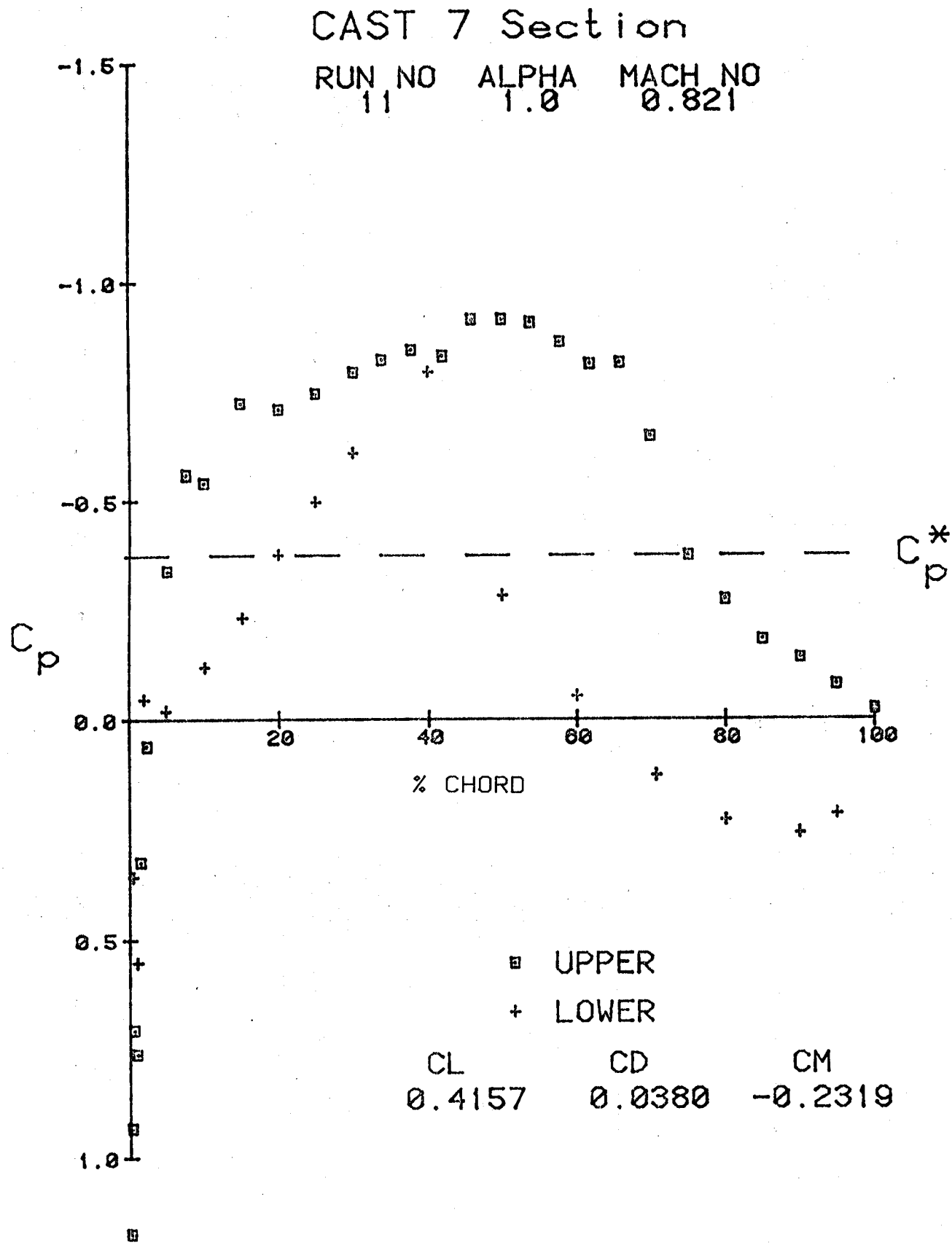


Figure 8(i). Angle of attack = 3.5^{o}



Figures 9. Airfoil pressure distributions at angle of attack giving the design lift coefficient at Mach 0.76.
(a) Mach 0.821

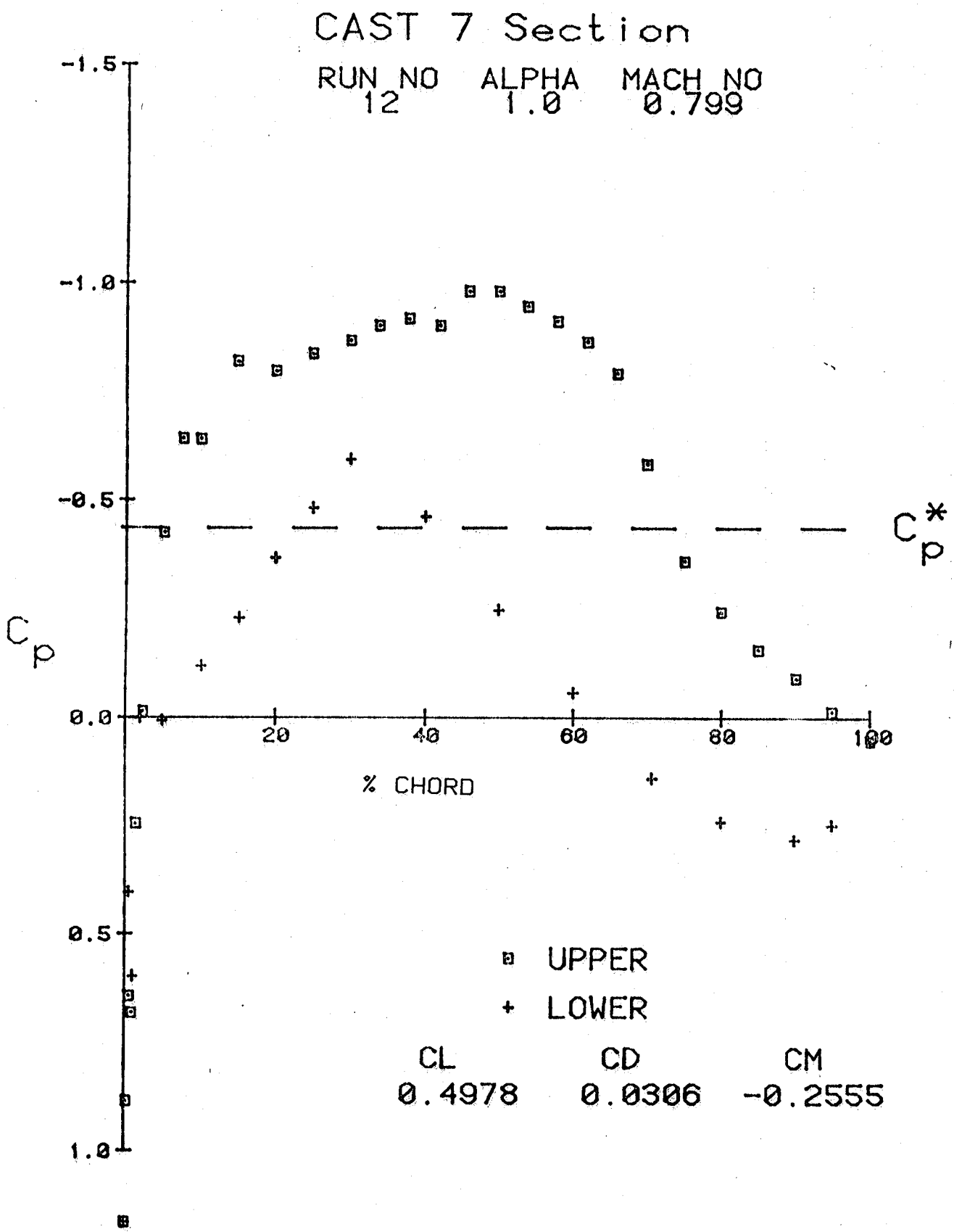


Figure 9(b). Mach 0.799

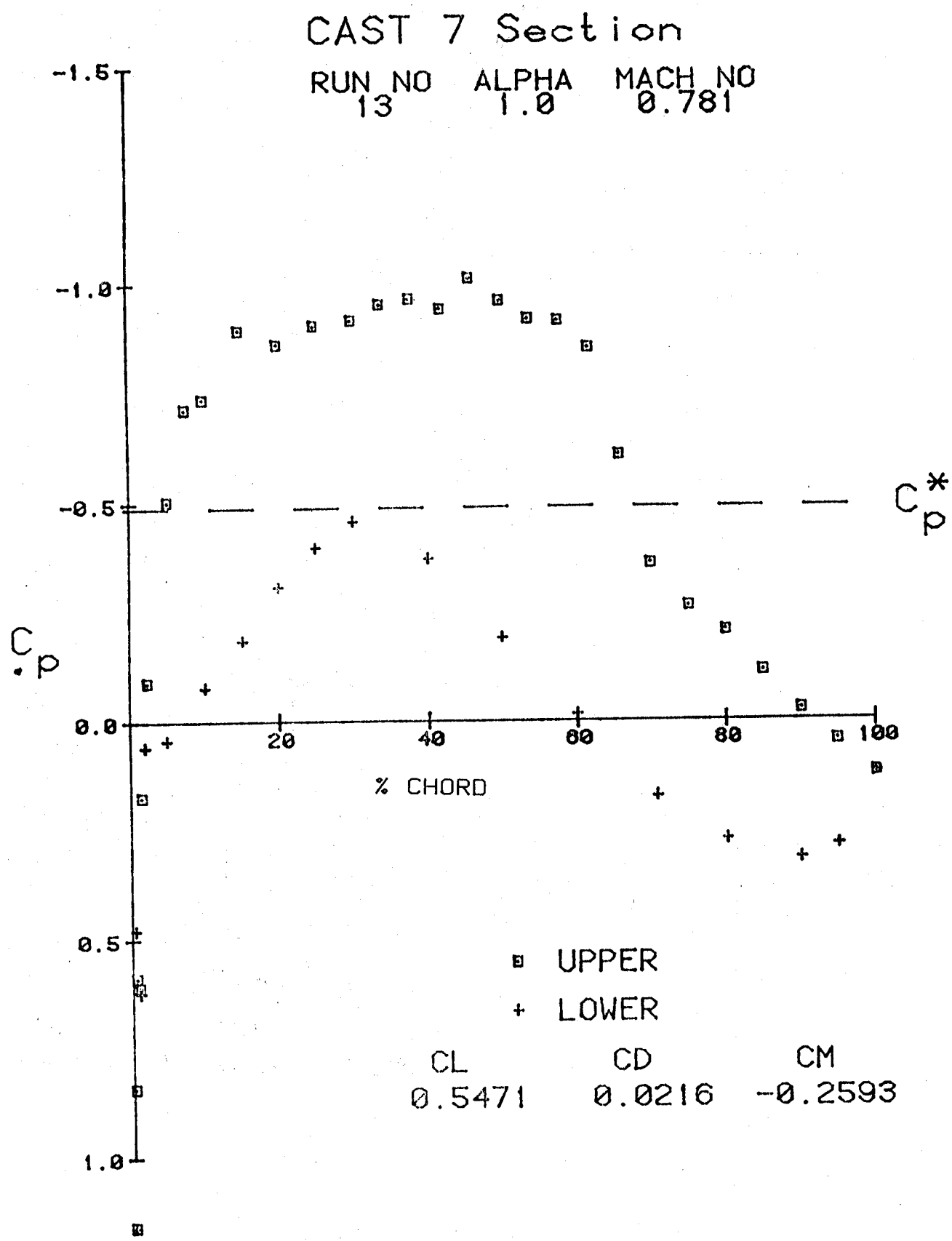


Figure 9(c). Mach 0.781

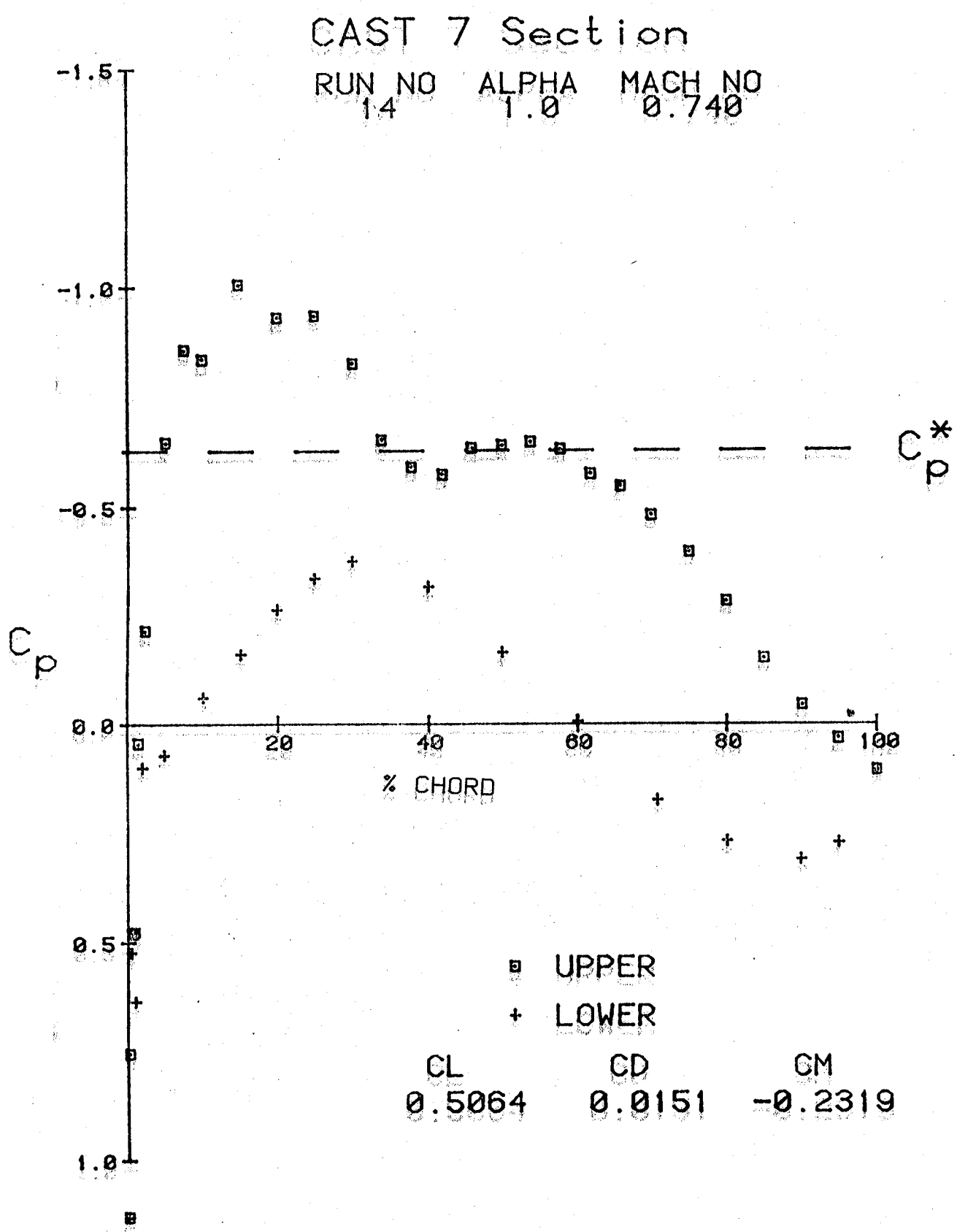


Figure 9(d). Mach 0.740

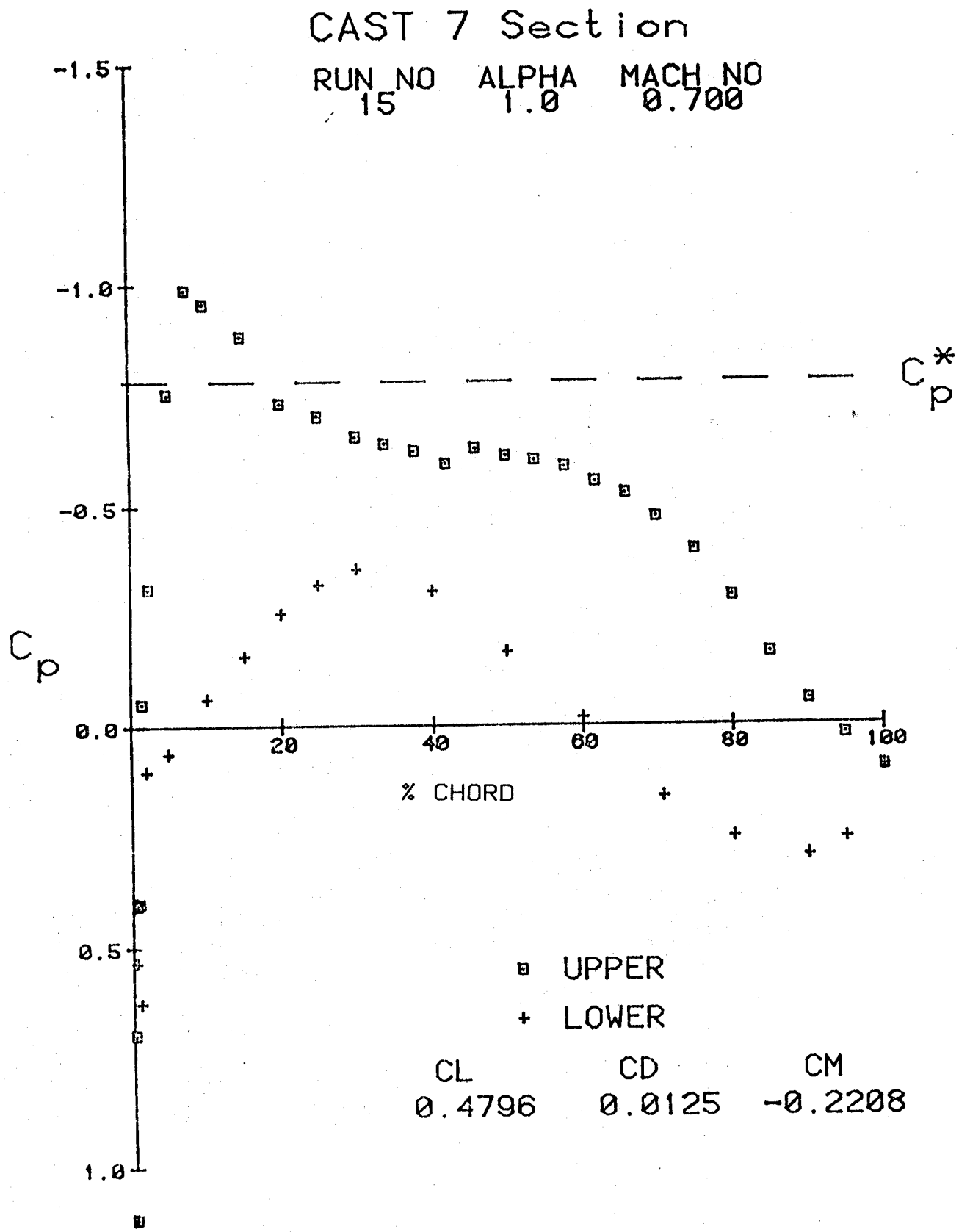


Figure 9(e). Mach 0.700

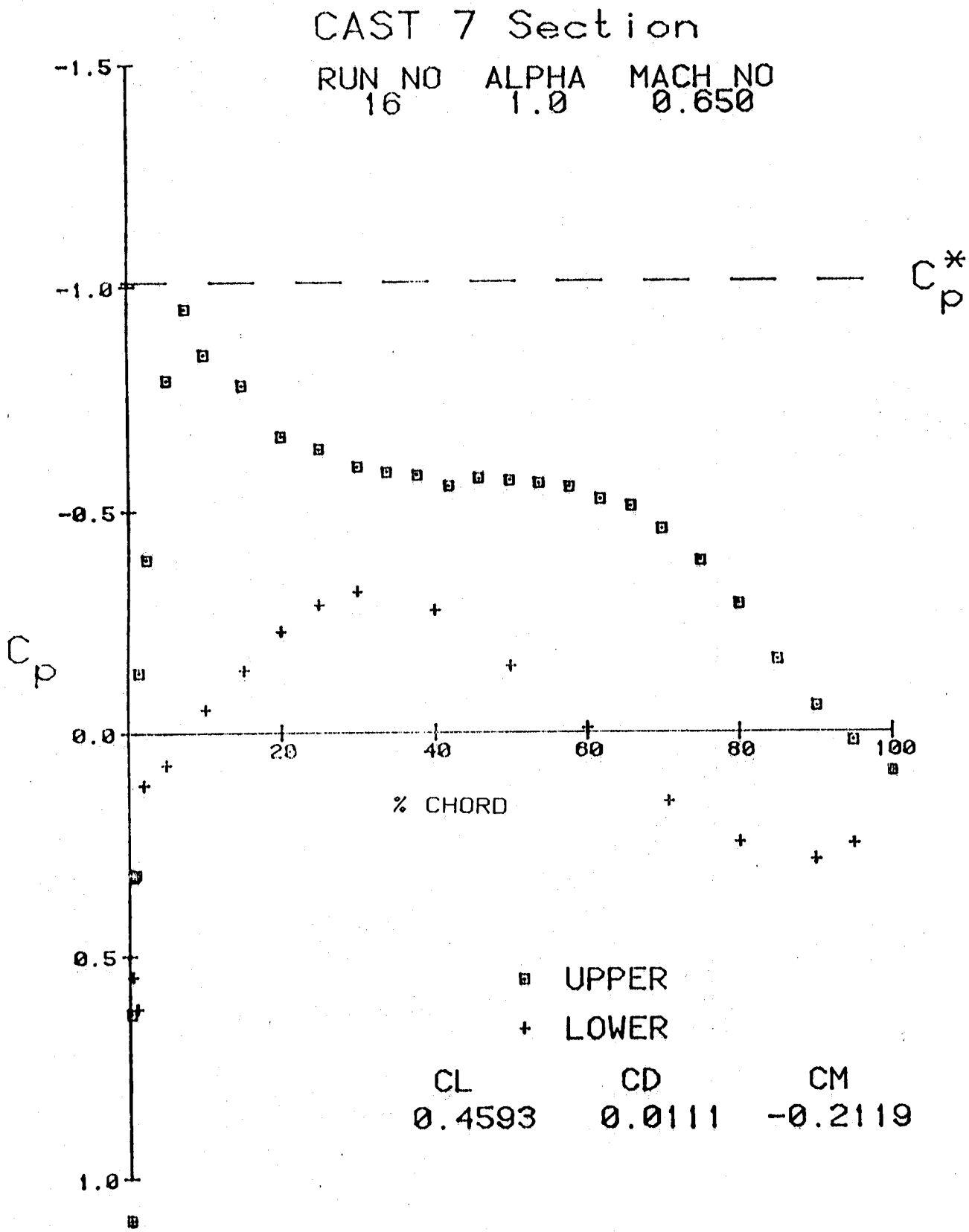


Figure 9(f). Mach 0.650

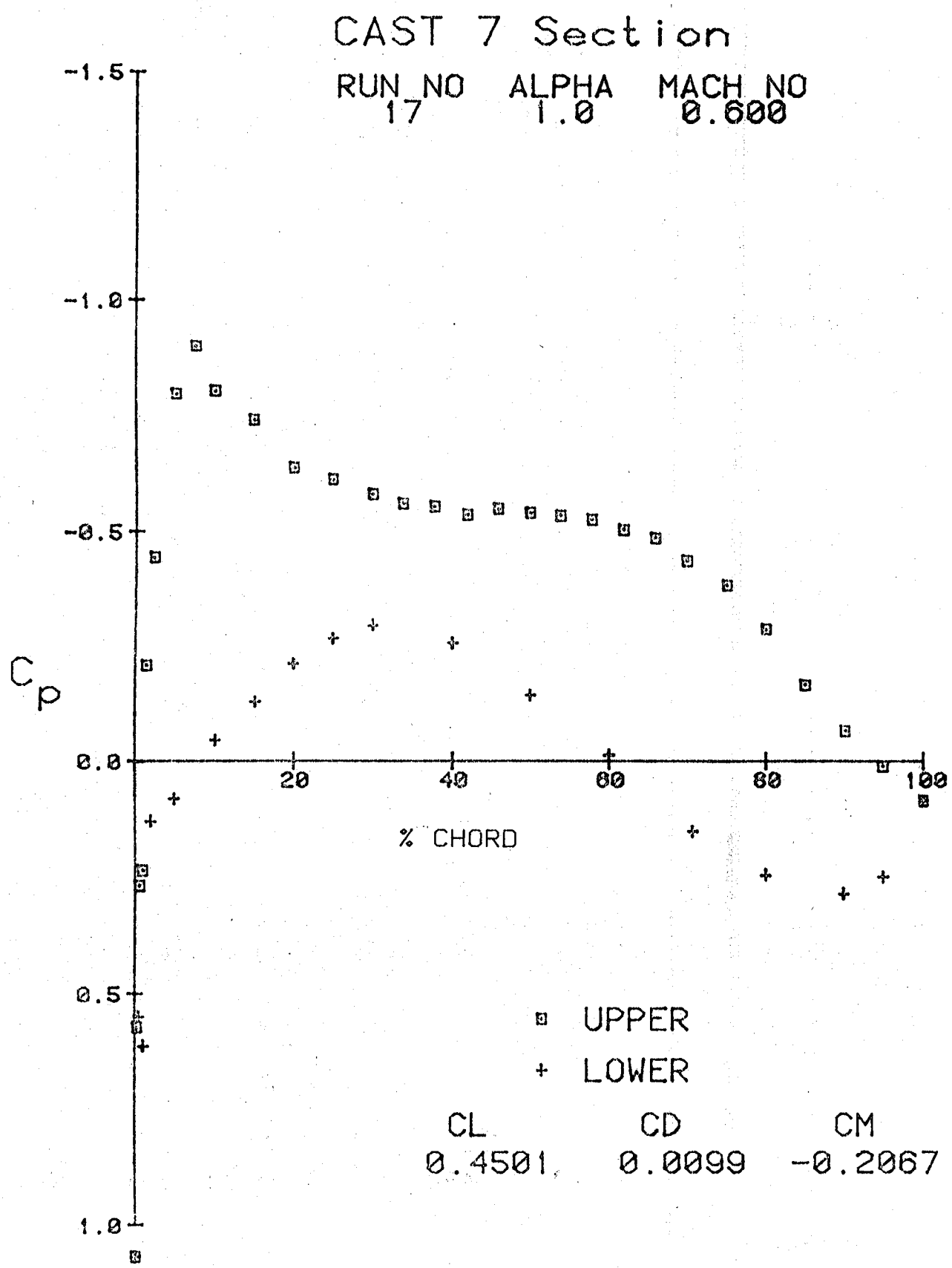


Figure 9(g). Mach 0.600

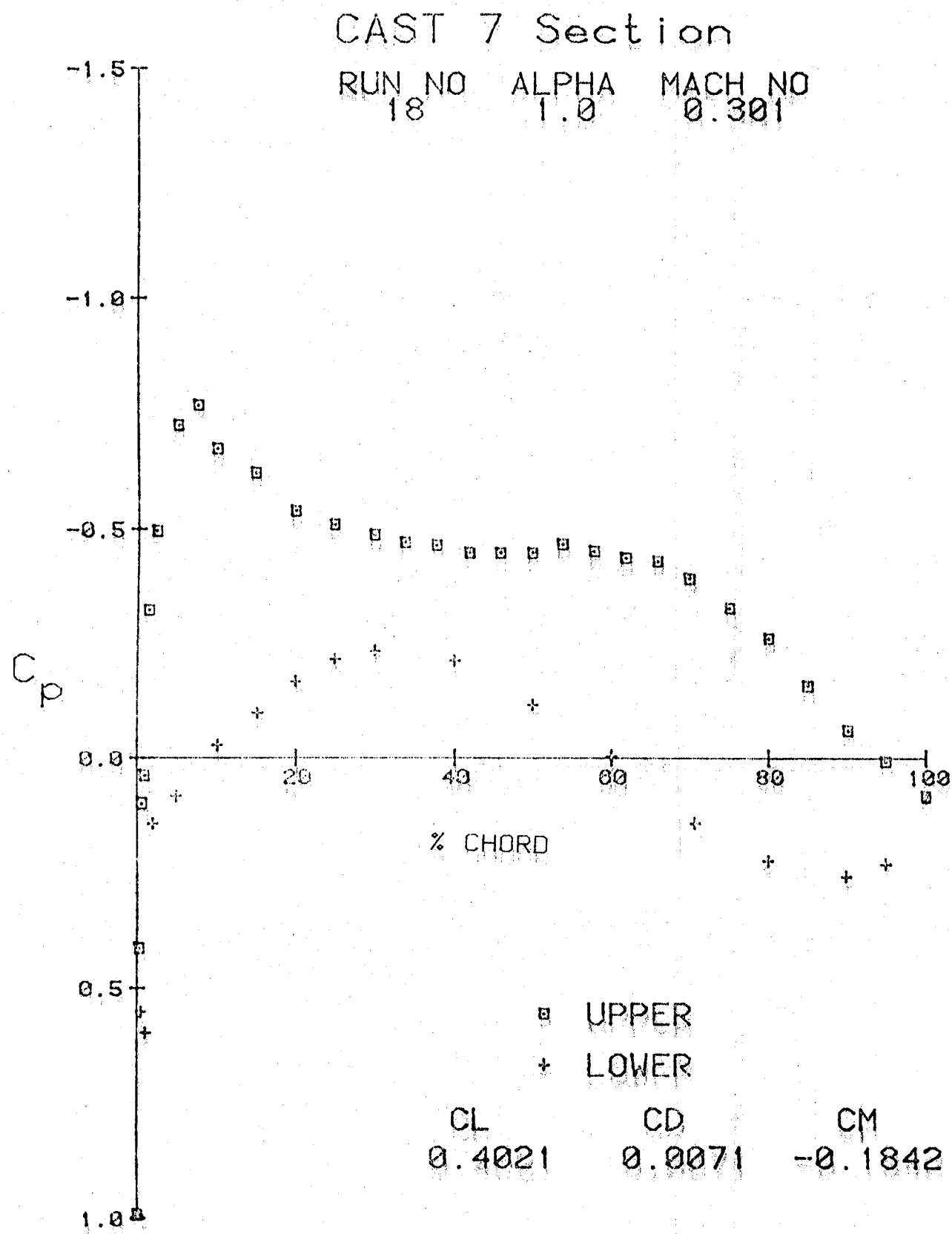


Figure 9(h). Mach 0.301

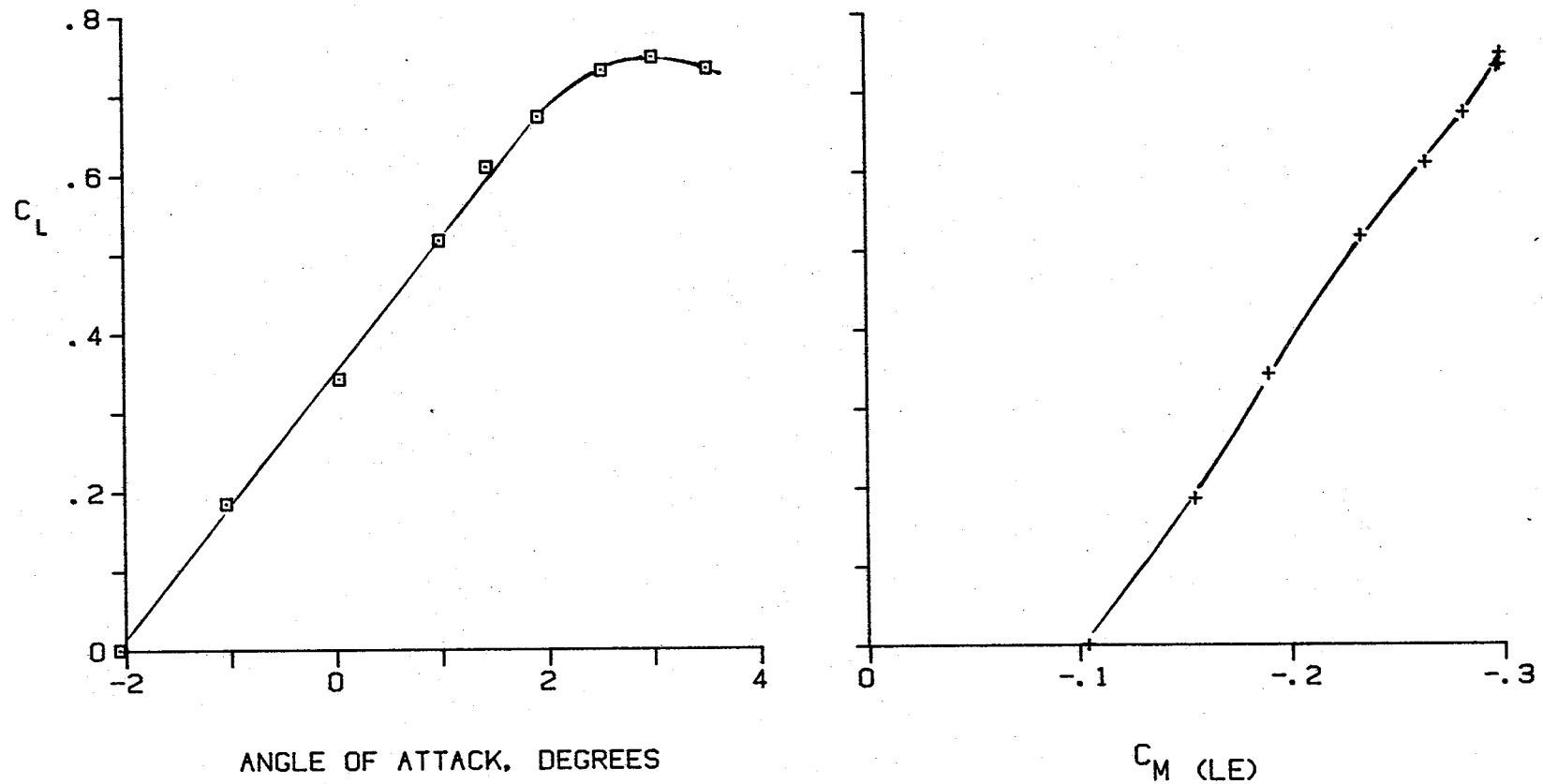


FIGURE 10. CAST 7: VARIATION OF LIFT AND PITCHING MOMENT COEFFICIENTS WITH ANGLE OF ATTACK AT MACH 0.76

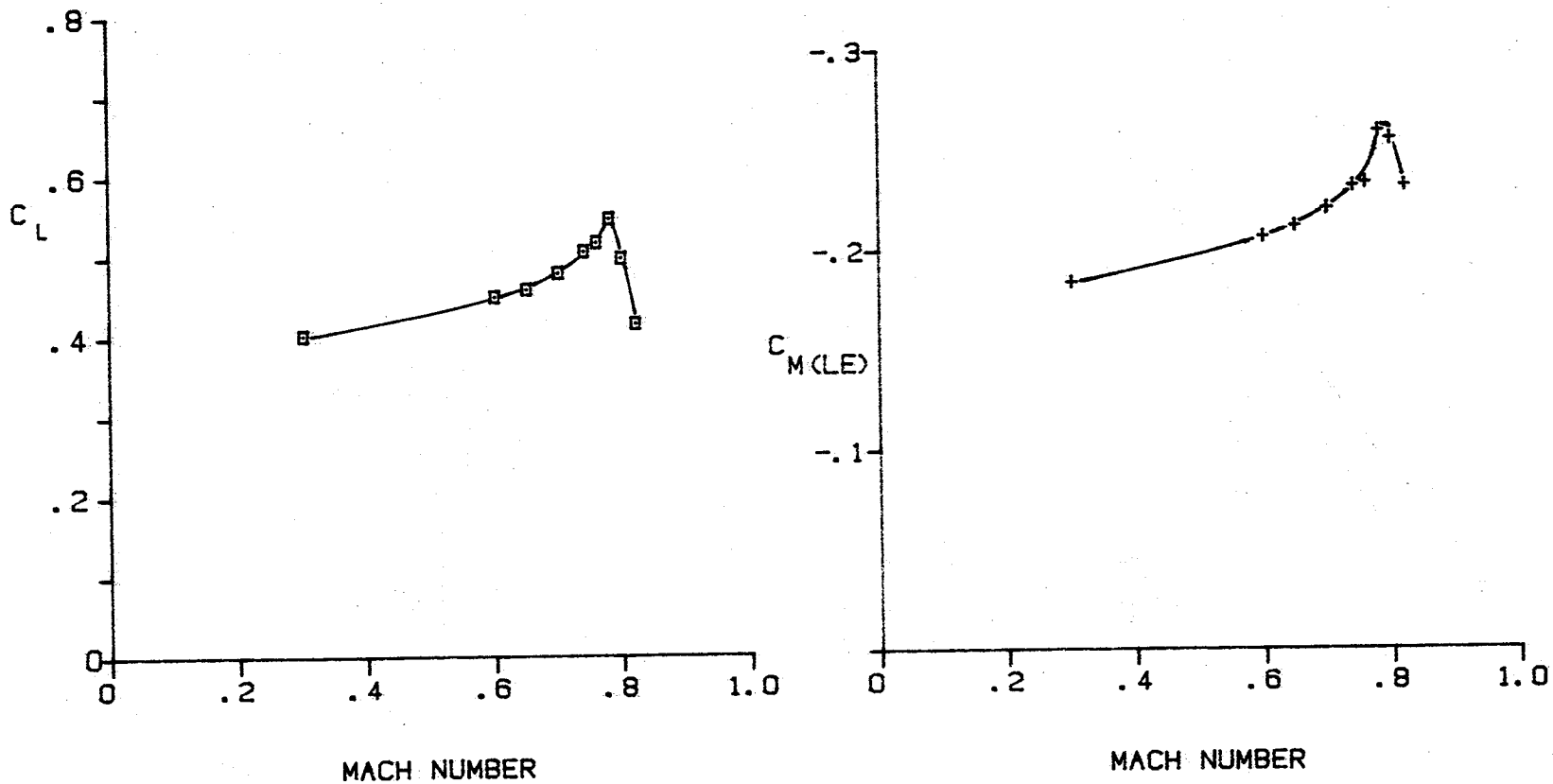


FIGURE 11. MACH NUMBER SWEEP WITH CAST 7 SECTION AT 1 DEGREE ANGLE OF ATTACK.

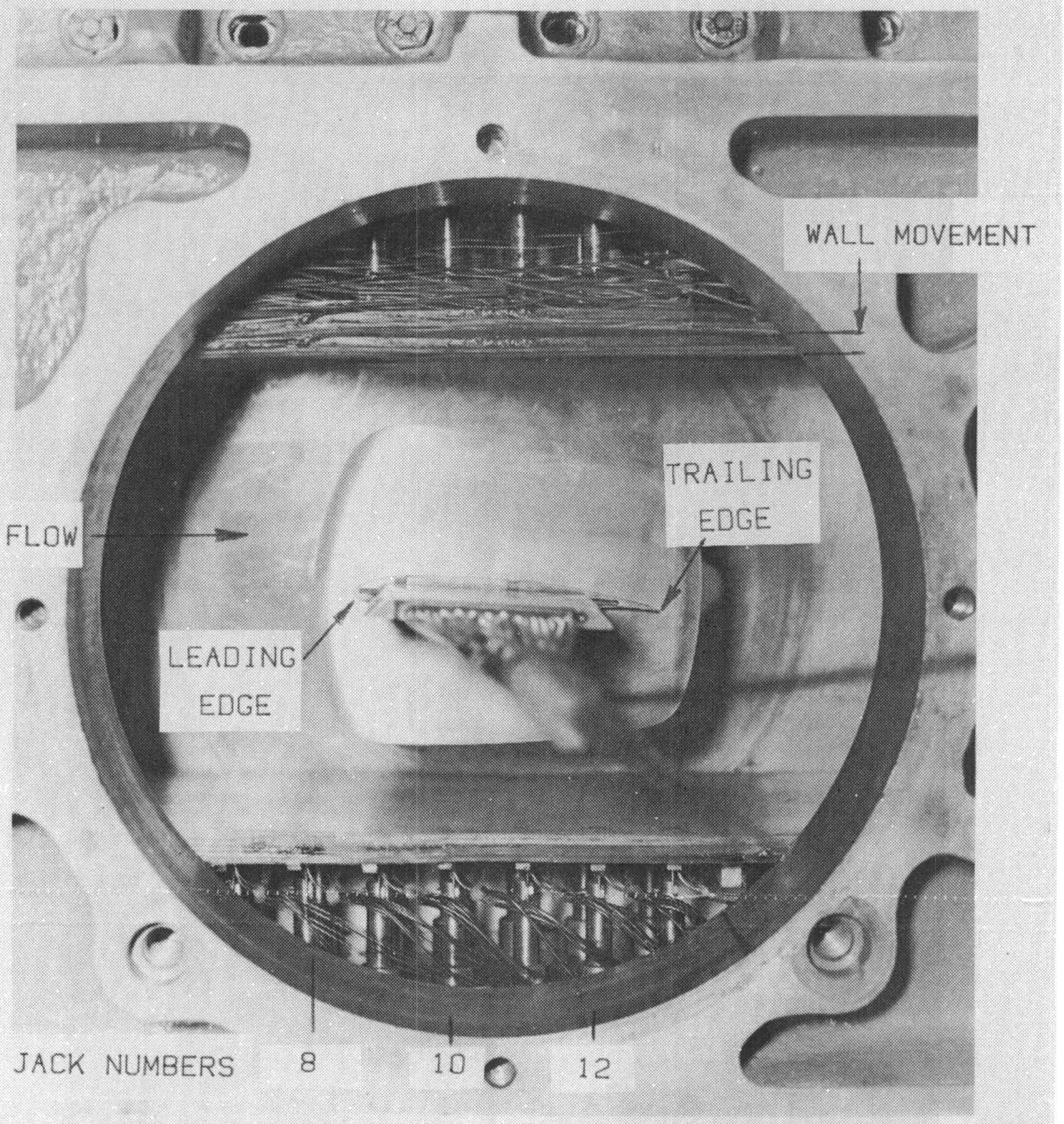


FIGURE 12. CAST 7 AT 3.5 DEGREES ANGLE OF ATTACK. DOUBLE EXPOSURE WITH WALLS STRAIGHT AND STREAMLINED AT MACH 0.76

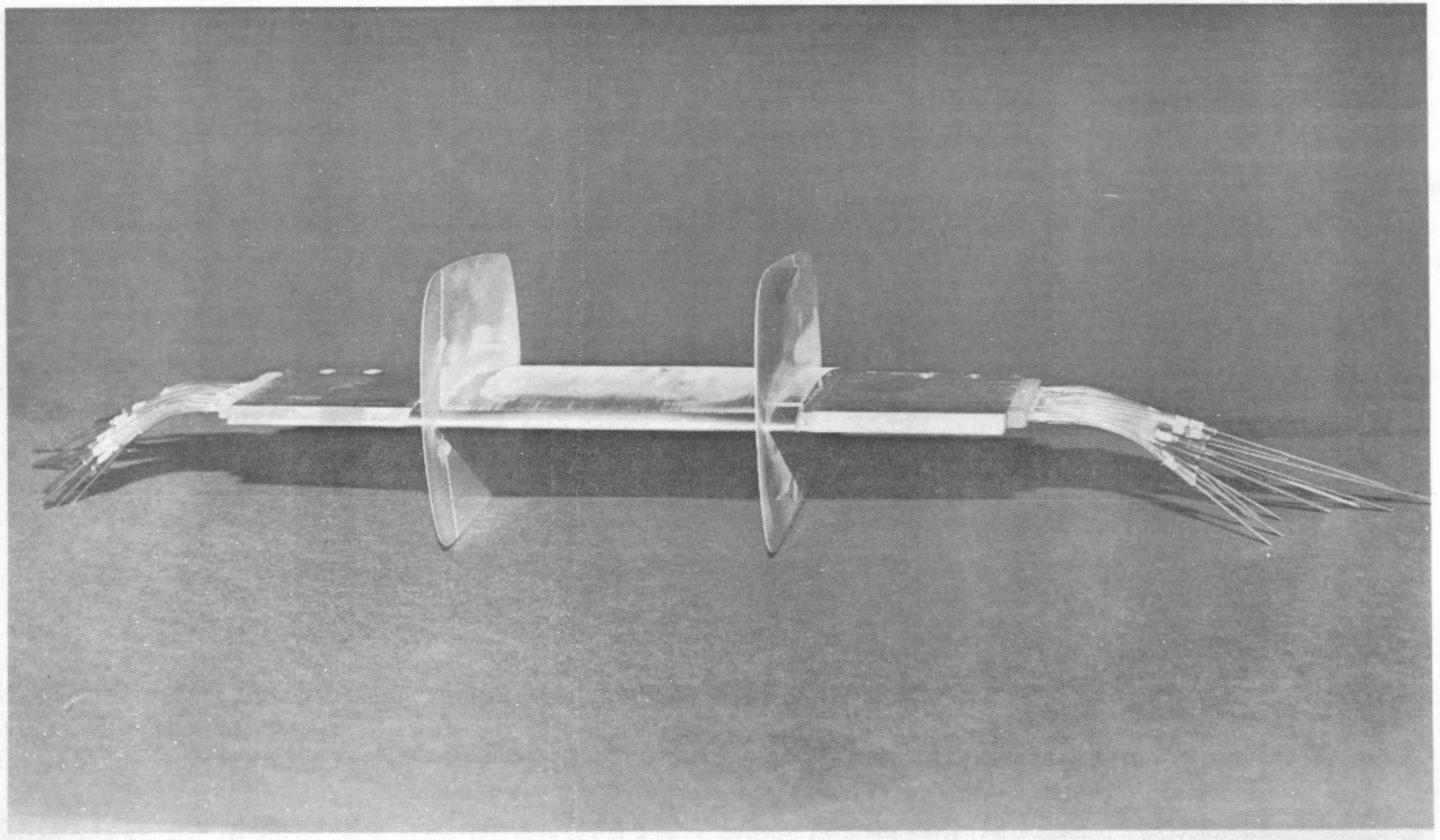


FIGURE 13. THE MODEL WITH END PLATES AFTER TESTING. THE LIGHT AREAS ARE DEPOSITS OF SILICA GEL POWDER.

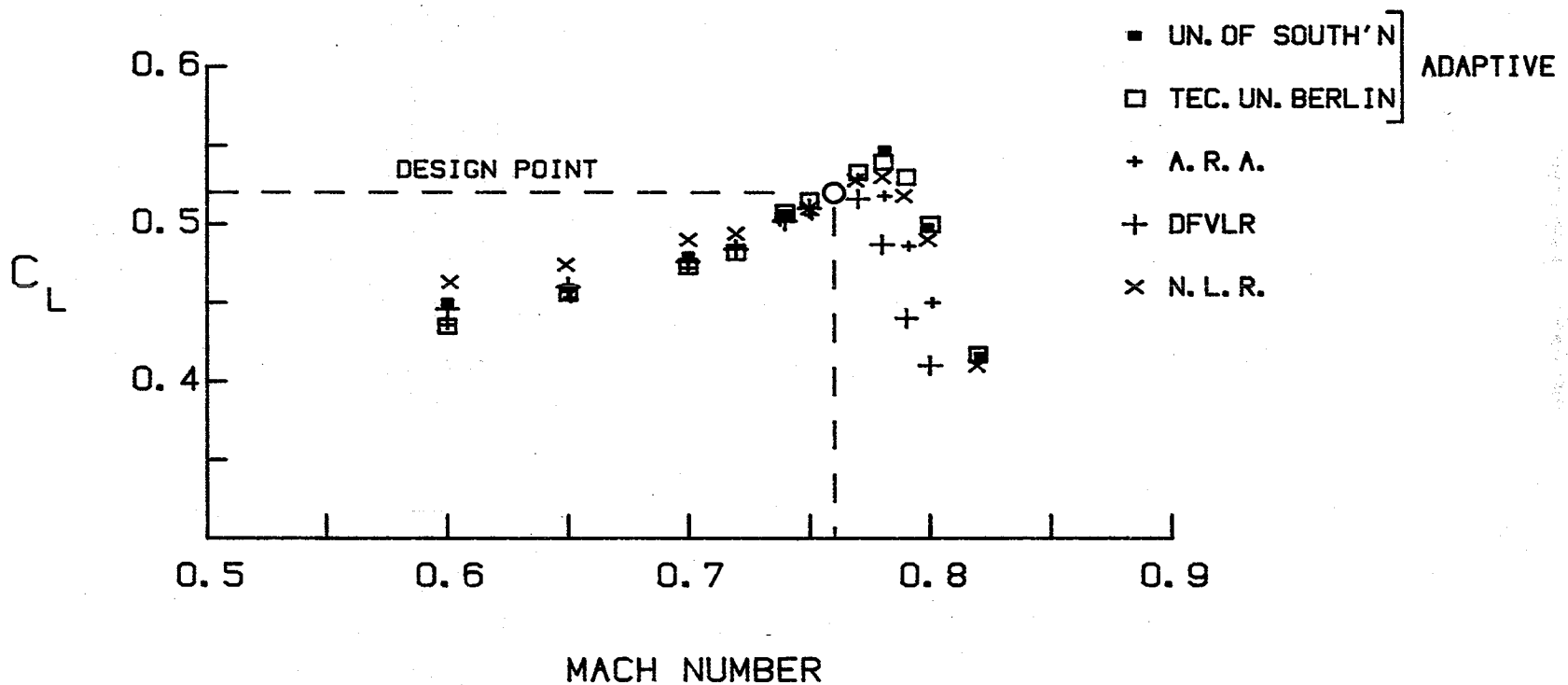


FIGURE 14. CAST-7 DATA COMPARISONS AT ANGLE OF ATTACK GIVING DESIGN C_L AT MACH 0.76

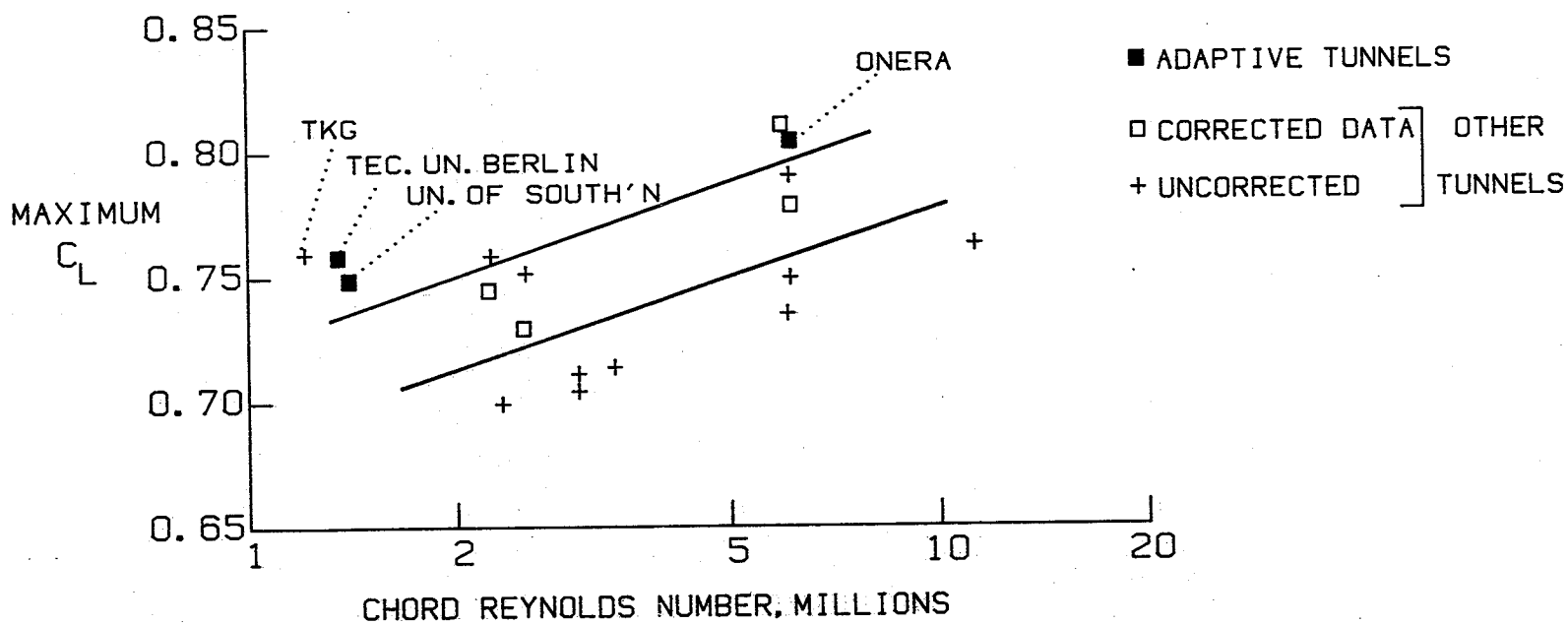


FIGURE 15. MAXIMUM LIFT COEFFICIENTS RECORDED IN ADAPTIVE AND CONVENTIONAL TEST SECTIONS.

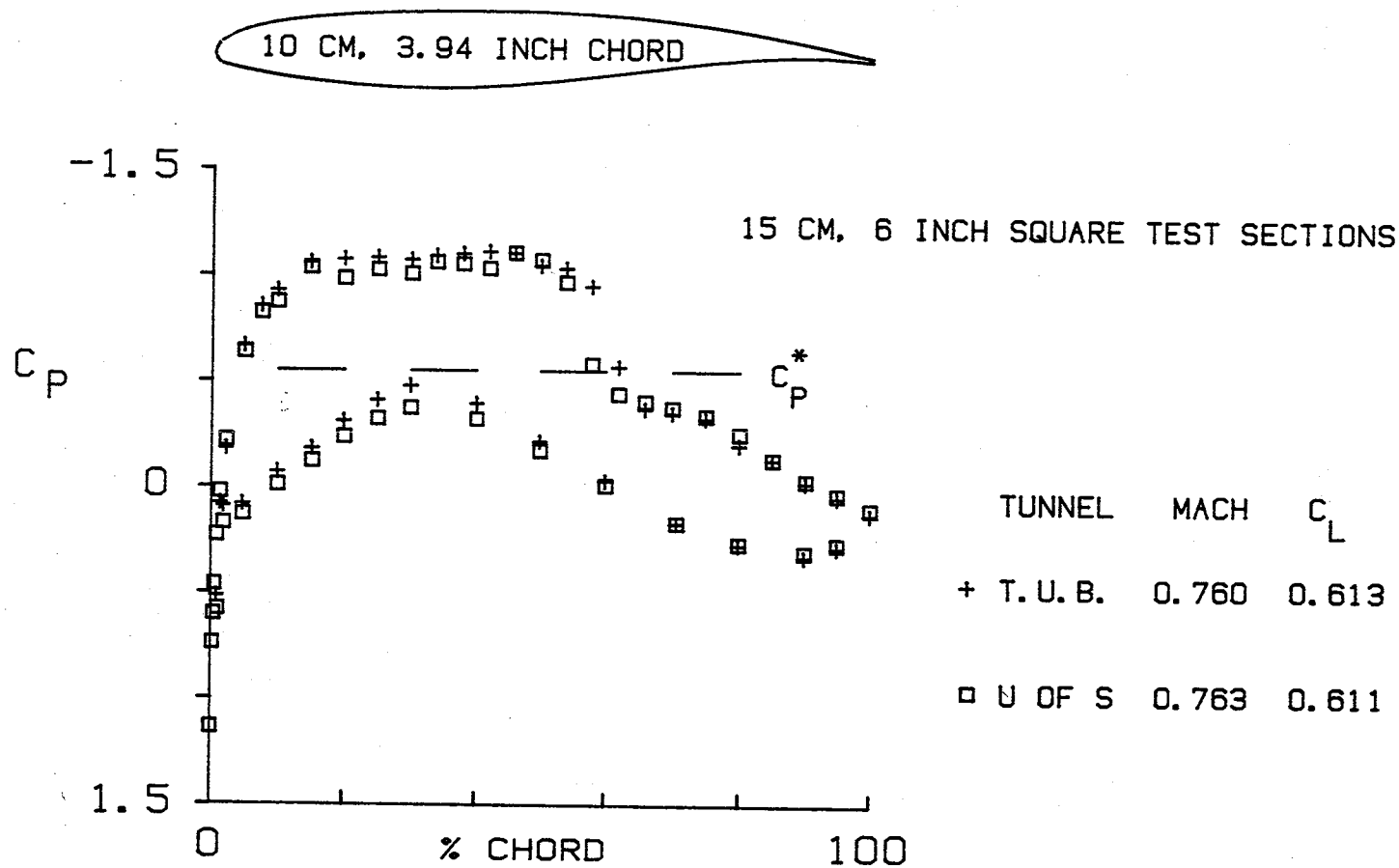


FIGURE 16. COMPARISON OF PRESSURE DISTRIBUTIONS OBTAINED IN TWO ADAPTIVE TUNNELS AT THE SAME MACH NUMBERS AND LIFT COEFFICIENTS.

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15. Supplementary Notes

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16. Abstract

A unique opportunity has arisen to test one and the same airfoil model of CAST-7 section in two wind tunnels having adaptive walled test sections. The tunnels, at the Technical University of Berlin and at the University of Southampton, England, are very similar in terms of size and the available range of test conditions, but differ principally in their wall setting algorithms. This report includes detailed data from the tests of the model in the Southampton tunnel, with comparisons between various sources of data indicating that both adaptive walled test sections provide low interference test conditions.

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