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Department of Mechanical and Aerospace Engineering

School of Engineering

North Carolina State University

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PREDICTED AND MEASURED PRESSURE DISTRIBUTIONS ON TWO AIRFOILS AT MACH NUMBER 1

by

Frederick O. Smetana

and

Donald P. Knepper

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by

North Carolina State University

Introduction

The behavior of transonic flow over bodies is one of the most difficult to predict numerically not only because of its inherent non-linearities but also because the viscous effects in the flow outside the boundary layer can have a significant effect on the body pressure distribution. Shock-induced boundary layer separations or thickening, of course, also have a significant effect on the body pressure distribution. The complexity of the analytical task is in part responsible for the halting improvement in performance exhibited by successive generations of aerodynamic configurations designed for the transonic flow regime.

A frontal assault on the problem —— solving the general viscous equations of motion directly throughout the flow field —— while conceptually feasible with advanced modern digital computers appears to entail such a programming task and computational time requirements that it cannot be pursued. One must rely, therefore, on insight guided by careful experimentation to devise analytical methods of treating the situation which are at the same time more accurate and not significantly more difficult to evaluate than existing techniques.

It is the purpose of this program to provide both useful experimental results and a contribution to the fundamental understanding of transonic flow. Recently, significant progress has been made in including viscous effects in the calculation of pressure distributions on bodies in transonic flow. The paper by Truitt (AIAA Paper No. 70-187) applies one such technique to the determination of the aerodynamic characteristics of three airfoil sections described in the literature.

Some data at M=1 are available on two of these sections, a modified circular arc section and the NPL 491 section. It seemed appropriate, therefore, to conduct additional tests on such airfoils to (1) compare the data obtained in the new NCSU transonic wind tunnel with that obtained previously in other facilities, (2) extend the Mach number and angle of attack range for which data are available, and (3) provide data on the airfoil for which data were not previously reported. In conjunction with surface pressure measurements it would be desirable to obtain visual indications of the behavior of the flow field (via schlieren techniques) in the neighborhood of the model as well as velocity measurements by probe techniques. Such data would permit one to determine the conditions under which Truitt's theory provides an adequate representation of physical reality and those conditions for which further efforts are necessary.

Data acquisition during this first year of a three year program was delayed somewhat by late delivery of the tunnel test section and the need to bring the noise level of the operating tunnel within tolerable limits. Delivery of the test section was originally scheduled for June, 1969 but was not made until October. When the tunnel began operation, it was found that the sound level in the laboratory exceeded 120 db, being sufficiently high at subaudible frequencies that personnel became ill even when wearing ear protectors. A series of acoustical treatments reduced the noise level to 85 db by late February 1970. The next four months were occupied by a calibration of the tunnel. It was found during this time that test section suction in addition to that originally planned would be required to attain supersonic Mach numbers because diffuser losses were higher that anticipated. Accordingly additional portions of the hypersonic tunnel pumping system were connected to the test

section suction line to double its mass handling capability. (It is now about 6.5% of the primary air supply.) Testing of two airfoil models therefore was begun in late June 1970. The data acquired to date are presented herein.

Apparatus and Models

The experimental phase of the program was conducted in the N. C. State University continous flow transonic wind tunnel. The 7" by 7" test section was fitted with slotted upper and lower walls and solid side walls. The tunnel is powered by two Roots blowers with a combined pumping speed of 16,500 cfm. To attain supersonic flow in the test section air is pumped through the slotted upper and lower test section walls by an auxillary suction system. Speed control of the tunnel is achieved with by-pass values at the main blowers and by throttling the suction from the plenum chamber.

The calibration of the tunnel (Fig. 1) showed that at present the Mach number range of the empty tunnel is 0.65 to 1.10. The corresponding Reynolds numbers are 3.65×10^6/ft. to 4.84×10^6/ft. The variation in Reynolds number is due to the fact that the tunnel always operates at atmospheric stagnation pressure. The flow angularity in the test section was determined using one of the airfoil models as a yawmeter. The pressures at one chordwise location were plotted verses angle of attack for the upper and lower surface of the model. The angle for which the pressure coefficients were the same was taken to be zero angle of attack.

Because of model blockage, the maximum Mach number with the models installed at zero angle of attack was 1.04. This maximum Mach number decreased when the airfoil was mounted at an angle of attack since the effective blockage area was increased.

The airfoil models employed during the program were two sections studied in AIAA Paper No. 70-187: the modified circular-arc airfoil and the peaky airfoil. The airfoil contours are shown in Figure 2, and the coordinates of the modified circular-arc are given below:

x/c	y/c
0	0
0.1	0.0180
0.15	0.0255
0.20	0.0320
0.25	0.0375
0.30	0.0420
0.35	0.0455
0.40	0.0480
0.45	0.0495
0.50	0.0500
0.55	0.0490
0.60	0.0475
0.65	0.0435
0.70	0.0380
0.75	0.0270
0.80	0.0170
0.85	0.0095
0.90	0.0040
0.95	0.0015
1.00	0

There is no analytic expression for the modified circular arc, and thus a table of ordinates has been given. The Peaky airfoil contour can be expressed by

$$y/c = \frac{9}{4\sqrt{3}}(x/c)^{\frac{1}{2}}(1-x/c)$$

The model sizes with pressure tap locations are shown in Figures 2 and 18. The size of the models was chosen so as to give an area blockage of approximately 3½%. This size was chosen for two reasons. (1) Because of tunnel interference effects the model size must be kept small in relation to the tunnel. (2) The fabrication process for a model smaller than the ones used will become quite expensive. The models were made of stainless steel with the maximum allowable tolerence during the fabrication process of ± 0.002". Optical comparator studies on the models indicated the tolerances were met. The size of the pressure taps was 0.035".

Both models were pressure distribution models which spanned the 7" width of the tunnel. The models were mounted in brass contoured clamps and supported by one side wall of the tunnel (Figures 16 and 17). Air

leakage around the clamps was prevented by a combination of rubber and a hard sealing wax.

The actual testing procedure consisted of setting the model to the desired angle of attack and then operating the wind tunnel at succesive Mach numbers through the available range. The pressure distributions were indicated on a multiple mercury manometer board (resolution ±0.5 mm.) and recorded for each run though the entire Mach number range of the tunnel. The peaky airfoil model was tested at angles of attack of 0^{o}, 1^{o}, and 2^{o}. The modified circular-arc airfoil was tested at angles of attack of 0^{o} and 1^{o}.

Operation with atmospheric inlet has the advantage that local pressures are relatively constant with time. Repeatability is thus good.

The data was reduced to the usual pressure coefficient form

$$Cp = \frac{P - P_{\infty}}{q_{\infty}}$$

The data are shown in Figures 4 through 15.

Results

The comparisons of the experimental results with the available vicous transonic theory for the two experimental airfoils is shown in Figures 3a and 3b. (AIAA Paper No. 70-187)

Modified Circular-Arc Airfoil

Briefly, the essence of Truitt's viscous transonic theory for the modified circular-arc at M=1 is that the flow will experience an abrupt shock-like deceleration from supersonic speeds to the sonic value at the body inflection point. The modified circular-arc is shaped such that an inflection point exists at 0.75c. As can be seen from Figure 3a the experimental results agree quite well with the theorectical curve. The experimental data seems to indicate that a shock wave is located on the surface in the vicinity of the 75% chord location. The exact location of the shock was not determined at this time. Planned future tests with pitot-static probes and shadowgraph should accomplish this task.

Peaky Airfoil

The viscous transonic theory states that a body free of an inflection point at M=1 should be free of surface shocks. The peaky airfoil has no inflection point, and the experimental results are compared with the viscous transonic theory in Figure 3b. The solid curve represents the results for the peaky airfoil based on a sonic point located at x/c=0. As can be seen there is some discrepancy in the results. By assuming the sonic point at 0.1c a new theoretical curve was generated. This curve is shown as the dashed line in Figure 3b. As can be seen the correlation is now quite good.

The correlation between the dashed curve and the experimental results can be improved by accounting for the compressive waves reflected from the sonic line. It should be noted that the theoretical curve taken from Truitt's paper was generated from 0.333c to the trailing edge using a simple wave theory which does not take these reflected waves into account. The computed curve over the rear two thirds of the airfoil will therefore tend to be somewhat too negative (above the data points). The reason for the apparent shift in the sonic point of the peaky airfoil will be investigated in detail later.

Future Work

As indicated earlier, many of the details of the flow so important to providing guidance for theoretical development cannot be determined from model surface pressures alone. The existing pressure distribution models, in order to minimize tubing lengths and flow interference, were mounted from the side wall. This, of course, makes it impossible to obtain schlieren pictures of the flow. For this reason new models of the same airfoils, without pressure taps and especially designed for sting mounting, have been ordered. Movable pitot and static probes will be positioned in the flow from just above the surface to one chord length away in the neighborhood of the nose and the 0.75c point on both airfoils.

Attention will also be devoted to recontouring the tunnel geometry just downstream of the test section. The calibration tests (See unpublished Master's thesis, "A Preliminary Calibration and Flow Investigation of the North Carolina State University Transonic Wind Tunnel" by Scherf, P. H.) revealed that a second throat is formed in this region and that the flow expands downstream of this point to M=1.28 before shocking down. This shocking down limits the mass that can be pumped by the main drive blowers and raises the power consumed by these pumps to the point that the circuit breaders frequently trip. If the effort is successful, it is expected that the models can then be operated at angle of attack to M= 1.1. Consideration is also being given to providing additional bypass to reduce the minimum Mach number in the transonic test section to about 0.4. Essentially incompressible flow data (M=0.1) can be obtained in the 14" by 20" test section upstream of the transonic test section.

Later in the second year of the program, tests of a wavy wall model are contemplated. The design details of this model have not as yet been worked out.

The analytical portion of the work during the next year will be concerned with several topics:

(a) Approximate effect of small changes in airfoil nose geometry on sonic point location (for the purpose of specifying tolerances on model construction).

(b) Inclusion of reflected compressive waves in the prediction of airfoil surface pressure distribution.

(c) Iterative computation of the boundary layer displacement thickness along the airfoil under the influence of the external transonic flow field which in turn is produced by the body plus the displacement thickness.

(d) Possibilities for the removal of some of the restrictive assumptions in the theory of minimum drag transonic airfoils.

(e) The significance of the test results in terms of the theory as it new exists.

WIND TUNNEL CALIBRATION

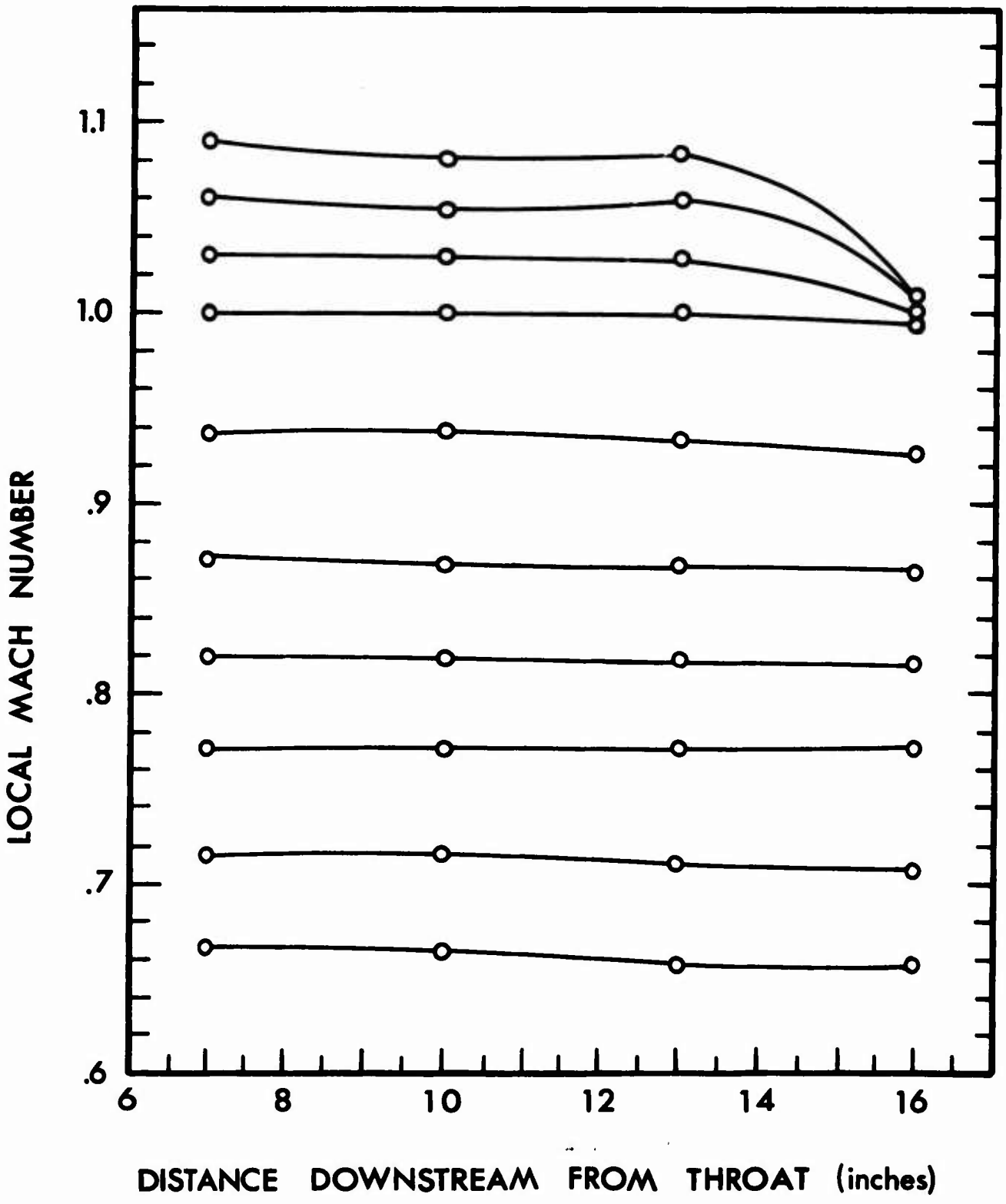
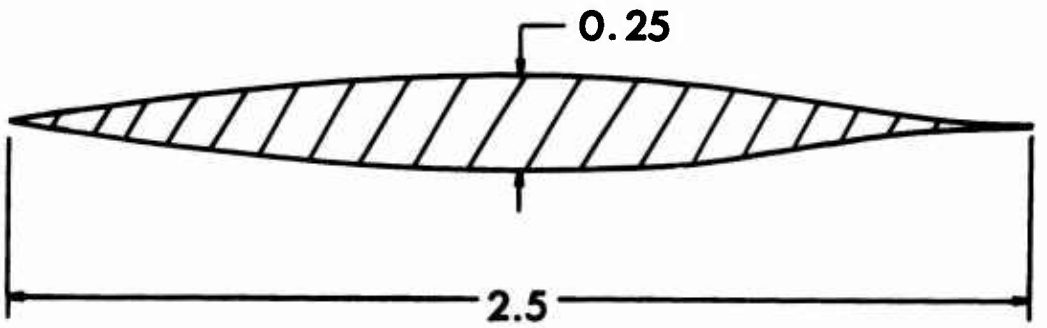


Figure 1

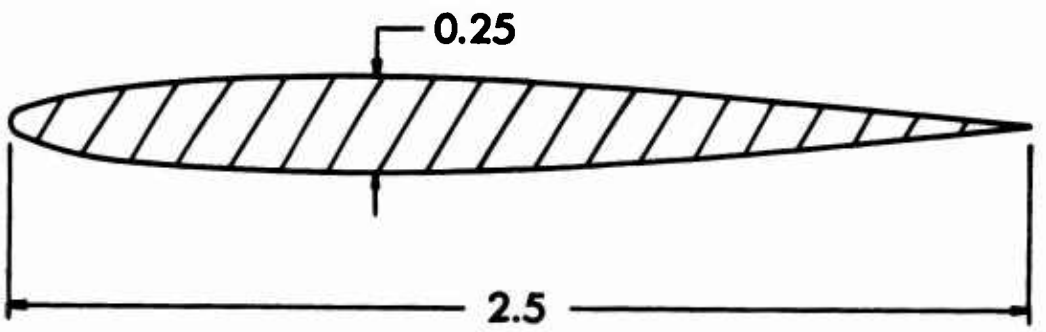
AIRFOIL CONTOURS

MODIFIED CIRCULAR-ARC



orifice location (top)
x/c = .1, .2, .3, .4, .5,
.6, .7, .75, .8

PEAKY AIRFOIL



orifice location (top)
x/c = .1, .2, .3, .4, .5,
.6, .7, .8

ALL DIMENSIONS IN INCHES

Figure 2

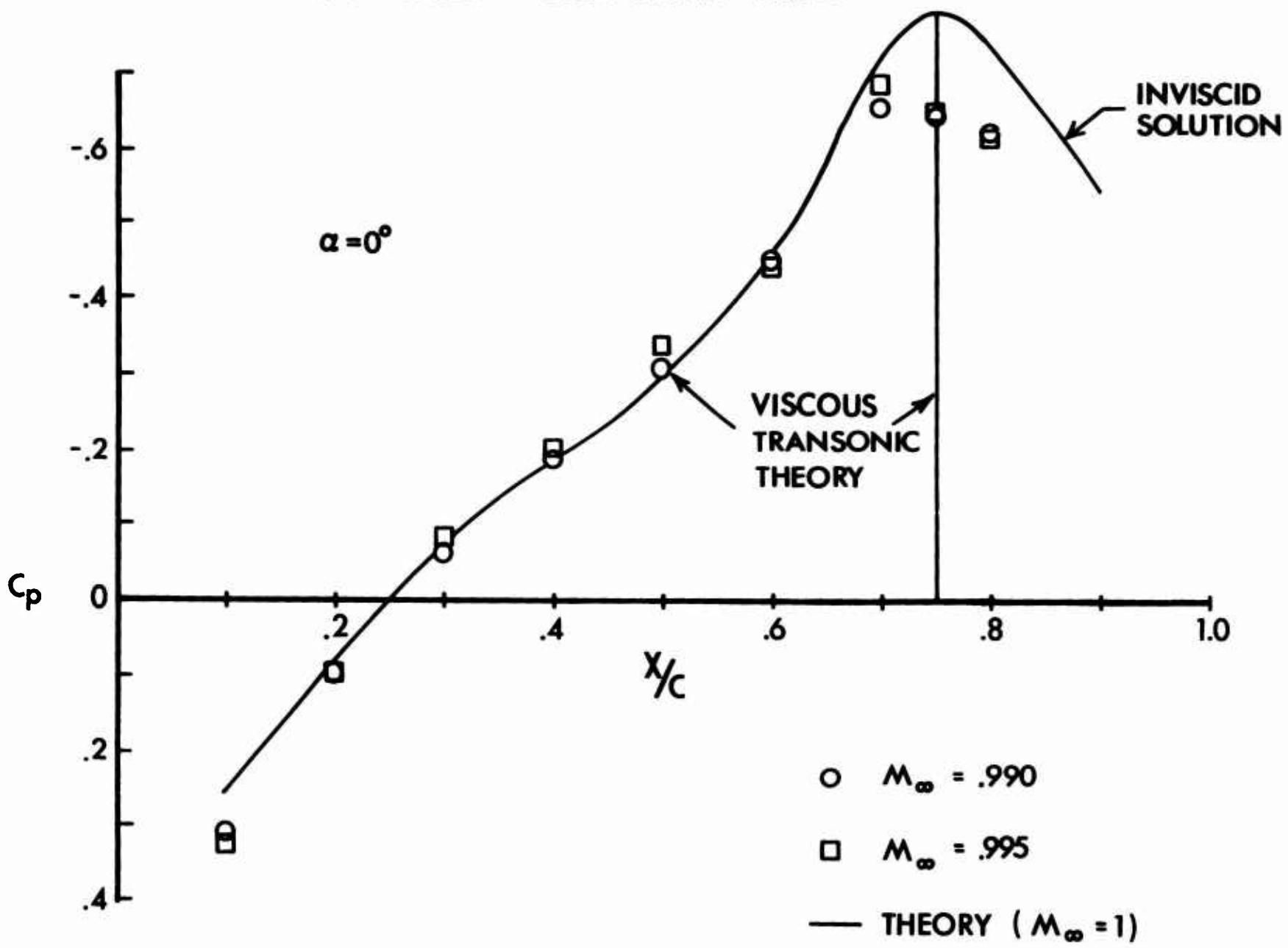

MODIFIED CIRCULAR ARC
α = 0°
INVISCID SOLUTION
VISCOUS TRANSONIC THEORY
C_p
-.6
-.4
-.2
0
.2
.4
.2
.4
.6
.8
1.0
X/C
○ M_∞ = .990
□ M_∞ = .995
—— THEORY (M_∞ = 1)

Figure 3a

PEAKY AIRFOIL

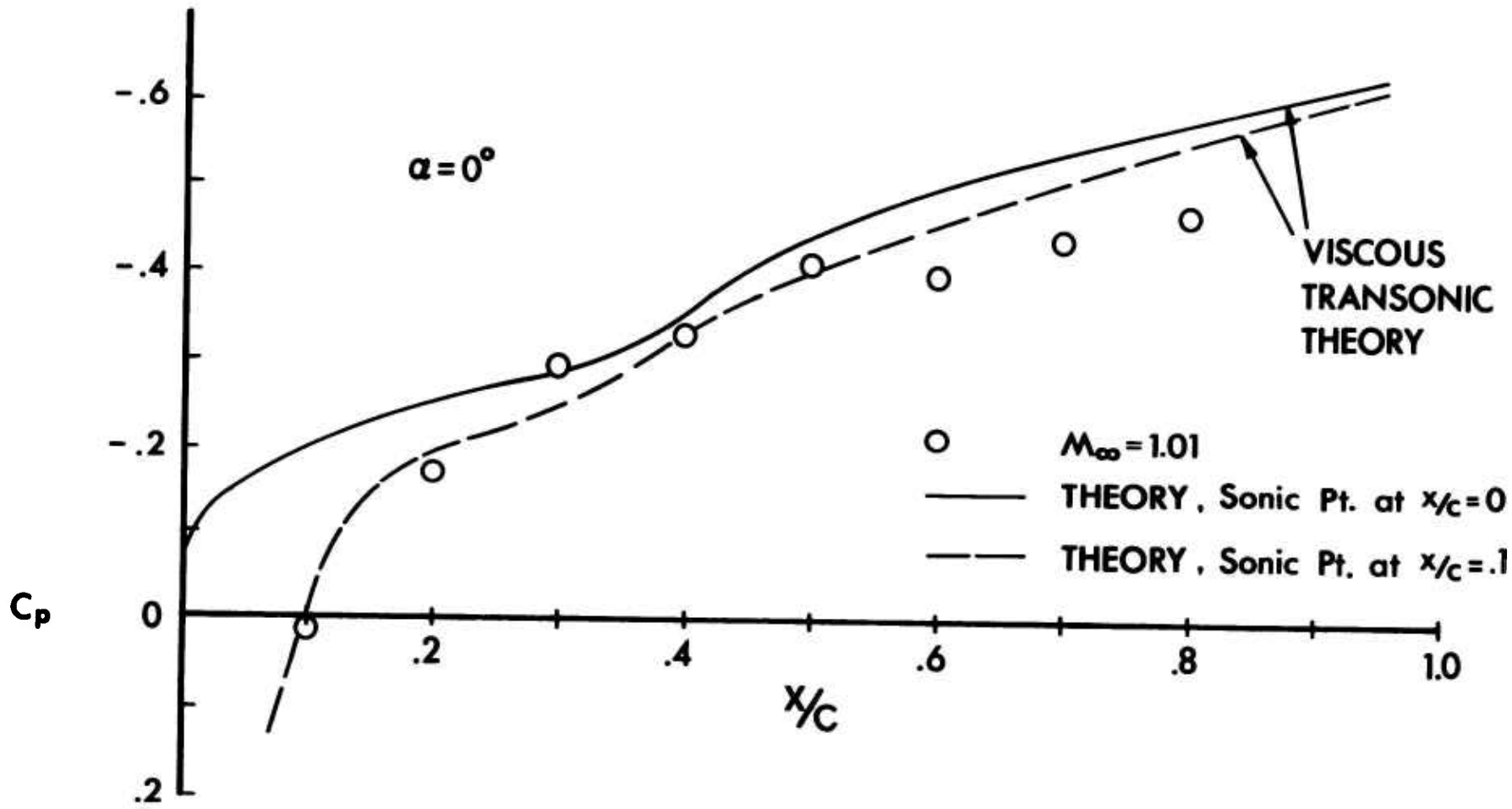


Figure 3b

MODIFIED CIRCULAR-ARC

$\alpha = 0°$

$C_p = 0$ for $M_\infty = 0.654$

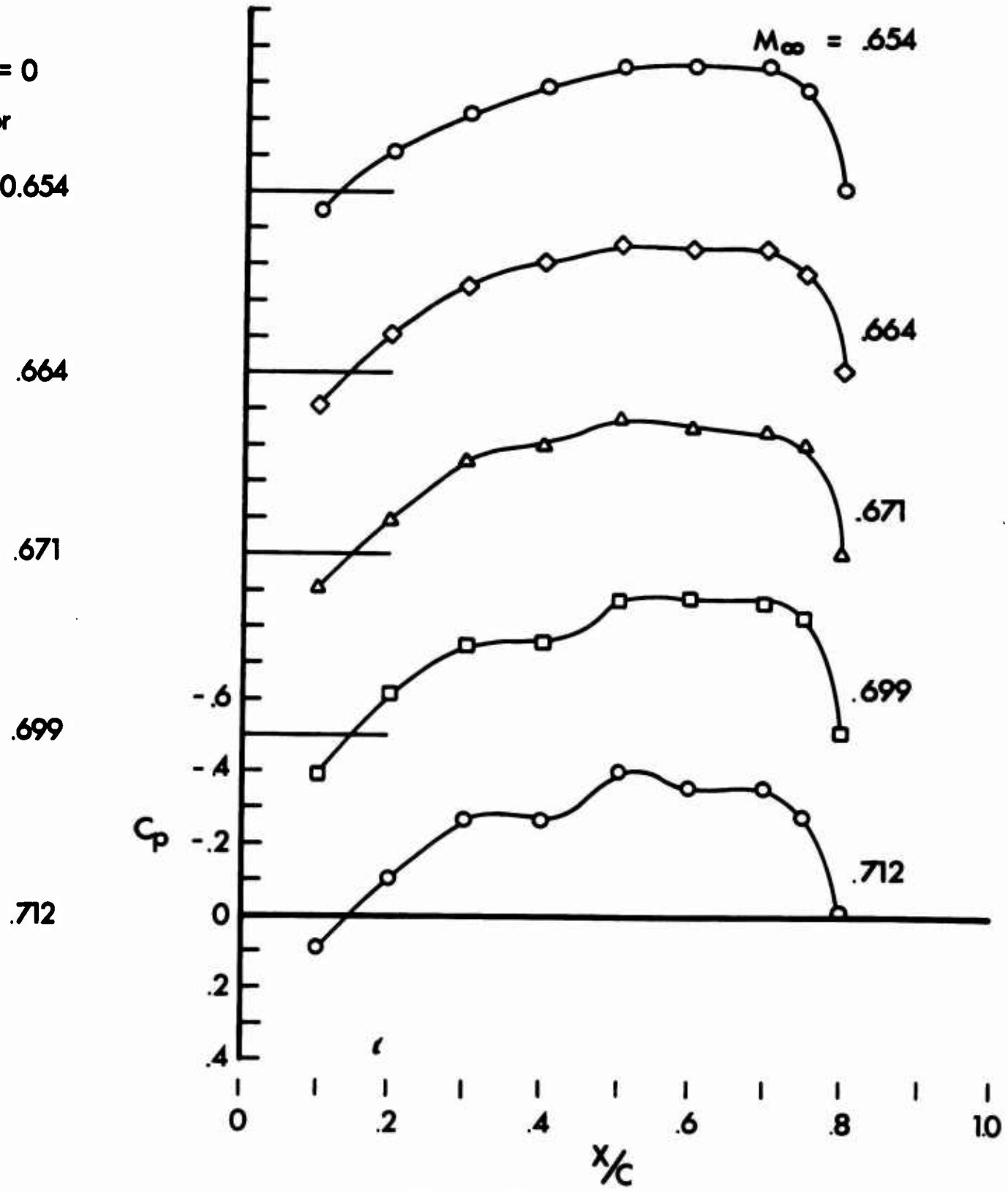


Figure 4

MODIFIED CIRCULAR-ARC

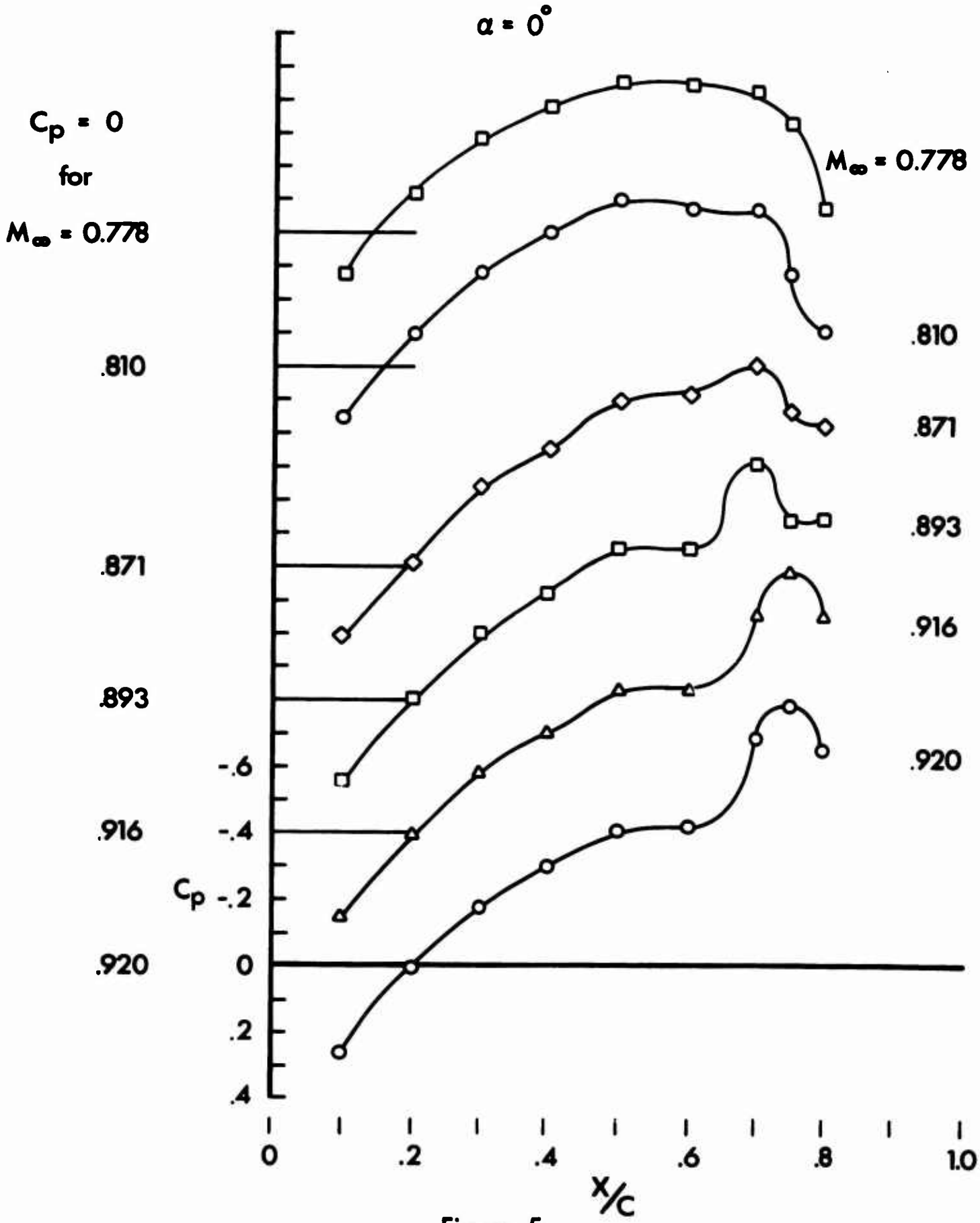


Figure 5

MODIFIED CIRCULAR-ARC

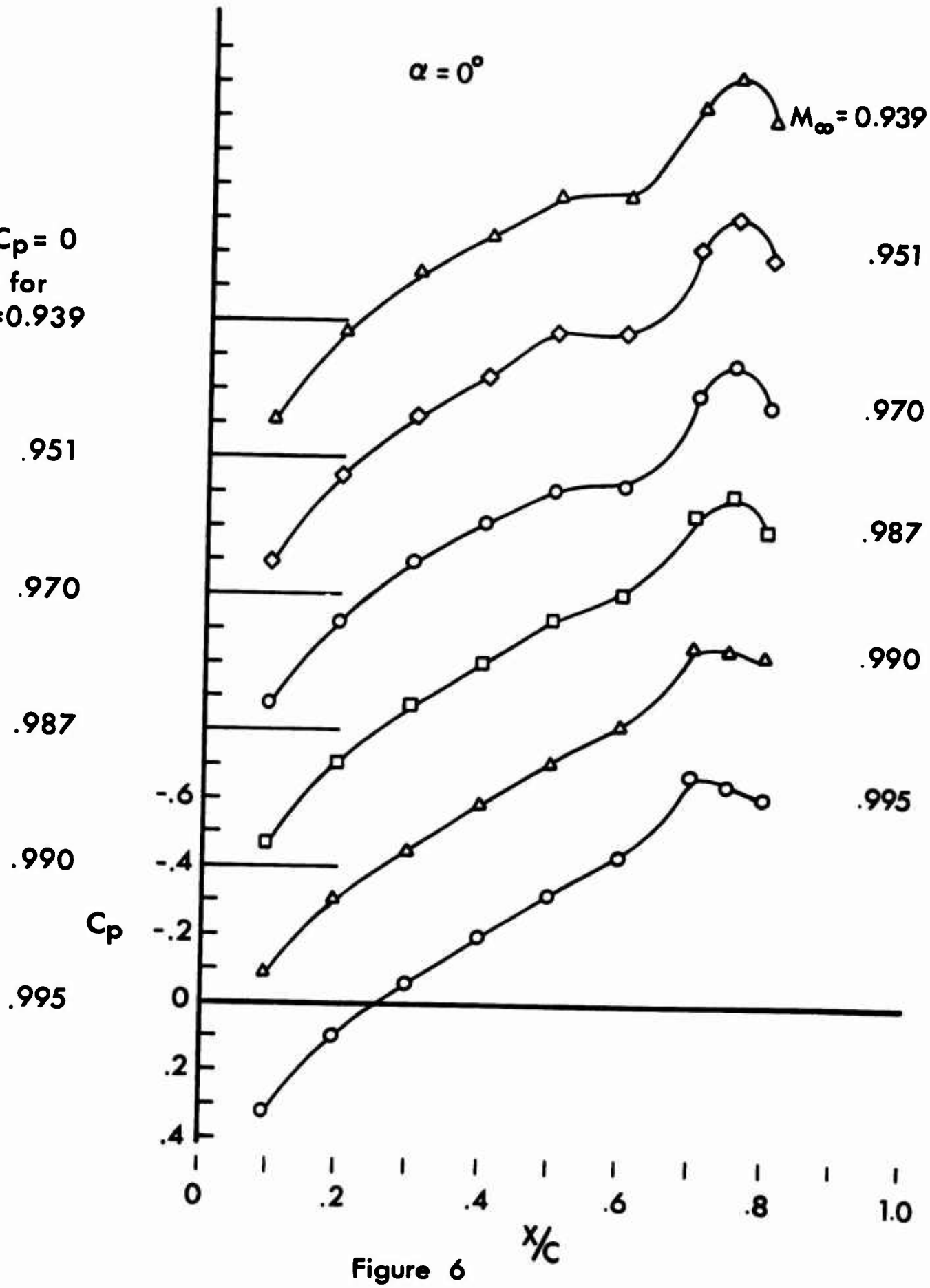


Figure 6

MODIFIED CIRCULAR-ARC

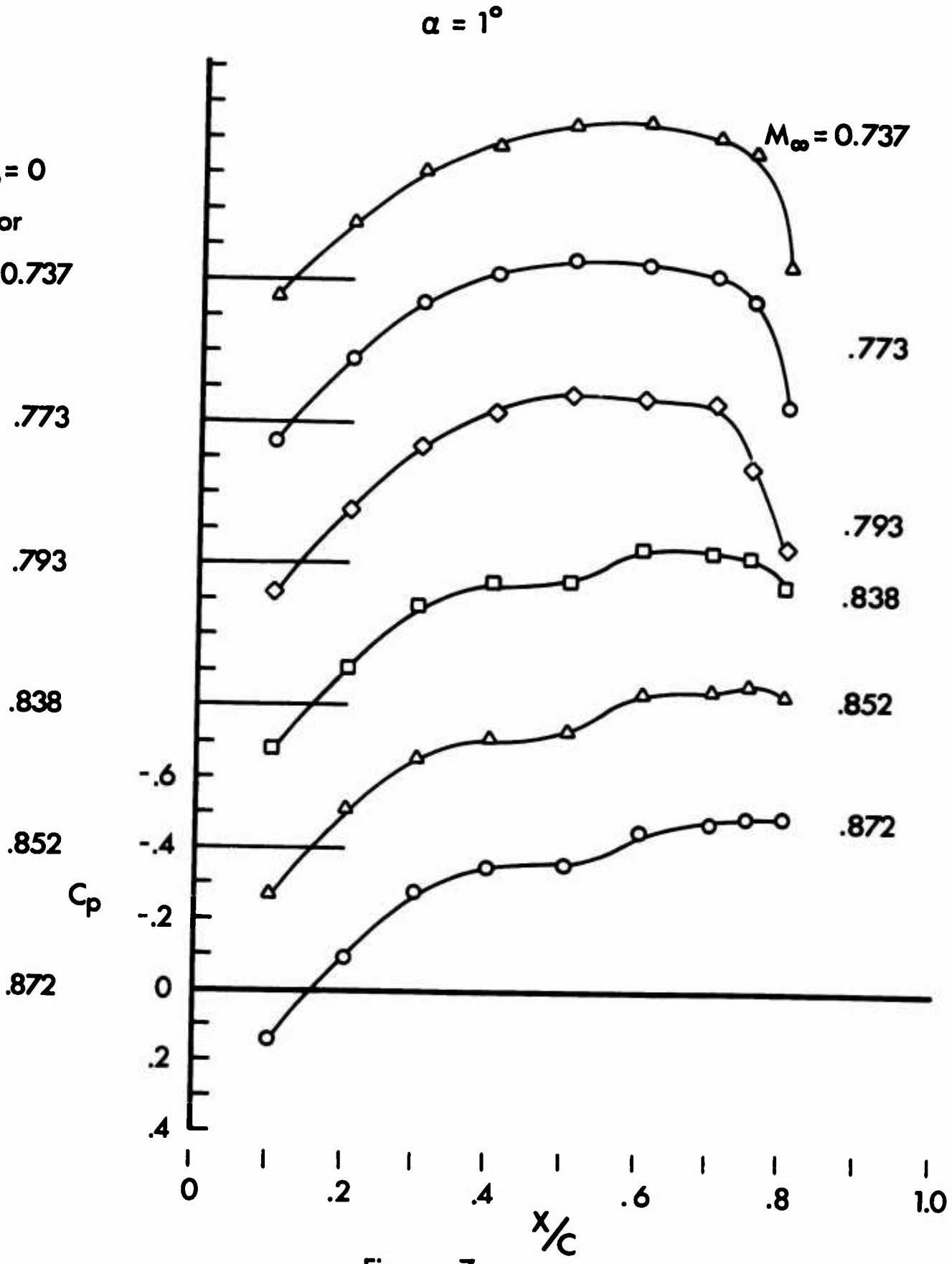


Figure 7

MODIFIED CIRCULAR-ARC

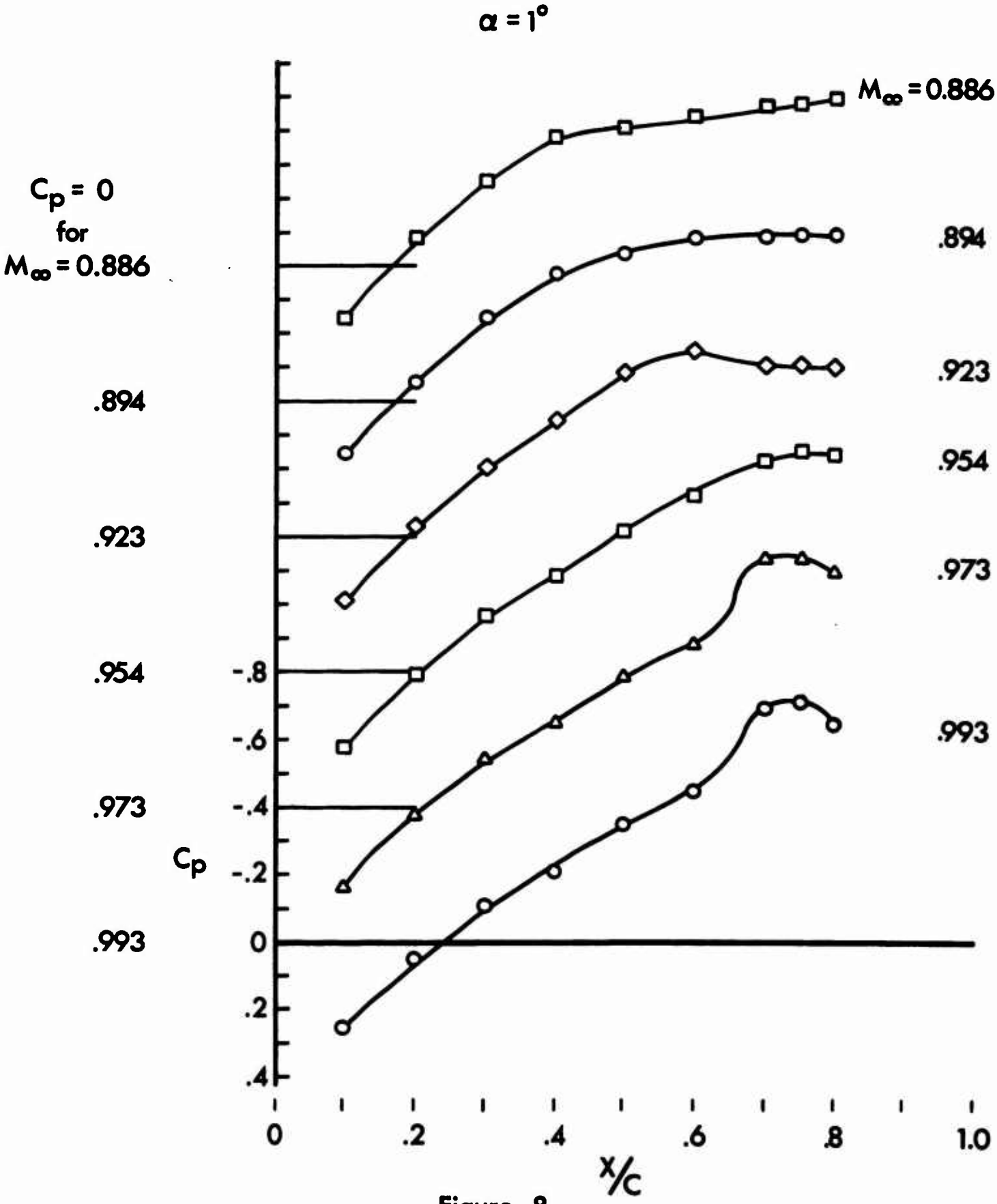


Figure 8

PEAKY AIRFOIL

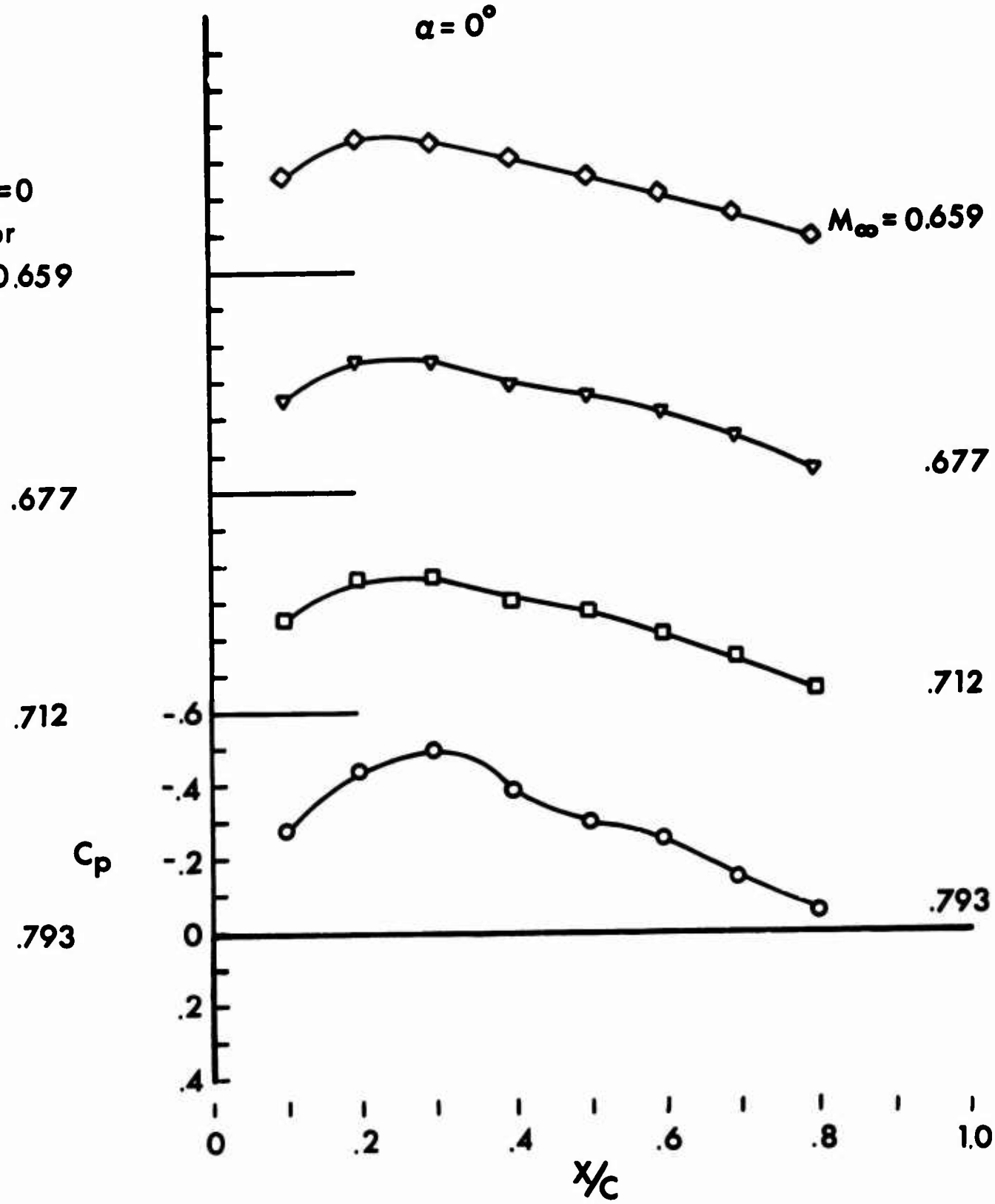


Figure 9

PEAKY AIRFOIL

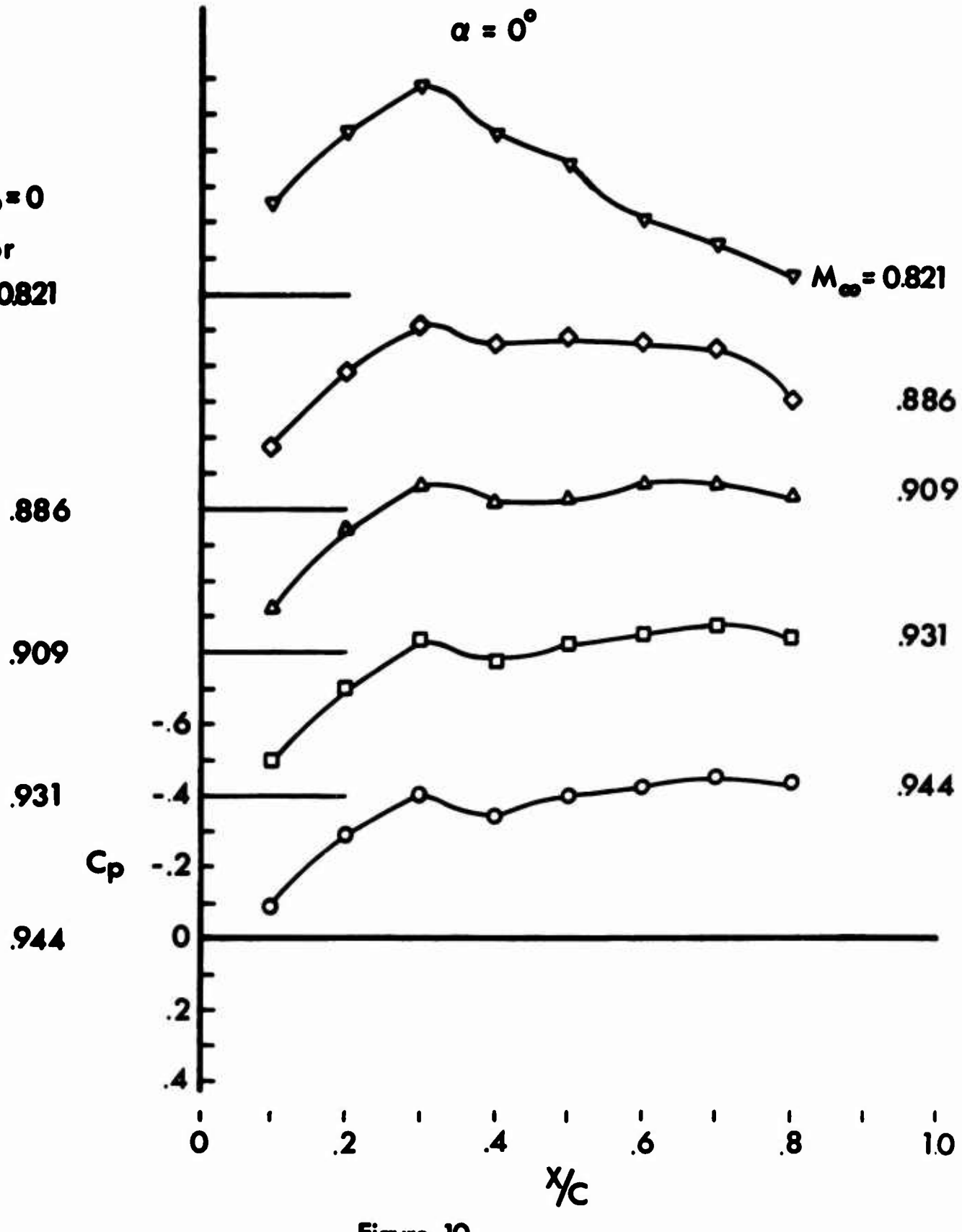


Figure 10

PEAKY AIRFOIL

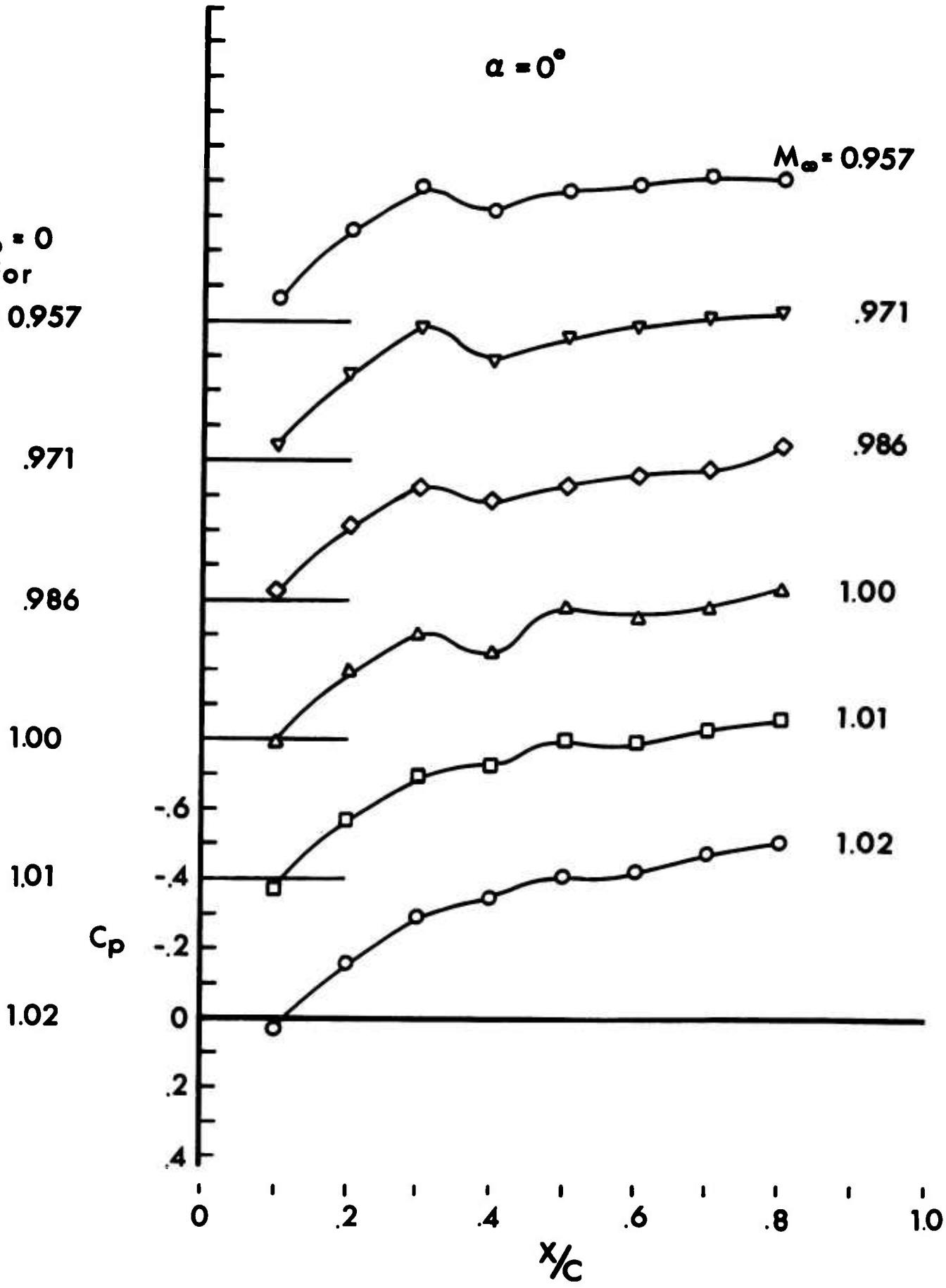


Figure 11

PEAKY AIRFOIL

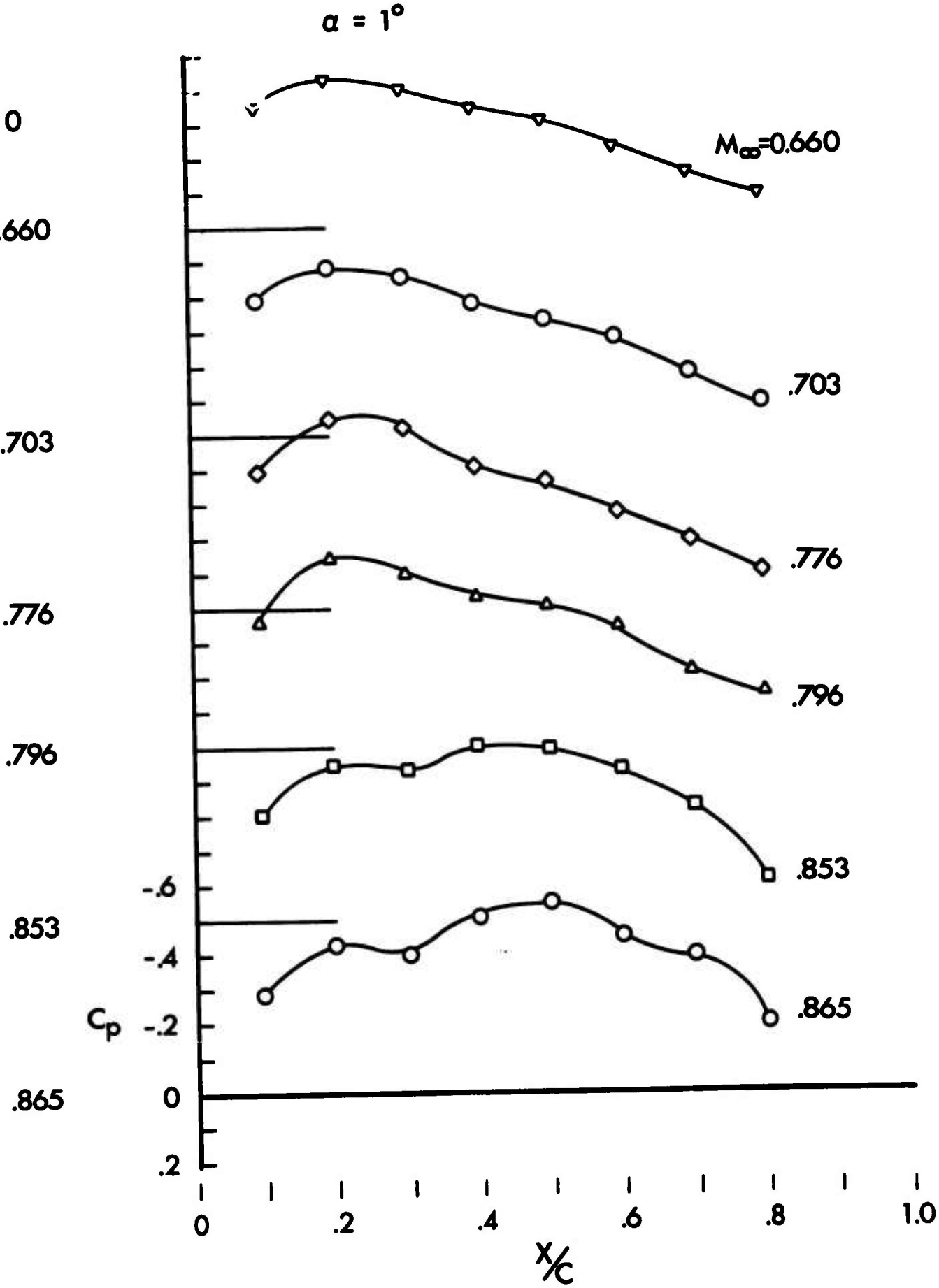


Figure 12

PEAKY AIRFOIL

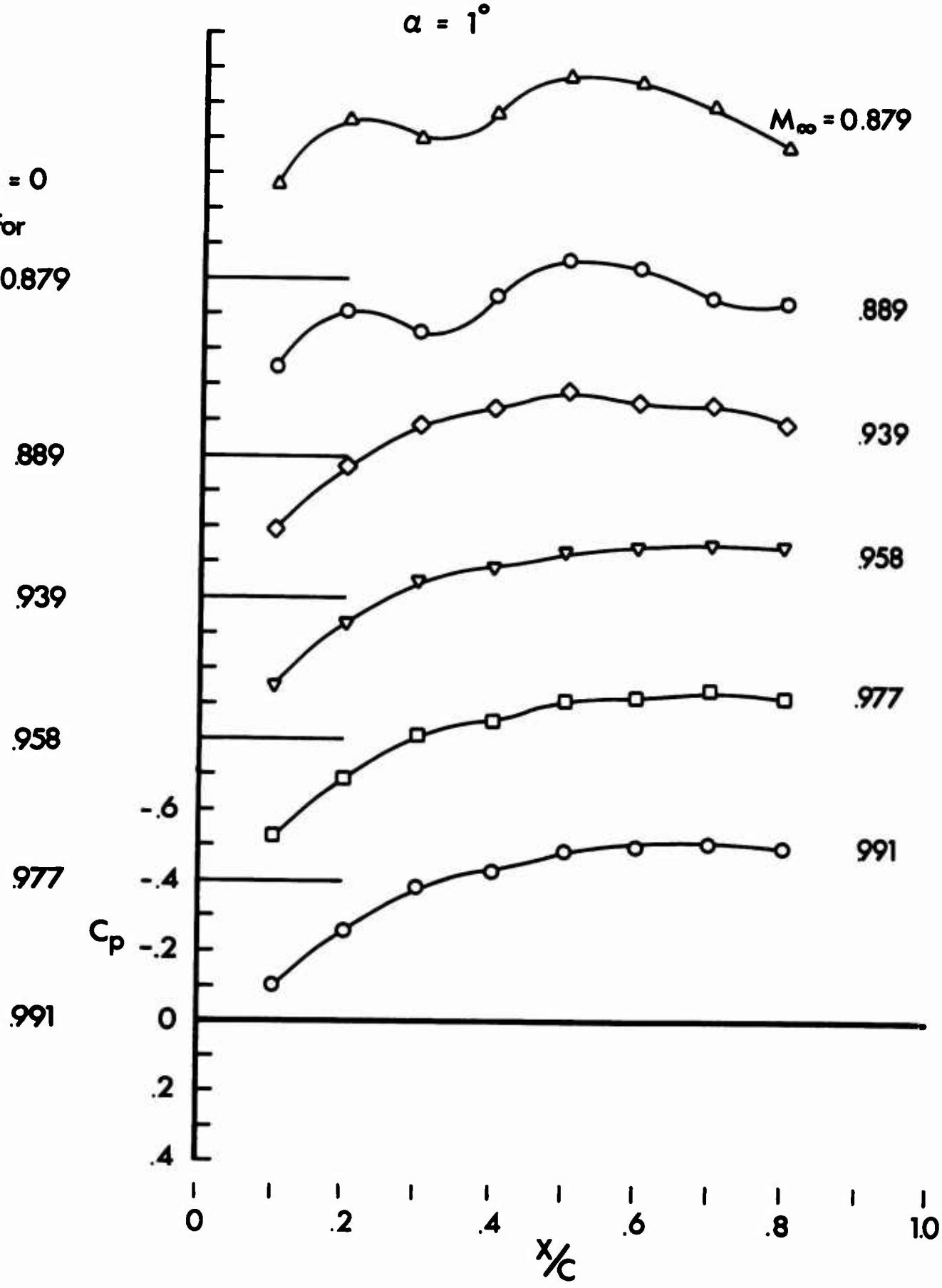


Figure 13

PEAKY AIRFOIL

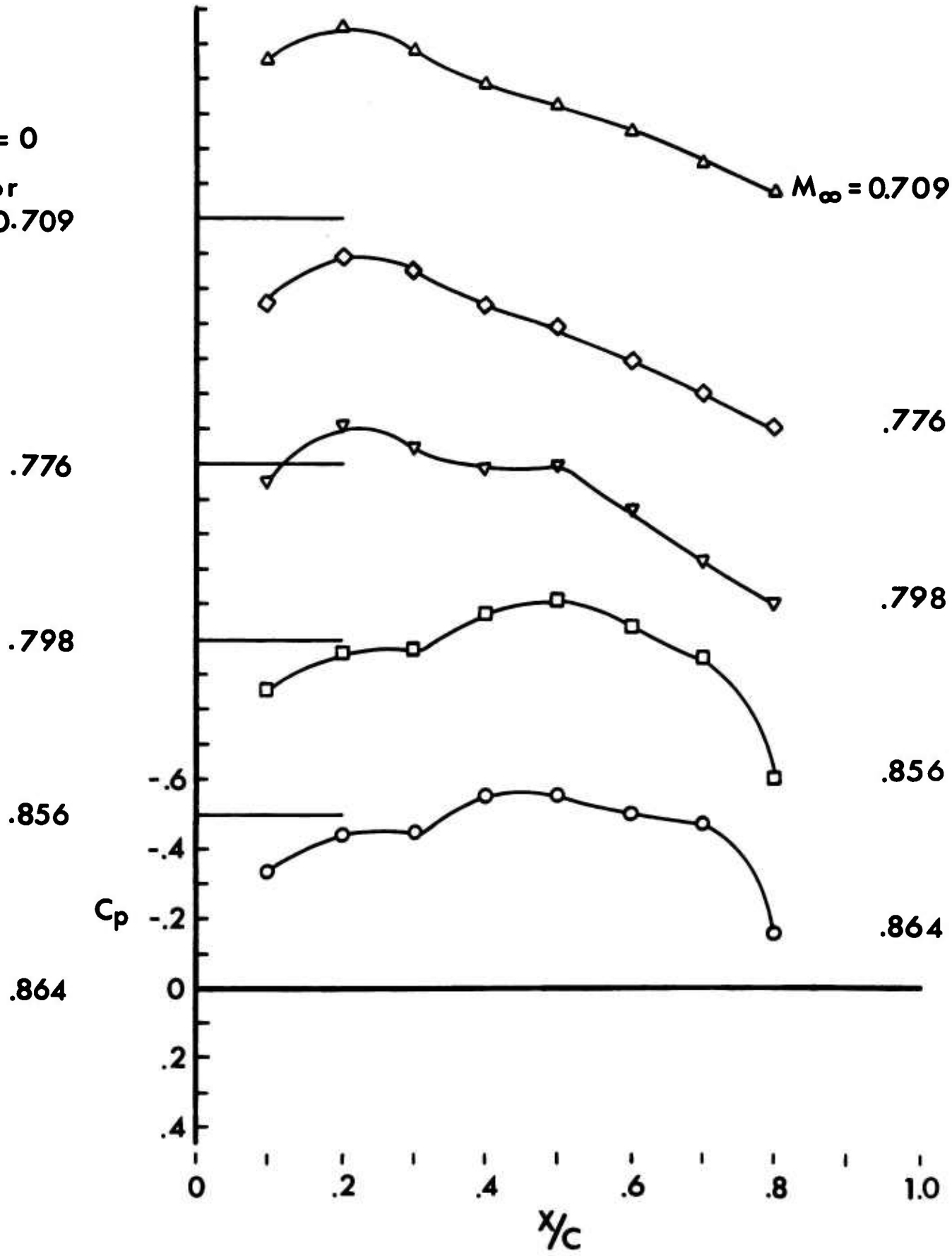


Figure 14

PEAKY AIRFOIL

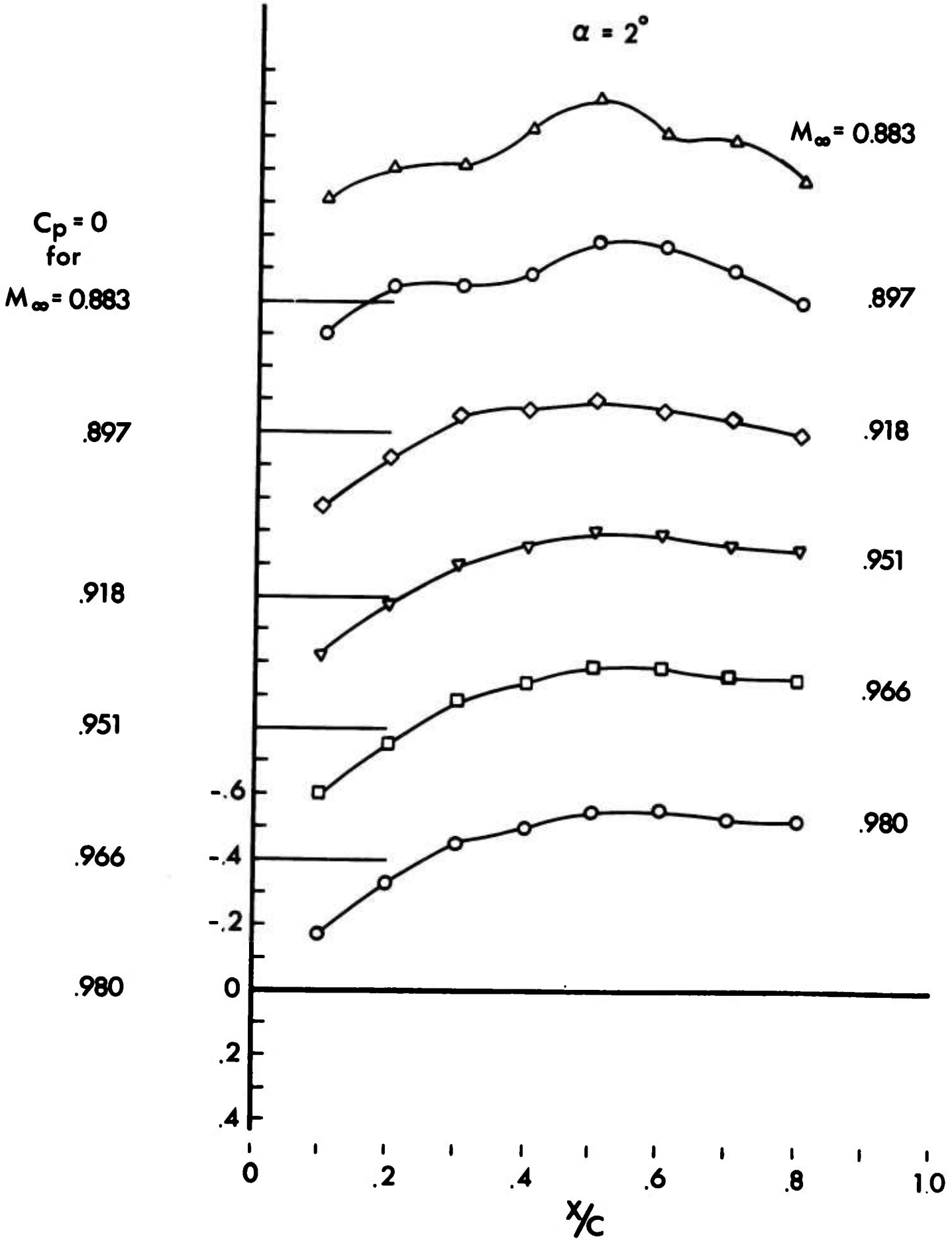


Figure 15

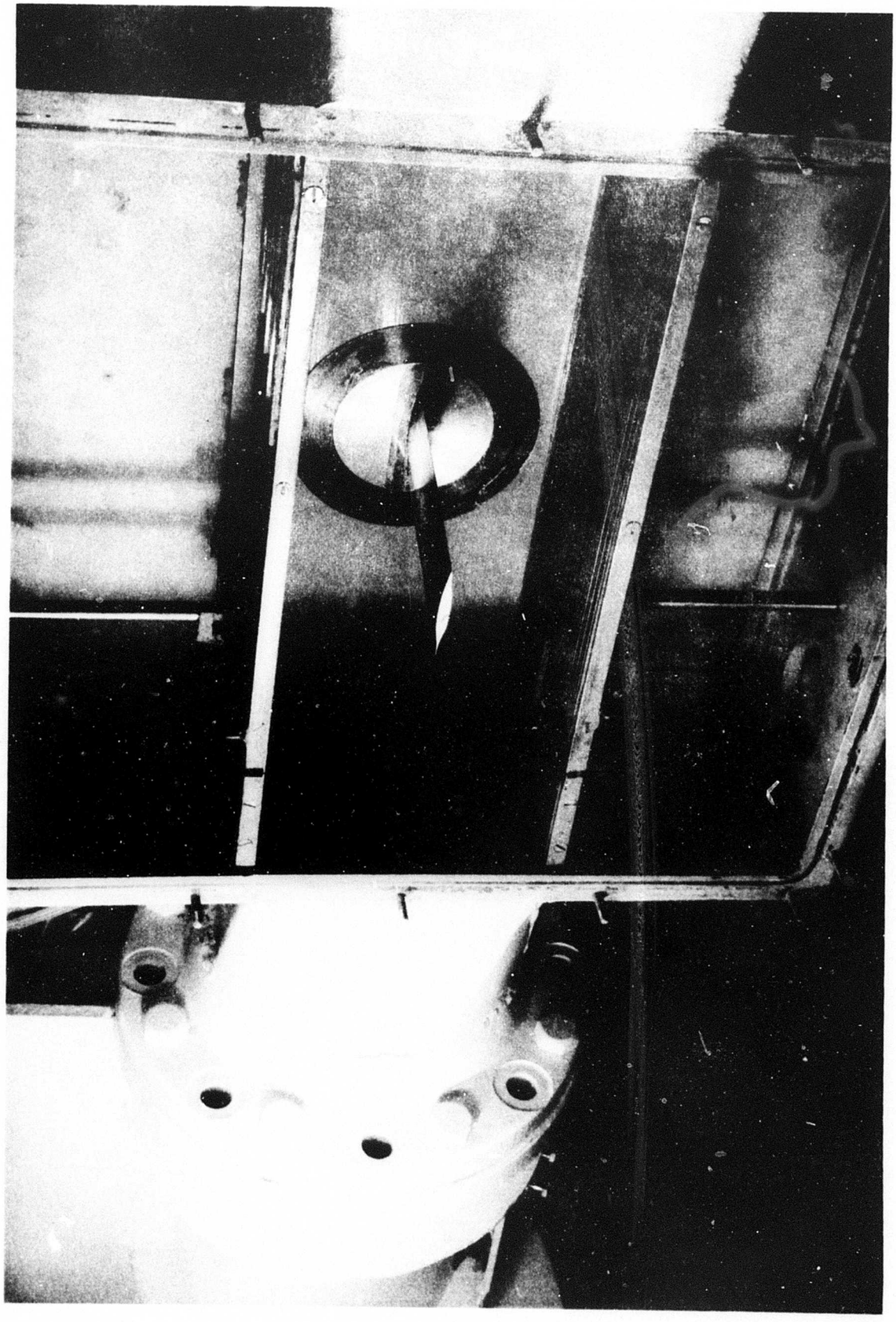


Figure 16

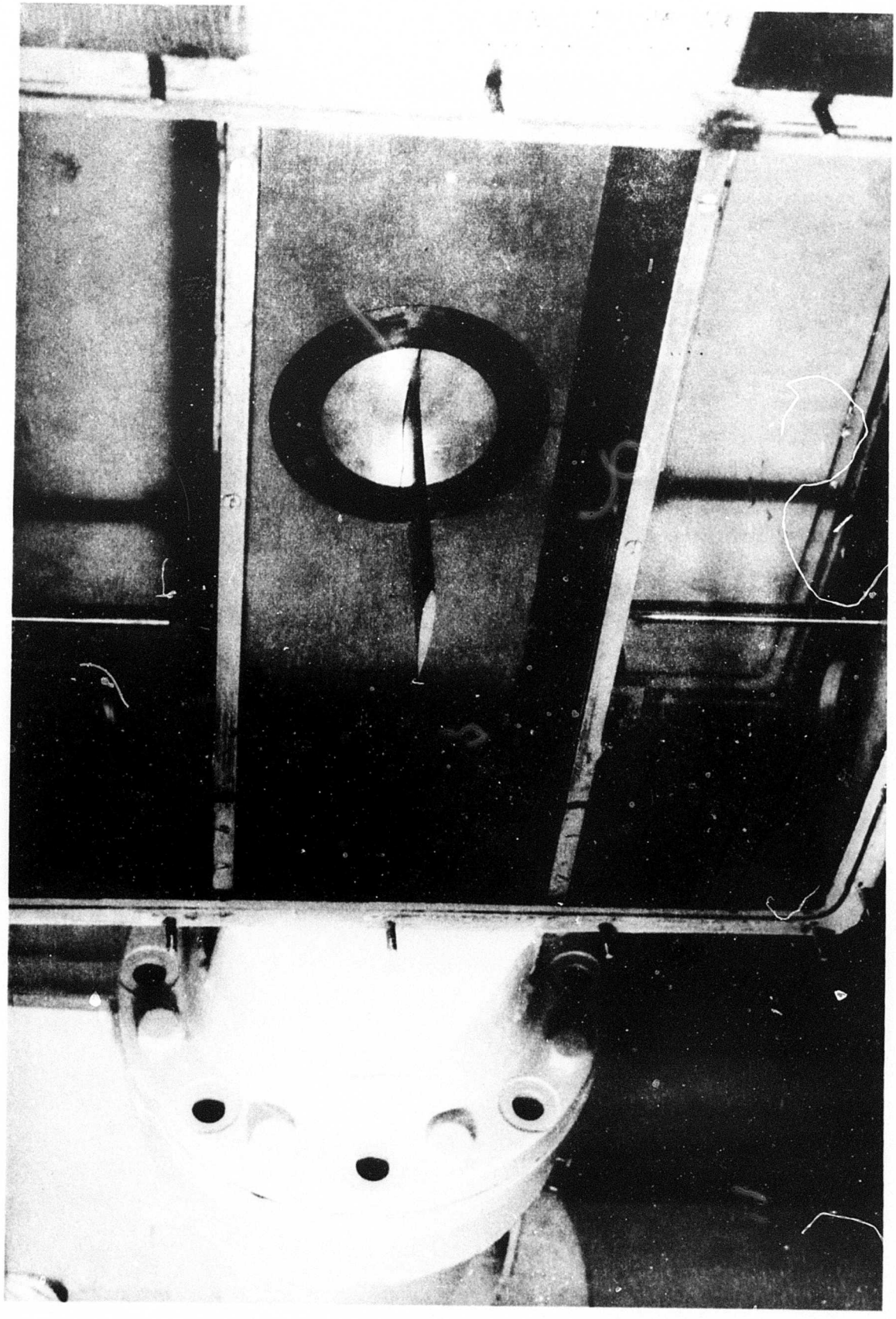


Figure 17

Figure 18

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13. ABSTRACT

This report describes the initial efforts of a study to provide fundamental understanding of transonic flow. It contains a partial description of apparatus and models used for this study including a continuous flow transonic wind tunnel and a comparison of the experimental results with the available viscous transonic theory on two experimental airfoils. The report also contains a discussion of future work.

14. KEY WORDS
Airfoils
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Wind Tunnel
Viscous Transonic Theory

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