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A COMPARISON OF THE THEORETICAL DETERMINATION OF THE DEVELOPMENT OF THE BOUNDARY LAYER MOMENTUM THICKNESS IN AN ARBITRARY PRESSURE GRADIENT WITH FULL-SCALE FLIGHT EXPERIMENTS ON A POROUS AIRFOIL SECTION WITH TRANSPIRATION

By

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and
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July 1965

U. S. ARMY AVIATION MATERIEL LABORATORIES

FORT EUSTIS, VIRGINIA

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A government review of this report was conducted by the U. S. Army Aviation Materiel Laboratories. The work was performed by the Aerophysics Department of Mississippi State University.

This report presents the comparison of experimental results with analytic results. The analytic results were derived from boundary layer momentum thickness theory. The experimental results were obtained during flight tests of a sailplane having a porous airfoil section with transpiration.

This report is published for the exchange of information and the stimulation of ideas.

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Aerophysics Research Report No. 59

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ABSTRACT

Calculation of the turbulent boundary layer momentum thickness around a NACA 4416 airfoil section has been made by a successive approximation method developed by one of the authors for two-dimensional and axisymmetric flows. These results are compared with experimental results obtained from flight tests with a sailplane--Schweizer TG-3--with reasonable results.

CONTENTS

ILLUSTRATIONS

Figure | **Page**

SYMBOLS

c	Chord length
C_f	Coefficient of skin friction
$\overline{H}$	Energy parameter
U	Potential velocity
U_o	Uniform reference velocity
v_o	Suction or blowing velocity
x	Variable taken along the chord line of the wing section
y	Variable taken normal to the surface of the wing section
Y	Suction or blowing velocity distribution function
θ	Momentum thickness
θ_o	Impervious momentum thickness

INTRODUCTION

Since the concept of the boundary layer was established in 1906 by Prandtl, boundary layer control has been one of the most important problems in the field of fluid mechanics. Numerous reports in both the experimental and theoretical fields have been published concerning boundary layer control. Experimentally, it has been reported that boundary layer control has been applied very effectively to a sailplane, a powered plane, a diffuser, and a compressor (Reference 5). Theoretically, on the other hand, most works have been done for the laminar case because of the mathematical difficulty of the treatment of the problem (References 1 and 2).

Most fluid dynamic problems can be classified as turbulent. On rare occasions the entire flow can be described as laminar, but generally transition from a laminar flow to a turbulent flow occurs. To achieve a wider application of the method, it is desirable that theoretical solutions can be obtained for both the laminar and turbulent cases without difficulty. This was done by Truckenbrodt for the impervious case (Reference 3).

A practical method for calculation of the laminar and the turbulent boundary layer momentum thickness for two-dimensional, axisymmetric flow with suction or blowing was developed and reported in Reference 4. This method was applied to a spheroid and to an elliptic cylinder having a fineness ratio of 0.3 for both the suction and blowing cases. A comparison with experimental results was not made.

In 1956, an experimental study of low-drag boundary layer control was made on a Schweizer TG-3 sailplane having suction applied through the wing surface by means of discontinuously distributed rows of suction holes. Measurements of suction velocity distributions and momentum thicknesses were made. One purpose of this study was the estimation of transition points on the wing surface. This was accomplished by two different methods.

Experimental data are analyzed herein and compared with the theory developed in Reference 4, with satisfactory results.

EXPERIMENTAL ARRANGEMENTS

In 1956, extensive boundary layer control experiments were performed on the porous wing of a sailplane. The sailplane used for the flight tests of this study was a Schweizer TG-3, which is shown in Figure 1. The aircraft had a NACA 4416 airfoil section which was modified such that suction boundary layer control could be applied to the entire wing. The wing section was divided into two compartments by the spar at 0.35 chord length location. The upper surface of the wing section was perforated by spanwise rows of small holes extended from the leading edge to the trailing edge of the wing with varying intervals in the chordwise direction, as shown in Figure 2. Each compartment had its own blower which was used as the suction source. However, experimental data used in this report were obtained by operating one blower which was connected to the region from 0.35 chord length location to the trailing edge of the wing. Suction velocity distributions were determined from the differences in pressure across the wing surface.

Chordwise pressure distributions along the wing surface were measured through pressure taps which were mounted flush to the wing surface from inside the wing section. These pressure taps were connected to a multitube water manometer which recorded results on film from which pressure distributions could be calculated.

Velocity distributions within the boundary layer were measured by means of the multitube boundary layer rake which is shown in Figure 3. Each tube of the rake was connected to a multitube water manometer which was installed in the sailplane. Velocity profiles were obtained in a manner similar to that used in the pressure distribution measurements.

Two methods were used to estimate the position on the wing where transition from the laminar to the turbulent boundary layer took place. The first was a sublimation method which consisted of spraying a saturated solution of naphthalene in petroleum ether on the wing surface, which had been painted black. The second was a stethoscope method which consisted of inserting a small total head tube in the boundary layer and detecting the difference in noise level. Through these methods, reasonable estimations of the transition points were made.

Flight tests were made early in the morning by towing the sailplane to an altitude of 10,000 feet. Results were obtained for five different cases which were represented by different reference velocities of U_o = 39, 40, 42, 45, and 50 mph. For each of these five cases, three different suction velocities were applied which were represented by Δp = 6.4, 7.7, and 9.2 psf. First, in each of the five cases, the velocity distribution outside the boundary layer was measured up to the 0.70 chord length location. There measurements began at the leading edge of the wing section and were taken at equal intervals of 0.025 chord length. Then, for each case a suction distribution was applied on the wing surface at three different magnitudes, starting from 0.35 chord length location. Measurements were made at each 0.025 chord length interval from the 0.35 to 0.70 chord position.

APPLICATION OF THEORY

In Reference 4, a method for the calculation of the laminar and the turbulent boundary layer momentum thickness was developed when suction or blowing was applied to two-dimensional, axisymmetric bodies. Two examples were chosen for the two-dimensional and the axisymmetric case, and calculations were made. However, comparison of theoretical results with experimental data was not made at that time.

In 1956, sailplane flight tests were made with suction applied to the upper wing surface of the sailplane through distributed rows of suction holes. The experimental data were analyzed and compared with the results of the theory developed in Reference 4.

In order to calculate the momentum thickness when suction and blowing was applied, it was necessary to obtain the potential velocity distribution on the wing surface. Reference 4 shows that momentum thickness and suction velocity distribution are related to each other, so that if one of them is given, the other can be calculated. For this report, the suction velocity distribution was determined from measurements which then allowed the momentum thickness to be calculated and compared with experimental results.

Since the coordinates of the airfoil section were known, it was possible to calculate the potential velocity distribution on the wing surface by an analytical method. However, since determination of the angle of attack was rather difficult, the potential velocity distributions were determined from the experimental results (Figures 4a-4e). The potential flow velocity was considered to be unaffected by the inflow velocity distribution through the upper surface of the wing. This assumption was based on three velocity distributions outside the boundary layer measured at various inflow velocity rates.

From the potential velocity distributions and profile shape of the wing section, impervious momentum thicknesses were calculated by means of the method given by Truckenbrodt.

$$\left(\frac{\theta_o}{c}\right)^{1+n} = \frac{\left(\frac{C_f}{2}\right)^{1+n}}{\left(\frac{U}{U_o}\right)^{3(1+n)}} \int_{x_1/c}^{x/c} \frac{\left(\frac{U}{U_o}\right)^{3+2n}}{\beta\left(\frac{x}{c}\right)} \, d\left(\frac{x}{c}\right) \qquad (1)$$

where

$$\beta\left(\frac{x}{c}\right) = \frac{1}{\sqrt{1+\left\{\frac{d(y/c)}{d(x/c)}\right\}^2}} \quad (2)$$

In the above equations, c is a chord length of the wing section, x is a variable taken along the chord line of the wing, and y is a variable taken from and normal to the surface of the wing section. The laminar case is given by $n = 1$ and the turbulent case by $n = 1/6$. For numerical evaluation of equation 1, it was necessary to know the locations of the transition points. These were determined by experimental means, allowing the impervious momentum thicknesses to be calculated and compared with experimental results. The calculated momentum thicknesses are shown in Figures 5a to 5e.

Inflow velocity through the upper surface of the wing was determined at three different suction rates. The experimental results, which are indicated in figures by small circles, were determined from 0.35 to 0.70 chord length location at each 0.025 chord length interval. The calculated suction distributions are shown in Figures 6a to 10c as solid lines. In the case of $U_0 = 50$ mph, $\Delta p = 6.4$ psf, it was found that suction applied was not strong enough to cause suction from the 0.35 chord length location where the suction or blowing application began. As a result, the air in this region escaped from inside the wing through the perforated surface. This can be seen in Figure 7a.

Using information about the impervious momentum thickness and the suction velocity distribution, the momentum thickness with suction or blowing was calculated by means of a successive approximation method developed in Reference 4. The suction or blowing velocity distribution function is determined by

$$Y\left(\frac{x}{c}\right) = \frac{1+n}{\bar{H}} \quad \frac{v_0/U_0}{U/U_0} \cdot \left(\frac{\theta_0}{c}\right)^n \quad (3)$$

where $\bar{H}$ is an energy parameter. In the suction case, $v_0 < 0$, and in the blowing case, $v_0 > 0$. The momentum thickness with suction or blowing was calculated by

$$\left(\frac{\theta_{c_1}}{c}\right)^{1+n} = \frac{1}{(U/U_0)^{3(1+n)}} \int_{x_1/c}^{x/c} \frac{(U/U_0)^{3(1+n)}}{\beta(x/c)} \cdot Y\left(\frac{x}{c}\right) d\left(\frac{x}{c}\right). \tag{4}$$

As a first approximation, the momentum thickness is given by

$$\left(\frac{\theta_1}{c}\right)^{1+n} = \left(\frac{\theta_0}{c}\right)^{1+n} + \left(\frac{\theta_{c_1}}{c}\right)^{1+n}. \tag{5}$$

This newly calculated momentum thickness was substituted in equation 3 and the above process was repeated until good convergence of the solution was obtained.

The calculations mentioned above were carried out by a graphical technique at intervals of 0.025 chord, starting at the 0.35 chord position where suction or blowing began, and ending at the 0.70 chord length location. All of the examples were calculated up to the third approximation and are shown in Figures 11a to 15c by solid lines and compared with the experimental results which are shown by small circles. Since the flow was turbulent in the region where suction was applied, it is expected that the convergence of the solution by the method of successive approximation is rapid. As an example, the case of U_0 = 50 mph, Δp = 9.2 psf was chosen and calculations were made up to the fourth approximate solution of the equation. The results are shown in Figure 16. It was noticed that there was no appreciable difference between the third and fourth approximate solutions. In this report, all of the examples were calculated up to the third approximation and are considered to be satisfactory solutions of the momentum thickness equation for the boundary layer with suction and blowing.

DISCUSSION

The velocity distribution outside the boundary layer should not be affected by the existence of the suction distribution on the wing surface. However, in the actual case the flow outside the boundary layer is not necessarily represented by the ideal condition. It is considered that if suction is applied, the ideal condition may be approached. In the impervious case, the velocity distribution outside the boundary layer was measured from the leading edge to the 0.70 chord length location of the wing section. With suction, the velocity distribution outside the boundary layer was measured from the 0.35 chord length location where suction or blowing began to the 0.70 chord position.

In this paper, the potential velocity distribution was determined from both pressure distributions mentioned above. In some cases when suction is applied, measurements of the velocity distribution outside the boundary layer in front of the 0.35 chord length location may be needed.

A method for the calculation of the momentum thickness was developed in Reference 4 for the case in which suction or blowing was applied continuously to the surface of a body. Experimental results were obtained for a wing section on which suction was applied through rows of suction holes extending in the spanwise direction, although there is a problem involved in testing this method of applying suction as a continuously distributed porosity. In most of the regions where suction is applied, however, there is sufficient agreement between the two cases; but if more exact results are required this problem must be considered.

In determining suction velocity distribution, very careful attention must be paid in the region where the distributed suction by rows of holes starts, since it is reasonable to assume that the effect of suction will be seen in front of the row where suction starts. Once this relationship is established, it is possible to calculate the suction velocity distribution from the predetermined momentum thickness distribution.

As mentioned in the section labeled "Experimental Arrangements", two methods were used for estimation of transition points. Since transition points could only be roughly estimated, convenient values were chosen for the calculation of momentum thicknesses. More advanced techniques should be selected for determination of transition points in future work.

Calculations were made according to the methods developed in Reference 4 and were compared with experimental results. These experimental results were obtained from measurements of flow around the sailplane wing section by use of a multitube boundary layer rake. It

$$\left(\frac{\theta_{c_1}}{c}\right)^{1+n} = \frac{1}{(U/U_0)^{3(1+n)}} \int_{x_1/c}^{x/c} \frac{(U/U_0)^{3(1+n)}}{\beta(x/c)} \cdot Y\left(\frac{x}{c}\right) d\left(\frac{x}{c}\right). \quad (4)$$

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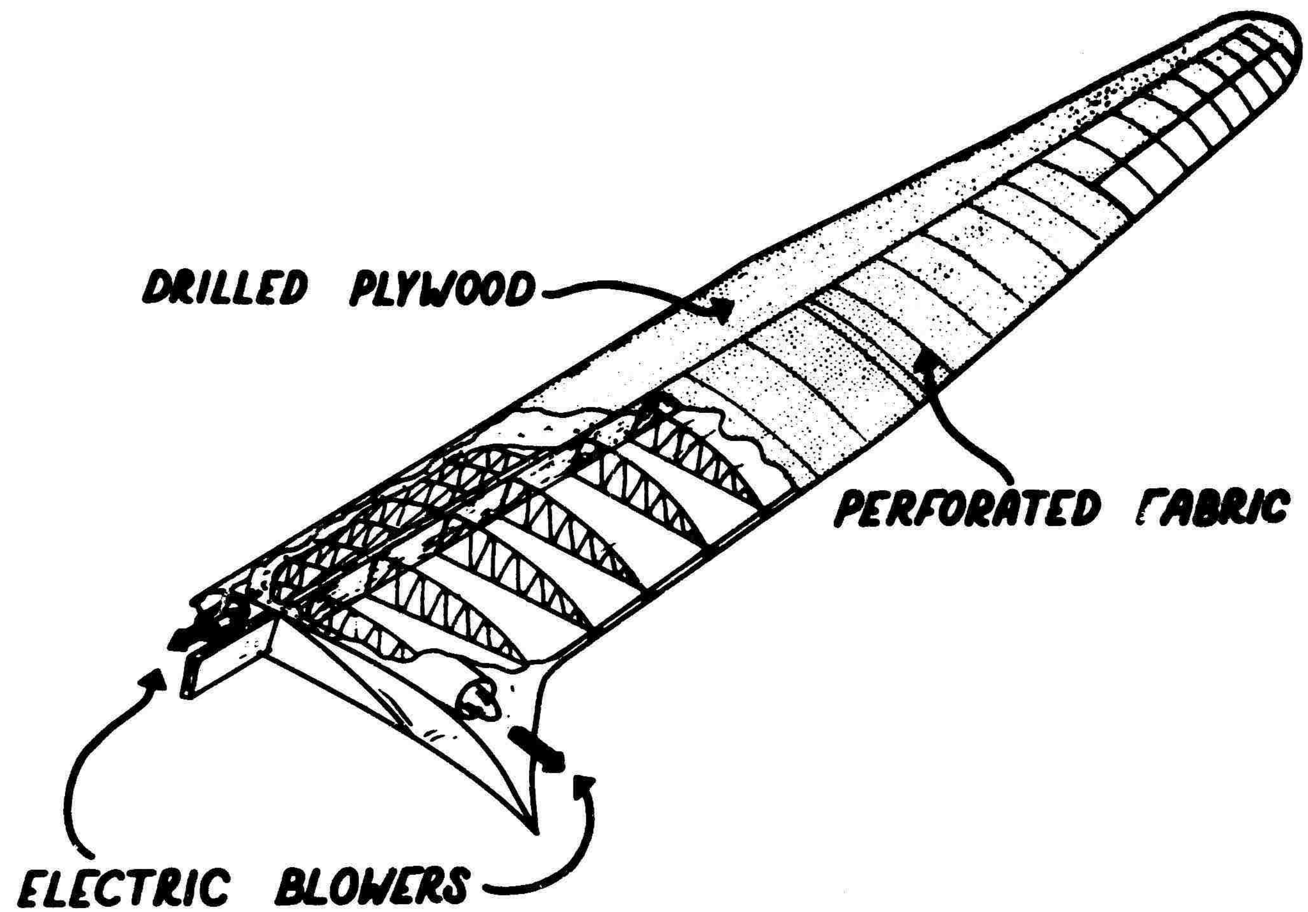
Calculations were made according to the methods developed in Reference 4 and were compared with experimental results. These experimental results were obtained from measurements of flow around the sailplane wing section by use of a multitube boundary layer rake. It would be desirable for experimental data of higher accuracy to be obtained for studies of this type.

One of the most important purposes of a study of the boundary layer problem concerns calculation of the skin friction of the body in question. If suction and blowing is applied to the body, it is not proper to determine skin friction by means of methods used for the case of an impervious surface. A different approach to the problem is necessary.

Figure 1. Schweizer TG-3 Used for the Flight Tests.



MODIFIED SCHWEIZER TG3-A

Figure 2. Drawing of Wing Section Modified for the Application of Boundary Layer Control.

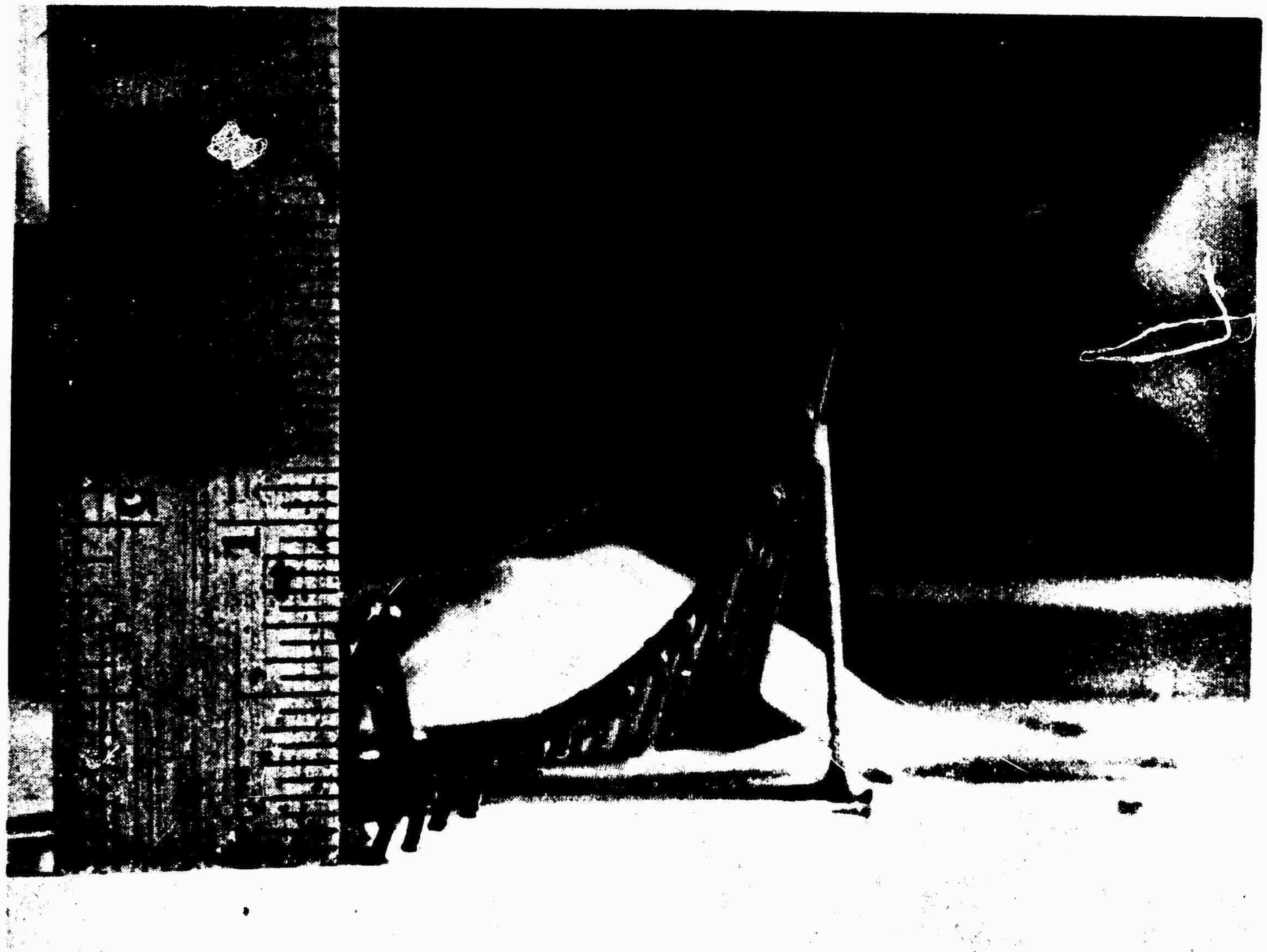


Figure 3. Multitube Boundary Layer Rake.

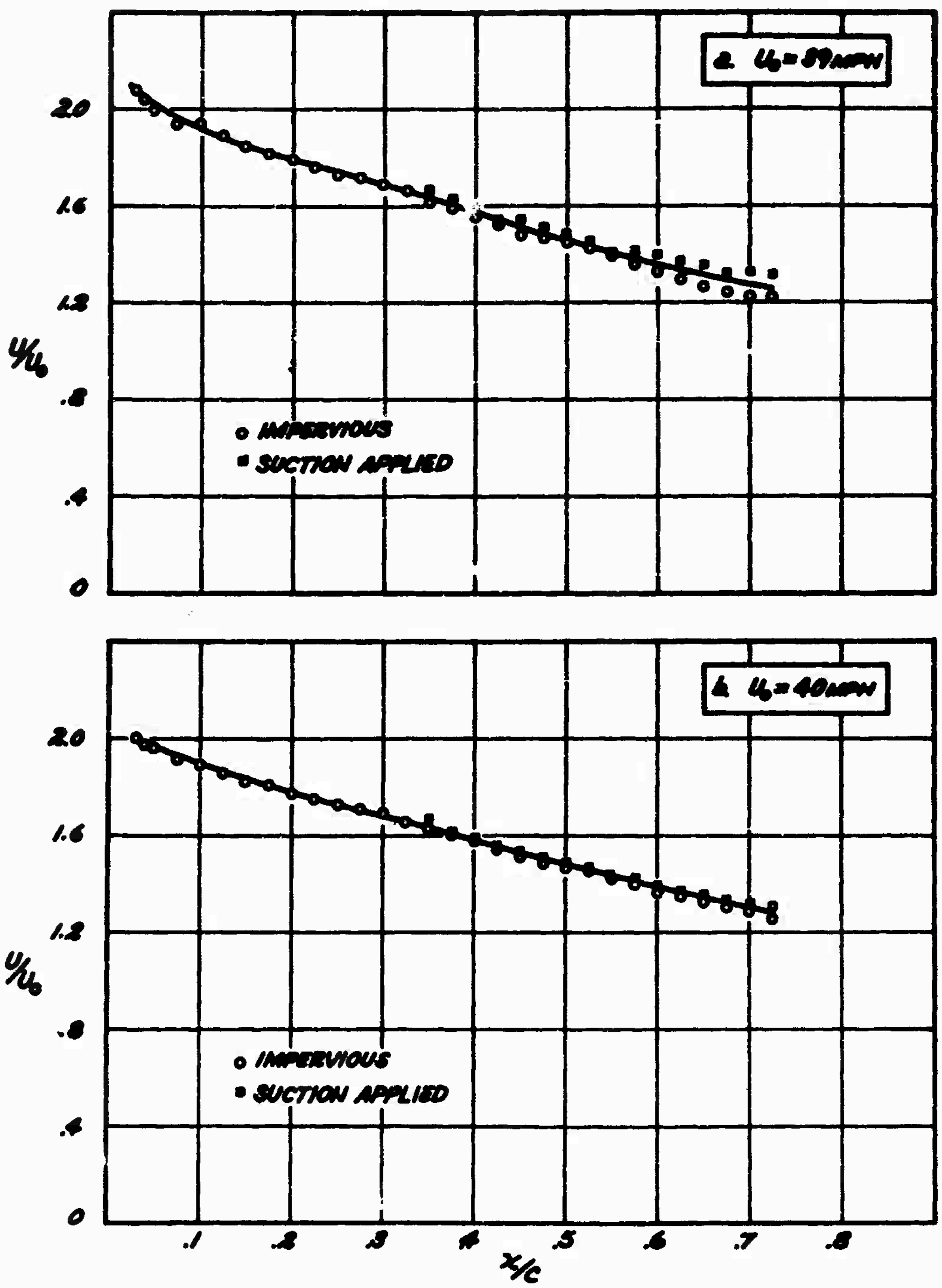


Figure 4. Determination of Potential Velocity Distribution.

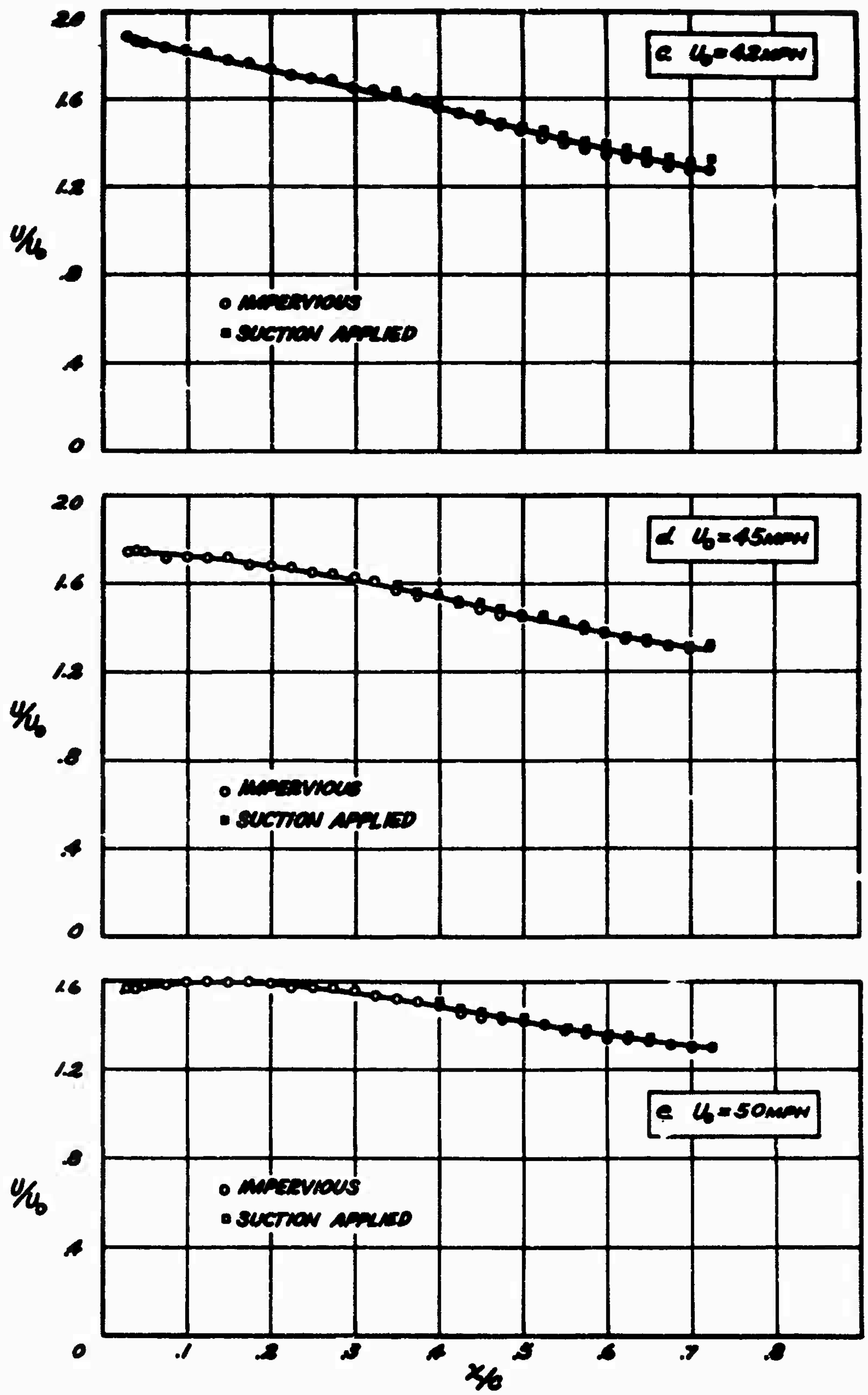


Figure 4 (contd.). Determination of Potential Velocity Distribution.

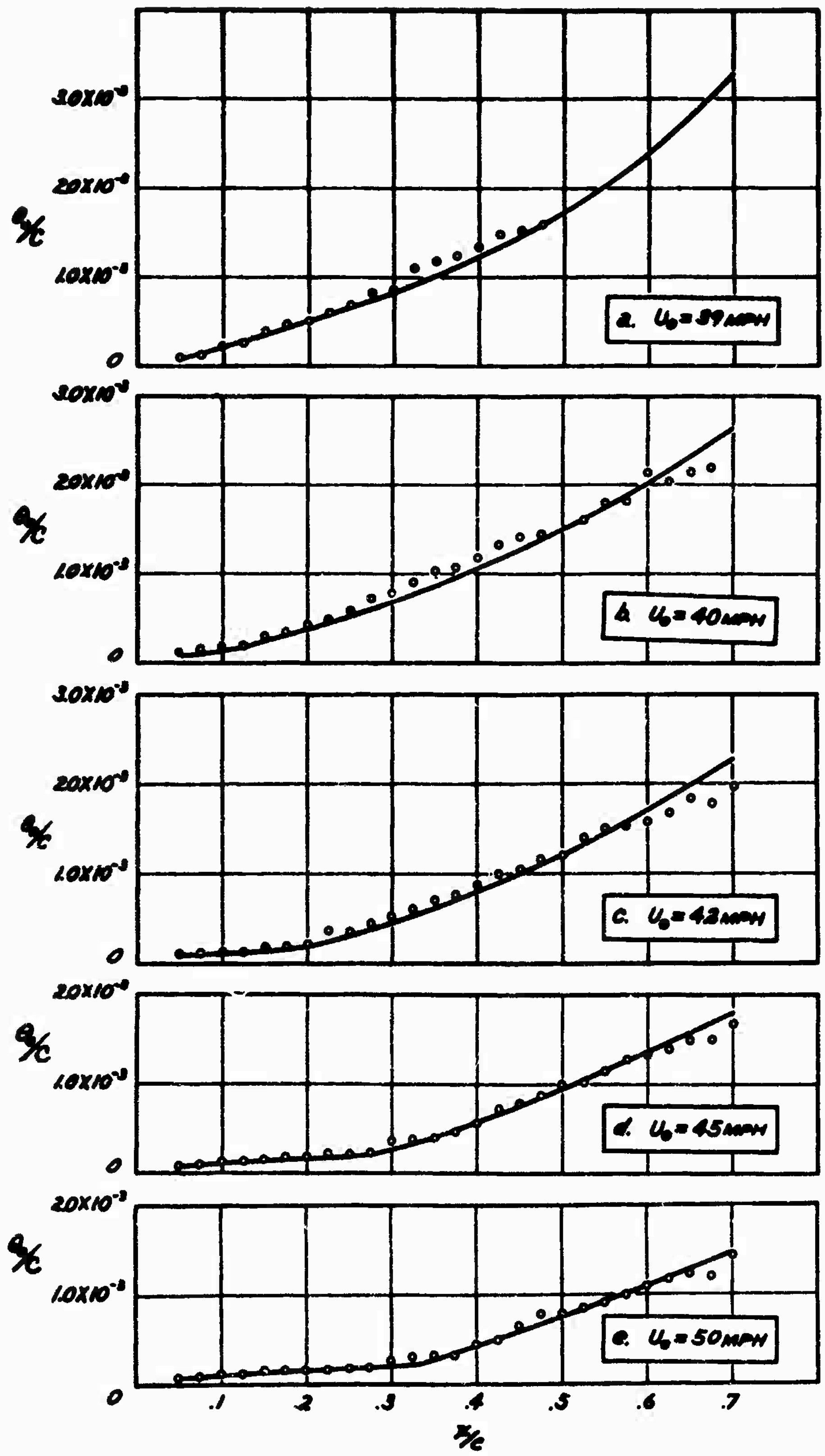


Figure 5. Calculation of the Impervious Momentum Thickness by Means of Truckenbrodt's Method.

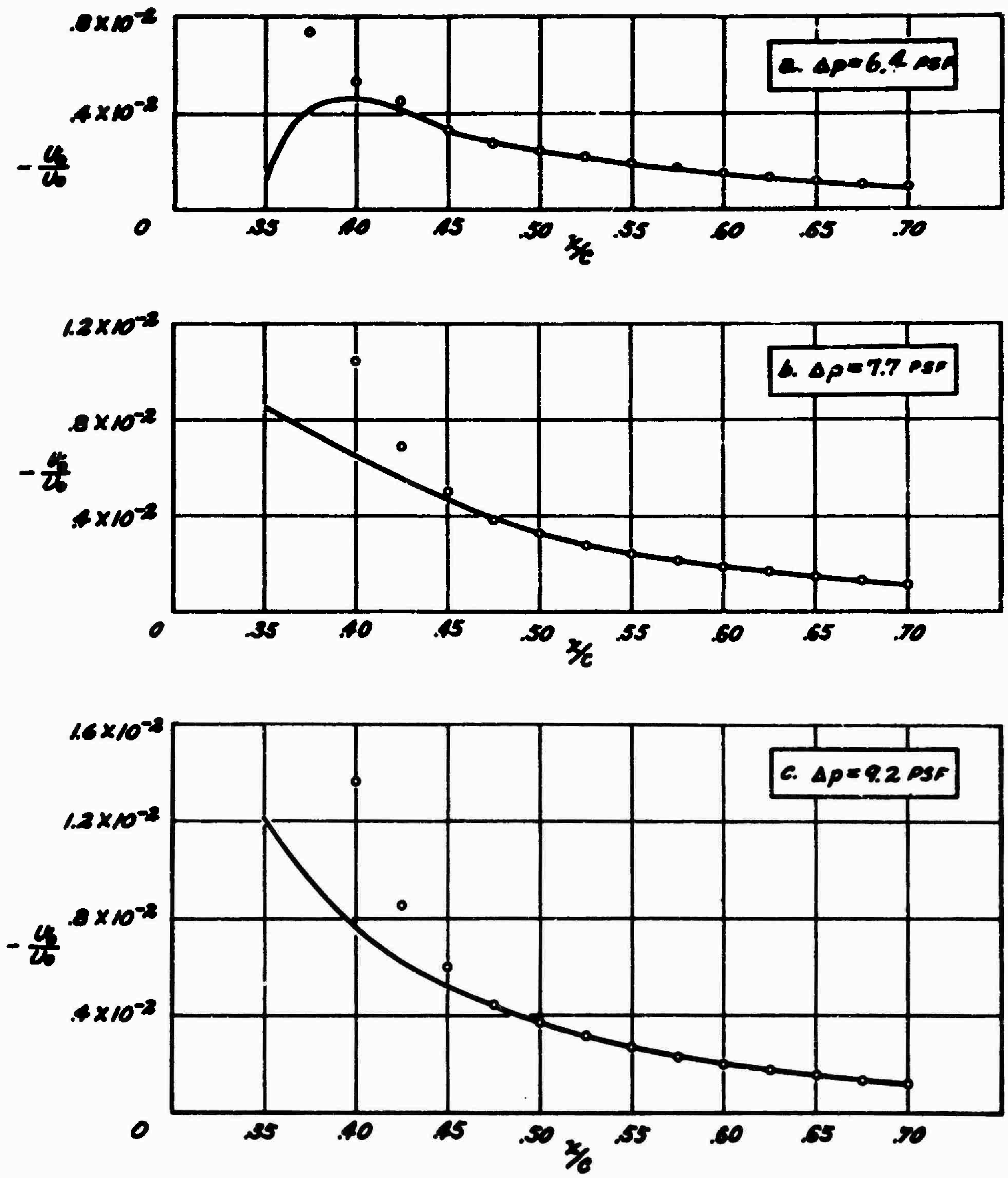


Figure 6. Suction Velocity Distribution for the Case of U_o = 39 mph.

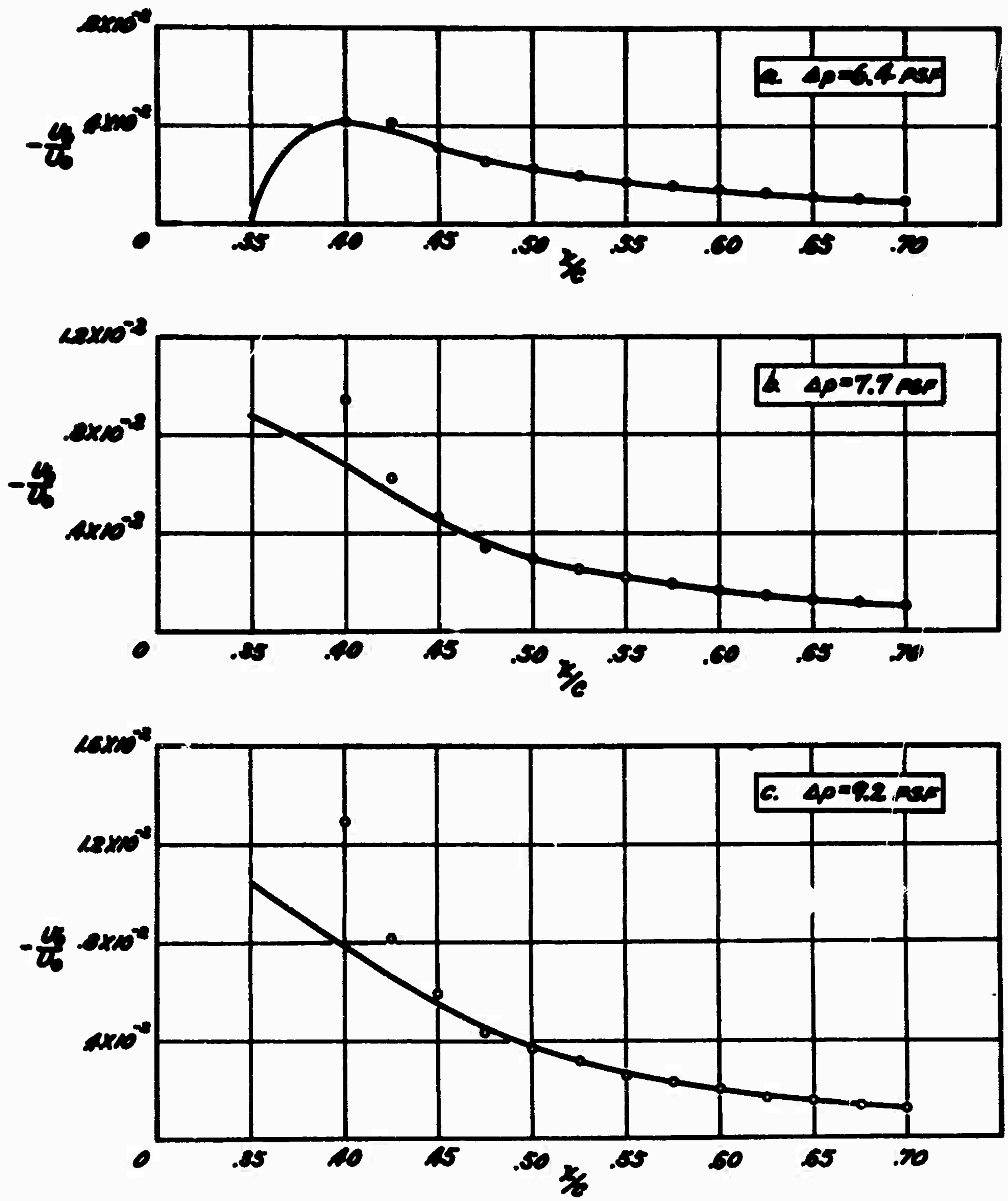


Figure 7. Suction Velocity Distribution for the Case of U_o = 40 mph.

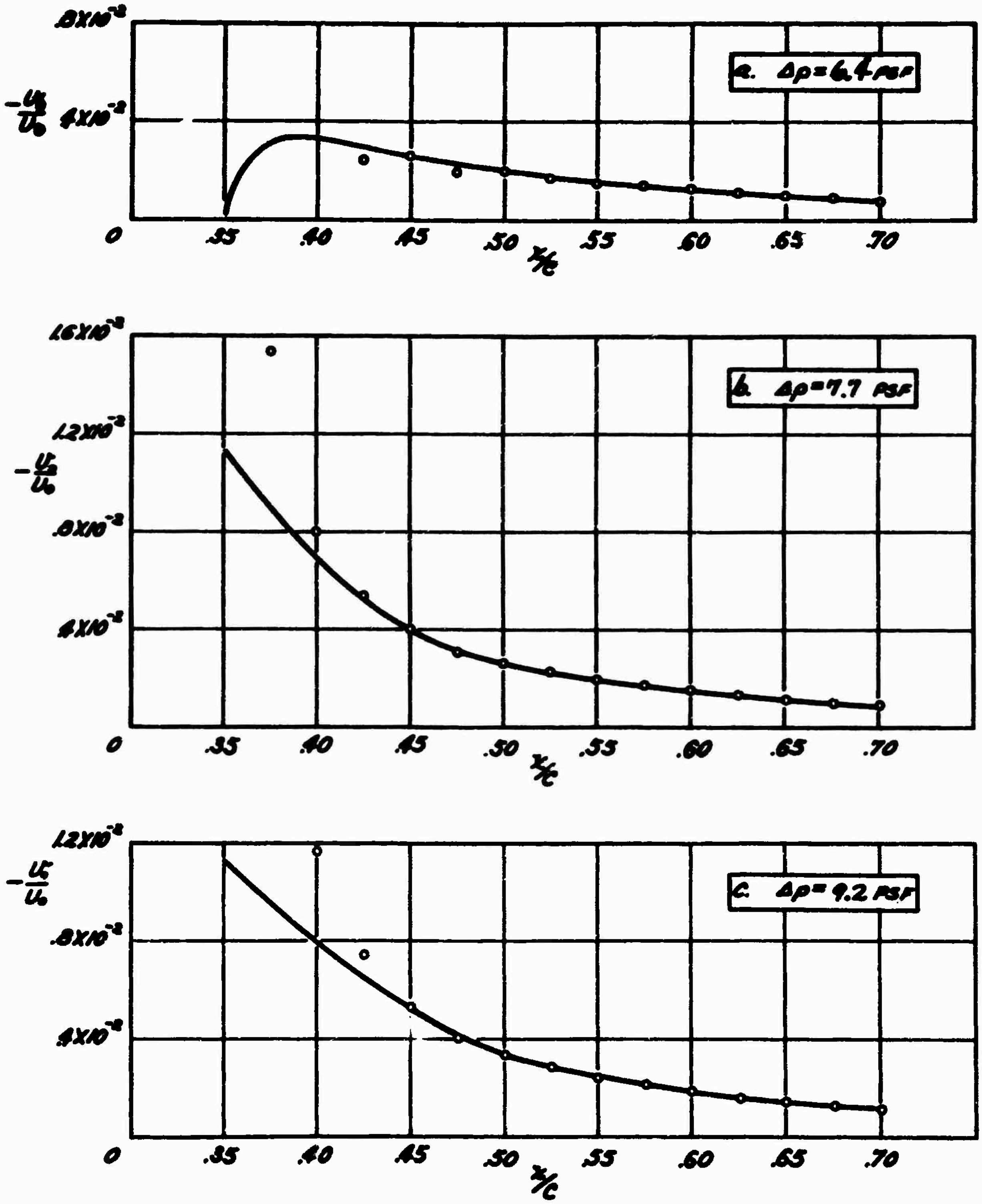


Figure 8. Suction Velocity Distribution for the Case of U_o = 42 mph.

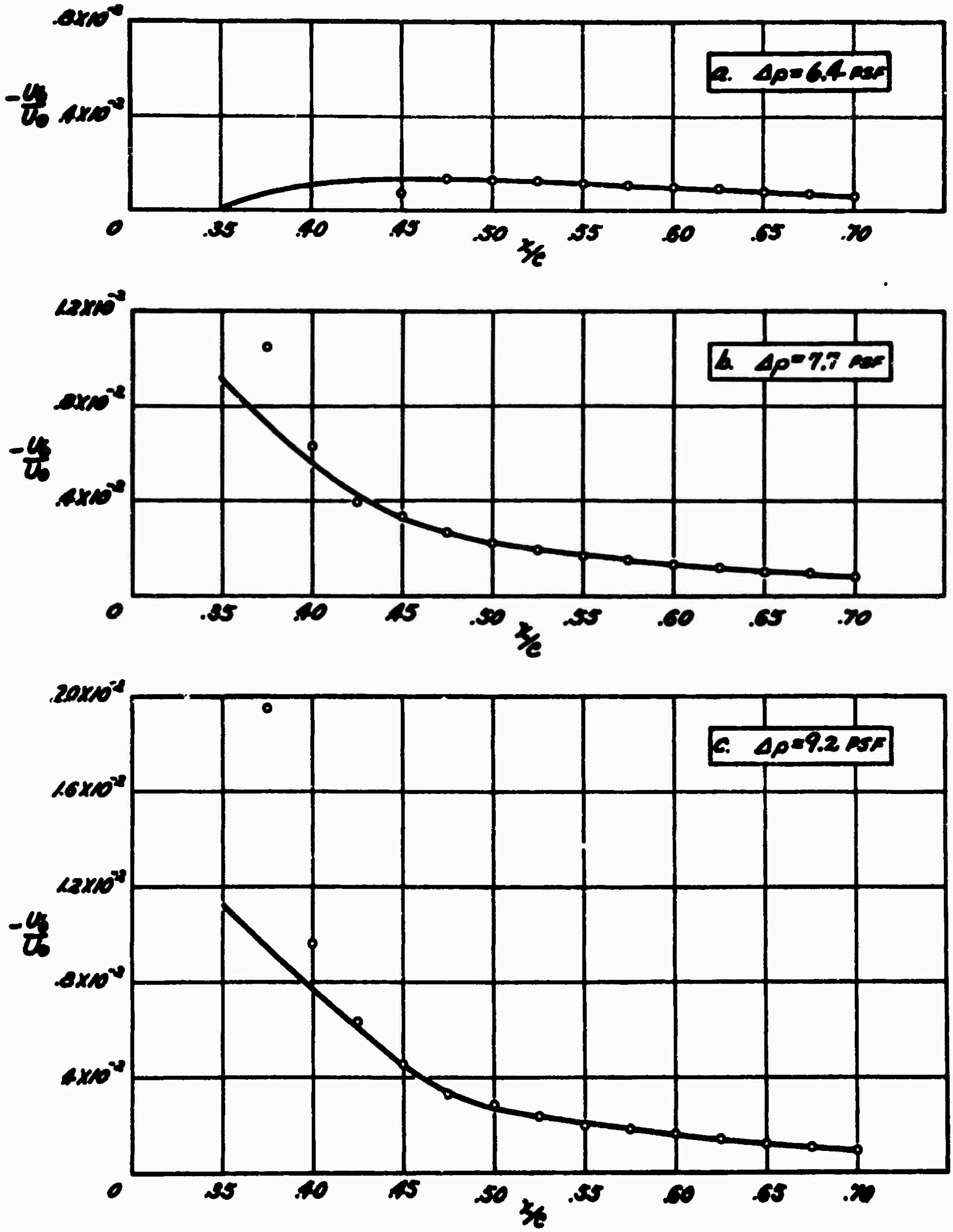


Figure 9. Suction Velocity Distribution for the Case of U_0 = 45 mph.

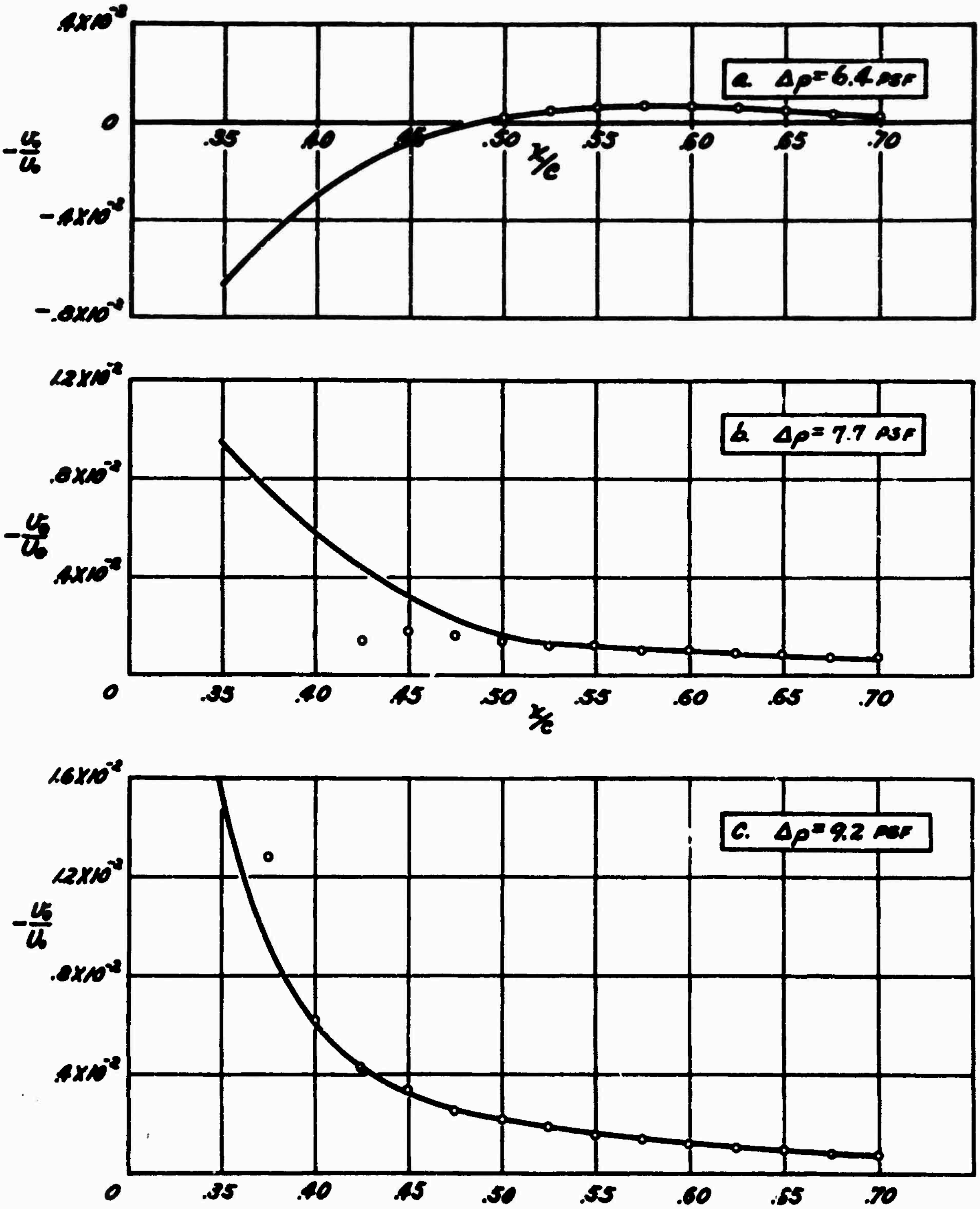


Figure 10. Suction Velocity Distribution for the Case of U_0 = 50 mph.

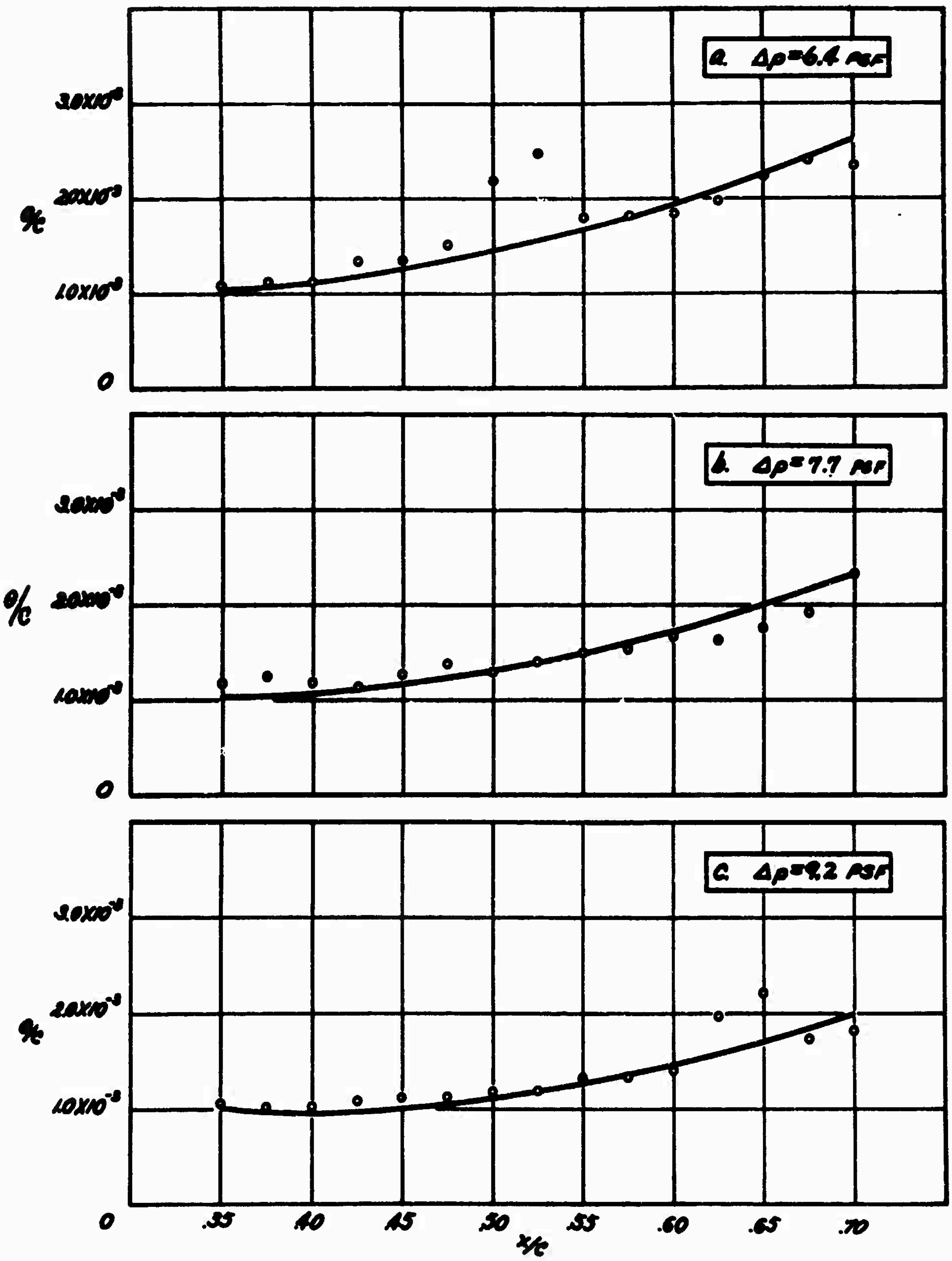


Figure 11. Calculation of the Momentum Thickness for the Case of U_o = 39 mph.

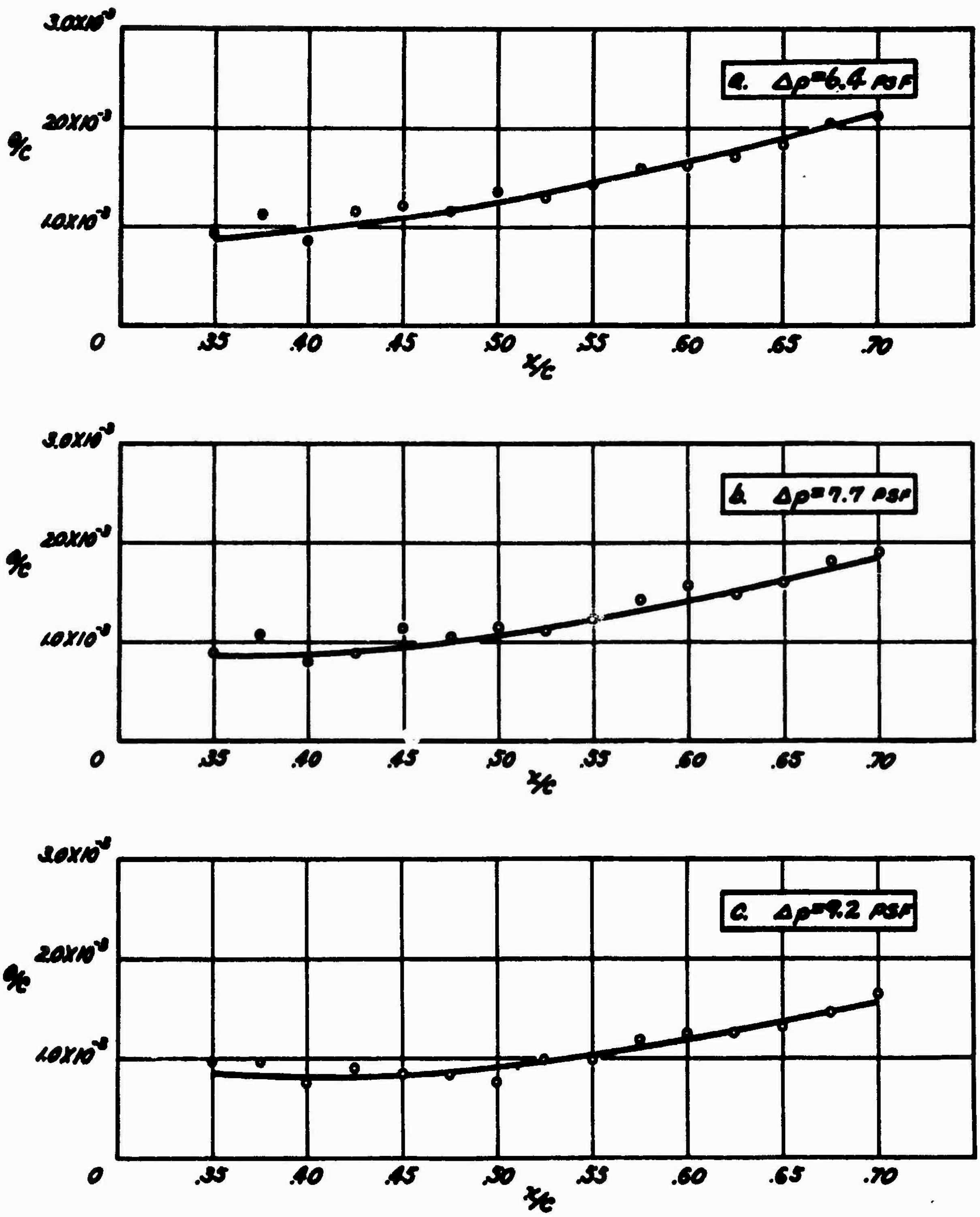


Figure 12. Calculation of the Momentum Thickness for the Case of U_o = 40 mph.

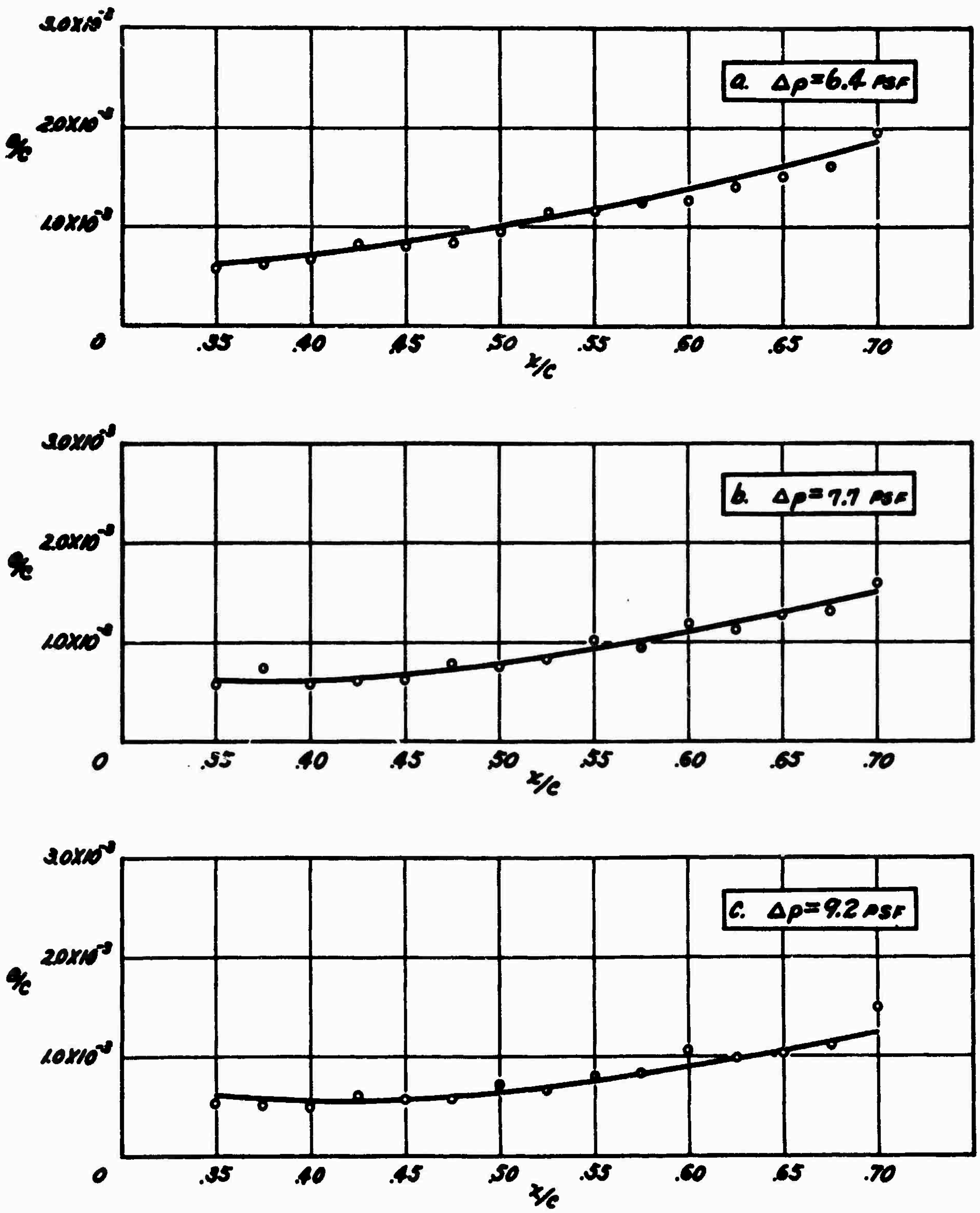


Figure 13. Calculation of the Momentum Thickness for the Case of U_o = 42 mph.

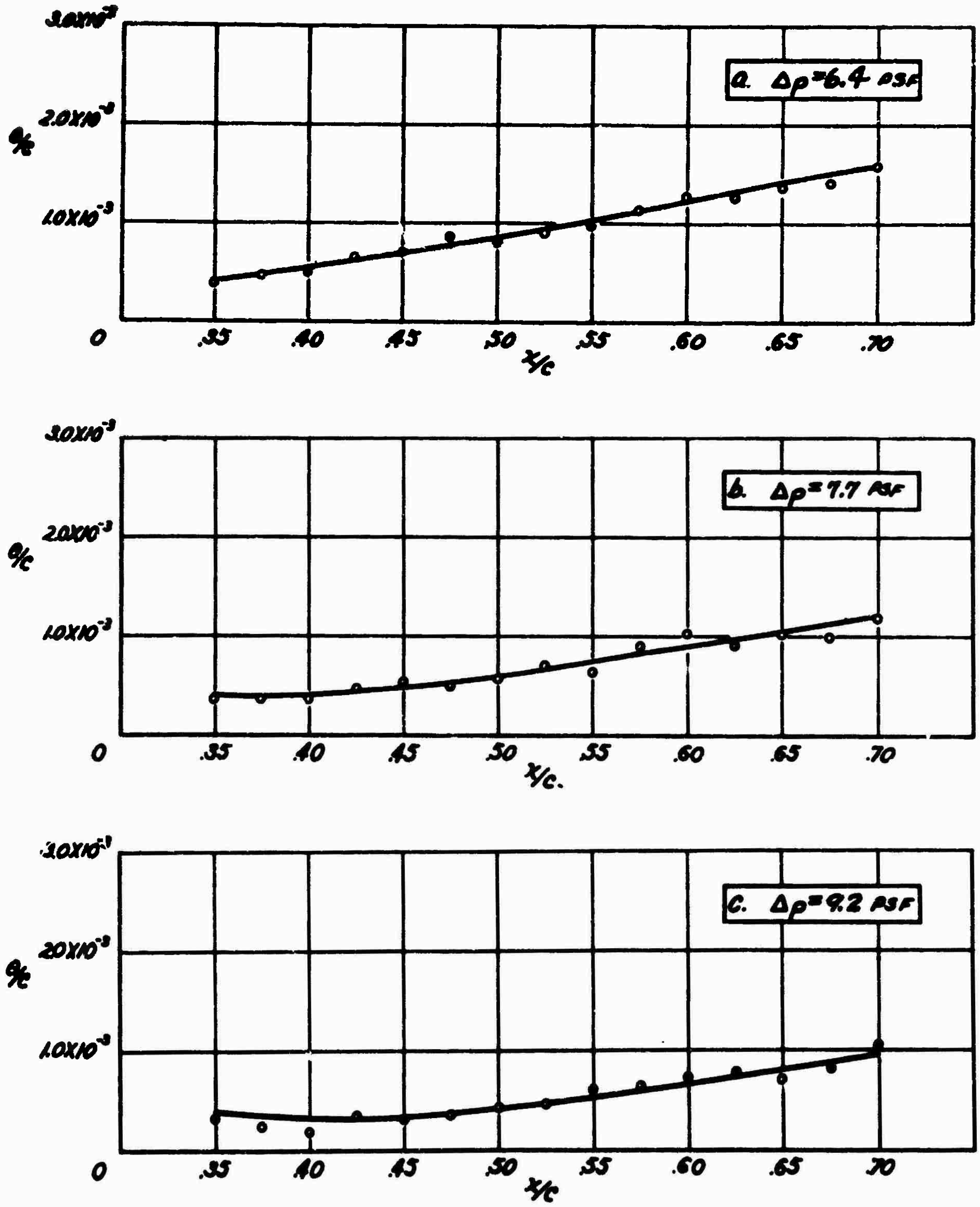


Figure 14. Calculation of the Momentum Thickness for the Case of U_o = 45 mph.

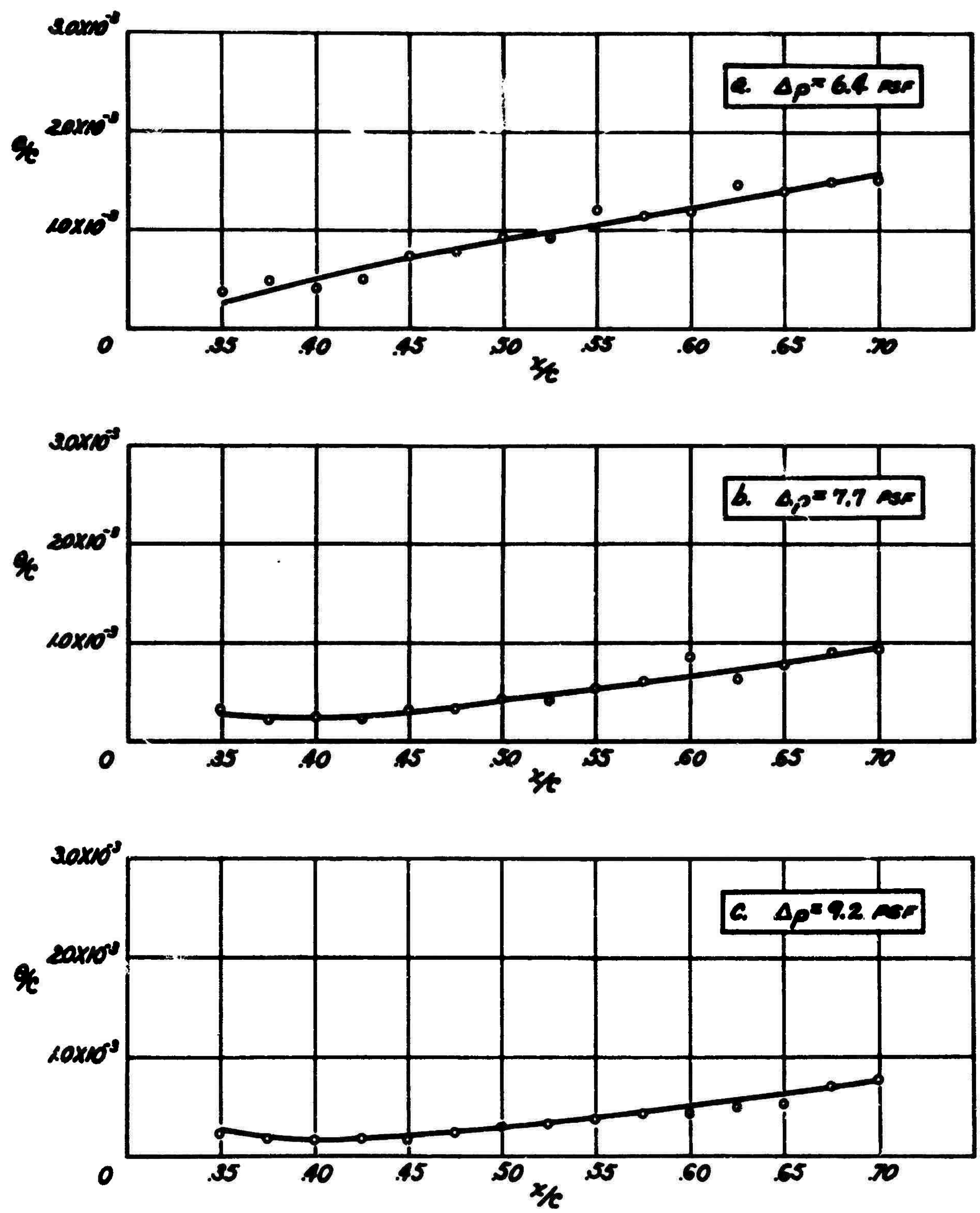


Figure 15. Calculation of the Momentum Thickness for the Case of U_0 = 50 mph.

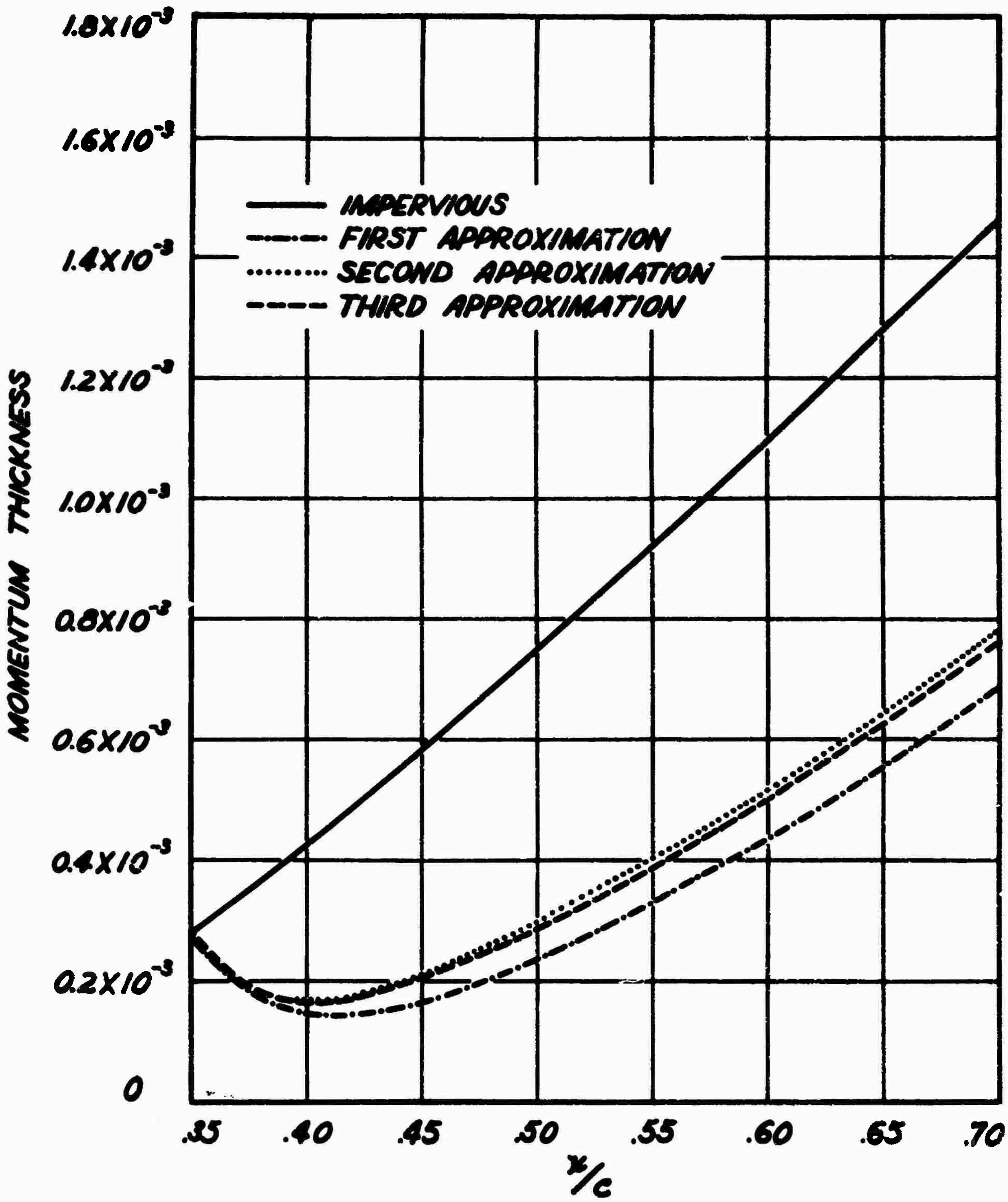


Figure 16. Convergence of the Solutions of the Momentum Thickness Equation by Means of the Su(:ssive Approximation Method for the Case of U_o = 50 mph, Δ p = 9.2 psf.

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