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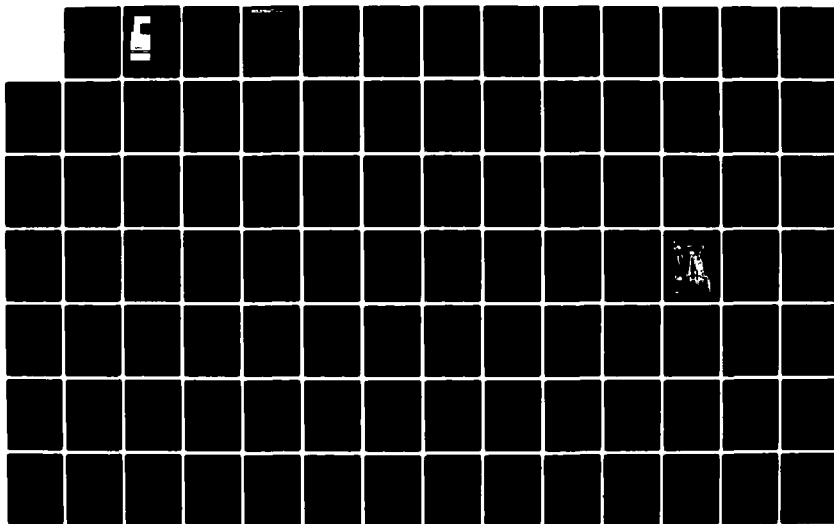
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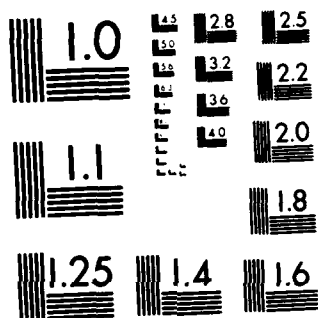
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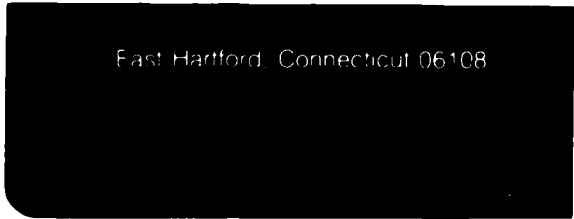


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The Effects of Free-Stream Turbulence
on the Turbulence Structure and Heat
Transfer in Zero Pressure
Gradient Boundary Layers

Contract No. F49620-81-C-0053

REPORTED BY

M. F. Blair

M. F. Blair

D. E. Edwards

D. E. Edwards

APPROVED BY

R. P. Dring

R. P. Dring

DATE November 1982

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Numerous measurements assured that the present test conditions (boundary layer development and free-stream turbulence distributions) duplicated those of the earlier AFOSR contract. The purposes for making these present detailed boundary layer turbulence measurements were: (1) to provide data to which current finite-difference boundary layer turbulence models could be compared, and (2) to generate a data base for the development of new analytical models for boundary layer heat transfer prediction. The results from the present program have shown that the distributions of both the turbulence kinetic energy and the turbulence structural coefficients were affected by increased levels of free-stream turbulence. Local profile measurements indicated that the effect of increased free-stream turbulence was to decrease the near-wall turbulent Prandtl number relative to values expected for low free-stream turbulence. Turbulent Prandtl numbers in the outer region of the boundary layer were slightly increased for higher free-stream turbulence. A turbulence dependent correlation for the measured distribution of turbulent Prandtl number is given. With the completion of the experimental portion of this investigation, a theoretical effort was made to assess the capability of a finite difference boundary layer computer program, ABLE (Analysis of the Boundary Layer Equations) for predicting the effect of free-stream turbulence on momentum and thermal boundary layers. Comparisons with experimental data of mean flow velocity, mean flow temperature, Reynolds shear stress, turbulent heat transport, and turbulence kinematic energy were made in this investigation. In addition, the turbulent Prandtl number correlation deduced from the experimental measurements was used in the boundary layer analysis and its effect on surface heating evaluated. The results indicated that this boundary layer analysis, which uses a one equation eddy viscosity turbulence model, can provide adequate predictions of zero pressure gradient flows with high free-stream turbulence and wall heating.

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The Effects of Free-Stream Turbulence on the
Turbulence Structure and Heat Transfer in
Zero Pressure Gradient Boundary Layers

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ABSTRACT

In an earlier AFOSR funded investigation, experimental research was conducted to determine the influence of free-stream turbulence on turbulent boundary layer heat transfer and mean profile development. The data obtained under this earlier contract indicated that both the skin friction and the heat transfer increased significantly with increased free-stream turbulence level. Under the present investigation, detailed boundary layer turbulence structural data and turbulent heat transfer data were obtained for experimental test conditions and profile locations selected from the earlier test matrix. Numerous measurements assured that the present test conditions (boundary layer development and free-stream turbulence distributions) duplicated those of the earlier AFOSR contract. The purposes for making these present detailed boundary layer turbulence measurements were: (1) to provide data to which current finite-difference boundary layer turbulence models could be compared, and (2) to generate a data base for the development of new analytical models for boundary layer heat transfer prediction. The results from the present program have shown that the distributions of both the turbulence kinetic energy and the turbulence structural coefficients were affected by increased levels of free-stream turbulence. Local profile measurements indicated that the effect of increased free-stream turbulence was to decrease the near-wall turbulent Prandtl number relative to values expected for low free-stream turbulence. Turbulent Prandtl numbers in the outer region of the boundary layer were slightly increased for higher free-stream turbulence. A turbulence dependent correlation for the measured distribution of turbulent Prandtl number is given.

With the completion of the experimental portion of this investigation, a theoretical effort was made to assess the capability of a finite difference boundary layer computer program, ABLE (Analysis of the Boundary Layer Equations) for predicting the effect of free-stream turbulence on momentum and thermal boundary layers. Comparisons with experimental data of mean flow velocity, mean flow temperature, Reynolds shear stress, turbulent heat transport, and turbulence kinetic energy were made in this investigation. In addition, the turbulent Prandtl number correlation deduced from the experimental measurements was used in the boundary layer analysis and its effect on surface heating evaluated. The results indicated that this boundary layer analysis, which uses a one equation eddy viscosity turbulence model, can provide adequate predictions of zero pressure gradient flows with high free-stream turbulence and wall heating.

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INTRODUCTION

The search for improved gas turbine performance has led steadily in the direction of higher turbine inlet temperatures. The last twenty years have seen an increase in turbine inlet temperatures of roughly 1400°F but an increase in allowable blade metal temperature of only roughly 200°F. The difference between these two increases in temperature can be related directly to improved cooling technology. As an integral part of this advancing cooling technology, engine manufacturers are continually seeking improved techniques for calculating heat transfer coefficient distributions on gas turbine airfoils. As the level of cooling technology has been driven upward, and with it turbine inlet temperature, it is not surprising that the result is a design methodology which is extremely unforgiving of even small errors. The temptation is always present to overcool the airfoils but this is unacceptable due to the powerful negative impact of cooling air on the cycle and on turbine efficiency. It is this dilemma which has often led to extremely long and expensive developmental testing of advanced technology turbines.

Gas turbine thermal design systems are typically not based on fundamental fluid mechanics and heat transfer data and analysis alone but rather they are calibrated, or adjusted, to provide agreement with engine experience. Without the benefit of a first-principles understanding of the effects involved there is the likelihood that a designer will unknowingly either overcool the component or go beyond the range of validity of the design system calibration. There is, then, a clear requirement for the development of airfoil heat transfer distribution prediction procedures which are based on fundamental fluid mechanics and heat transfer data. The great emphasis placed on the development of accurate boundary layer calculation techniques over the past few years reflects the recognition of these needs.

One particularly important topic in the general context of turbine airfoil convective heat transfer is the influence of the free-stream turbulence on fully turbulent boundary layer development. It has, of course, long been recognized that increasing the free-stream turbulence level can cause a forward shift of the laminar to turbulent transition region. This particular phenomenon, the reduction of the boundary layer transition Reynolds number with increased free-stream turbulence level, is well documented in the open literature for zero pressure gradient flows and can be adequately predicted with currently available boundary layer prediction schemes. In addition, a number of investigators have studied the effects of free-stream turbulence level on turbulent boundary layer growth, profile structure, skin friction distribution and heat transfer. The consensus of these studies, is that free-stream turbulence has a very large and important influence on both the heat transfer and the boundary layer characteristics. As an example, it has been shown in a recently completed AFOSR funded contract at UTRC that a free-stream turbulence intensity of 5 percent produces an increase in Stanton number of approximately 15 percent over the value expected for a low turbulence freestream. While a number of existing boundary layer analysis procedures (including the UTRC ABLE code) account reasonably well for the influence of free-stream turbulence on mean velocity profile development and skin friction, no currently available analysis satisfactorily predicts the observed increased heat transfer rates.

The present program was designed to provide detailed boundary layer turbulence and turbulent heat flux distribution data for a range of free-stream turbulence levels. As part of this program these experimental data were employed to evaluate the analytical turbulence models currently incorporated in the UTRC ABLE code. It is anticipated that in the future these experimental data will be used by both UTRC and other workers in the field of boundary layer computation for development of new analytical turbulence models.

The contract effort consisted of acquiring, documenting and analyzing experimental flat wall boundary layer mean and fluctuating profile data to determine the influence of free-stream turbulence on fully turbulent boundary layer flows. For fully turbulent, zero pressure gradient flows, the following profile data were obtained for a range of free-stream turbulence intensities; boundary layer mean and fluctuating velocities and temperatures, turbulent shear stresses, and turbulent Prandtl numbers. In addition, in order to improve the ability of the UTRC boundary layer deck to predict the effects of free-stream turbulence on heat transfer rates, a turbulent Prandtl number distribution model was incorporated into the UTRC boundary layer code. Calculations were carried out employing the measured turbulent Prandtl number distributions and comparisons made between the predicted and measured heat transfer distributions.

DESCRIPTION OF TEST EQUIPMENT

1. Wind Tunnel and Heat Transfer Test Surface

All experimental data for the present investigation were obtained in the United Technologies Research Center (UTRC) Boundary Layer Wind Tunnel (Fig. 1). This tunnel was designed specifically to generate large-scale, two-dimensional, incompressible boundary layers with Reynolds numbers and free-stream turbulence levels typical of turbomachinery airfoils. Complete descriptions of this facility including measurements documenting the tunnel flow uniformity and two-dimensionality of the test boundary layers are given in Refs. 1 and 2. The tunnel test section consisted of a flat upper wall instrumented for heat transfer measurements which served as the boundary layer test surface, plexiglass vertical sidewalls and a flexible lower wall. The test section was 34-in. wide, 96-in. long and 8-in. high at the entrance. For all test flows in this study the lower flexible test section wall was adjusted to produce a constant velocity along the test section.

A photograph of the Boundary Layer Wind Tunnel is presented in Fig. 2. Also shown in Fig. 2 are both the telescope used to position probes relative to the test wall and the computer controlled probe traverse mechanism.

The boundary layer test surface (upper wall of test section) consisted of a uniform heat flux electrically heated plate instrumented for the measurement of local convective coefficients (Fig. 3). The heated flat plate was constructed from a block of rigid urethane foam 34-in. wide by 96-in. long by 4-in. thick mounted in a plexiglass frame with 6-in. wide strips of 316 stainless steel foil cemented to the test surface. Details of the flat plate model and its instrumentation are presented in Refs. 1 and 2. Rigid foam was employed for the substrate of the heated flat plate model because of its extremely low thermal conductivity (0.025 Btu/hr ft²°F). Less than 1/2 percent of the heat generated on the surface of the plate was conducted away from the test surface. Electric current passing through the metal foil strips cemented to the test surface produced the surface heating. The metal foil strips were wired in series and were powered by a single low-ripple, regulated dc power supply. The foil test surface was instrumented with an array of 203 Cr-Al 0.13 mm diameter bead welded thermocouples. Each thermocouple was welded to the back surface of the foil through a hole in the rigid foam plate. Forty-eight surface static pressure taps were also installed along the test surface.

The dc power current passing through the surface strips was measured using two precision shunt resistors and a digital voltmeter. The temperatures of the test surface thermocouples were measured relative to a single test section free-stream reference junction using a digital voltmeter.

In order to insure a known, constant test surface emissivity and hence a known radiation loss, the completed foil test surface was coated with 3M C-101 high emissivity flat black paint ($\epsilon = 0.99$). Test results indicated that this surface was aerodynamically smooth, producing no premature boundary layer transition.

Local convective coefficients were determined by ignoring the negligible conduction losses, subtracting power lost through thermal radiation and dividing by the temperature difference from the wall (T_w) to the freestream (T_e). To illustrate the magnitude of the radiation losses from the test surface, for $U_e = 100$ ft/sec, for turbulent boundary layer flow with $T_w - T_e = 25^\circ\text{F}$, the radiation loss was approximately 4 percent of the total surface power.

As shown in Fig. 1, at the test section entrance a bleed scoop formed the leading edge of the heated boundary layer test surface. The scoop, which was mounted smoothly on the front edge of the heated test wall, provided a very short unheated starting length ($\xi = 1.7$ in.) upstream of the heated test surface. The leading edge of the scoop was a 4×1 ellipse in order to prevent a local separation bubble and premature transition of the test surface boundary layer. Details of the scoop including its instrumentation and adjustment are given in Refs. 1 and 2.

2. Turbulence Generating Grids

As described in Ref. 1, this wind tunnel has a relatively low residual test section turbulence level ($< 1/4\%$). Higher turbulence levels required for this study were generated by inserting various square array biplane grids constructed from rectangular bars at the entrance to the main tunnel contraction (see Fig. 1). Four turbulence generating grids were designed using the correlations of Ref. 3. The grids will be referred to as Grids 1, 2, 3 and 4 corresponding to mesh widths, M , of $7/8$, $2\ 9/16$, 7 and 9 in. The minimum turbulence configuration (no grid) will be referred to as Grid 0. Details of the grid configuration are given in Ref. 1. This present arrangement differs from that used for nearly all the earlier investigations of this subject in which the turbulence grids were located in the test section just upstream of the boundary layer test surface. The benefits derived from locating the grids at the contraction entrance were that the generated turbulence was more homogeneous and had a lower decay rate along the test section. Since grid generated turbulence decays approximately as $u'/U \propto (x/b)^{-5/7}$ (Ref. 3), the change in turbulence level with distance along the test section was reduced by increasing the distance from the grid to the test section entrance. In addition, the results of Ref. 3 indicate that approximately 10 grid mesh lengths are required to establish a uniform turbulent flow. Locating the grid a distance upstream of the test section requires, of course, a more coarse grid to achieve a given test section turbulence intensity.

Another effect considered was the expected influence of the contraction of the components of the grid generated turbulence. It was recognized that rearrangement of the relative magnitudes of the turbulence components would occur due to the contraction. However, since the contraction ratio was small (2.8), it was concluded that any effects of induced anisotropy would be small in comparison to the advantages gained in homogeneity and reduced decay rate. To determine the validity of the assumption, all three components of the test section turbulence were documented for all test cases.

3. Boundary Layer Total Pressure and Thermocouple Probes and Traverse Control

Boundary layer mean velocity profile data were measured using United Sensor Model Ba-0.020 impact probes with flattened tips. The probes used in the program were inspected for defects using both a Nikon Model II toolmakers microscope and a Jones and Lamson Model PC14 Shadowgraph. Mean temperature data were measured with miniature thermocouple probes designed using the results of Ref. 4. The thermocouple sensing elements for these probes were constructed from 0.001 in. dia. Chromel-Alumel bead welded wires. The thermocouple bead ($\approx$ 0.003 in. dia.) was located at the center of the probe support prongs which were fabricated of heavier Chromel and Alumel wire. The results of Ref. 4 indicate that a probe of this design was virtually free of wire conduction errors and was capable of measuring boundary layer mean temperature profile data into the viscous sublayer region.

Movement of the boundary layer probes was achieved using an L.C. Smith ball/screw traverse drive with an optical shaft encoder capable of resolving relative probe location to within 0.0005 in. The traverse mechanism was suspended on a linear ball bearing track beneath the test section. The traverse could be located anywhere in the center 75 percent of the test section width from the leading to trailing edges of the test wall. A telescope sighted through the tunnel sidewall was used to accurately position probes relative to the test wall. Estimated absolute accuracy of measured probe distance from the test surface was 0.002 in. for any location in the test boundary layers.

HOT WIRE DATA ACQUISITION AND ANALYSIS TECHNIQUES

1. General

Measurements of fluctuating velocities and temperatures in the test boundary layers were obtained using multi-element hot wire anemometry techniques. For a large number of the test cases the wind tunnel was operated without wall heating, the resulting boundary layers being isothermal. Both vertical and horizontal x-type 2 wire probes were employed for these isothermal test cases. For cases with wall heating the velocity and temperature fluctuations in the flows were determined by using specially designed 3 wire probes, one wire of which was operated at a lower overheat than the other two. Detailed descriptions of both the 2 and 3 wire probes are given below in section 2. The voltage signals from the various hot wire probes were digitized, recorded and subsequently reduced to fluctuating velocity and temperature records using a minicomputer. A detailed description of the data system is provided in section 4. An analysis of the uncertainties of the various hot wire measurements is given in Appendix A.

2. Description of the Hot Wire Probes

2.1 Probe Design

The present study involved the measurement, using arrays of inclined hot wires, of fluctuating velocities and temperatures within boundary layer flows. In order to minimize potential errors for these measurements (errors largely arising from the inherent mean velocity and temperature gradients in the flows and the finite probe size) the hot wire probes were custom-designed and fabricated specifically for this program. The results from a large number of previous boundary layer turbulence and general hot wire studies were incorporated into the probe designs (Refs. 5-14). For the 2 wire x-type probes used in the isothermal tests three important design principles were adopted from these earlier studies. (1) To reduce the effects of the mean gradients in the flows the active length (or the size of the array of wires in the direction of the gradients) of the wires should be minimized. (2) To reduce end effects (nonuniform temperature along the active length) and to insure that a "Champagne k^2 " (Ref. 7) form of angular sensitivity could be employed, an active length/diameter ratio of 200 was chosen. (3) To maximize the spatial correlation coefficient (maximum accuracy of cross-products such as Reynolds stress) without introducing wire cross-talk effects a transverse wire spacing of $3\lambda/4$ was chosen.

Considerations (1) and (2) required that the diameter (d) be as small as possible--the limitation being practical considerations of probe fabrication and sensor survivability. A probe development program (UTC funded) conducted jointly with DISA, Inc. resulted in the conclusion that the minimum practical wire diameter for these probes was $2.5 \mu\text{m}$ (0.0001 in.) for platinum plated tungsten wires. From consideration (2) the active length of the wires was chosen as .50 mm (0.020 in.) and from (3) the transverse spacing was selected as 0.015 in. These wire arrays were employed

for x-type configurations oriented in both the vertical and horizontal planes. As will be discussed in the results section, cross-checks indicate that the fluctuating data measured with probes of this design are consistent and accurate.

The special 3 wire probes consisted of vertical x-type wire arrays with a third wire mounted equidistant between the wires of the x. This third wire was parallel to one of the wires of the x array. All three wires were constructed from the same material (platinum plated tungsten) and had the same diameter (0.0001 in.) and active length (0.020 in.). The transverse separation between adjacent wires of the 3 wire array was 0.015 in. With this wire arrangement the two parallel wires of the array were exposed to equal effective velocities during any given data sample period. Details of the techniques used to determine instantaneous velocities and temperatures with the 3 wire probes are given in section 4.

2.2 Probe Calibration

Prior to calibration all probe sensors were operated for approximately two hours in the 100 ft/sec mainstream of the wind tunnel. During this "wire curing" step the sensors were set to operate at overheat ratios slightly higher than those used during actual testing. These "curing" steps (1) provided some assurance that the sensors on a given probe would be likely to survive the calibration and testing environments, and (2) improved the stability of the calibration constants of a given sensor. Each probe was calibrated for temperature-resistance characteristics in a low temperature recirculating oven. Typically five temperature vs. resistance points were measured for each sensor. A least-squares data reduction program was used to find a best temperature-resistance coefficient.

$$R_w = R_{32} [1 + \alpha (T_w - 32)] \quad (1)$$

where R_w = resistance of the active sensor
 R_{32} = sensor resistance at 32°F
 T_w = sensor temperature
 α = temperature-resistance coefficient

Following the preliminary "burn-in" and the resistance temperature calibration each sensor was calibrated for velocity and angular sensitivity in a low-turbulence 1½-in. dia. jet flow. The sensors of the 2 wire probes were calibrated to an overheat ($R_{w-hot}/R_{adiabatic}$) of 1.5. For the 3 sensor probes the outside two sensors were calibrated at an overheat of 1.5 while the center sensor was calibrated at an overheat of 1.2. With the main probe support stem oriented perpendicular to the jet axis (wires ± 45° to the jet axis) mean velocity and bridge output voltage were recorded for approximately 20 jet speeds ranging from 7 to 130 ft/sec. The mean response equation of each sensor was assumed to be of the form

$$Nu = A_1 + B_1 R_e^{0.45} \quad (2)$$

which can be algebraically manipulated to

$$E_w^2 = \frac{A_2(R_s + R_w)^2}{R_w} T^{0.76} (T_w - T) + \frac{B_2(R_s + R_w)^2}{R_w} (T_w - T) U_E^{0.45} \quad (3)$$

where E_w = wire voltage
 R_s = probe body, cable and internal anemometer resistance
 R_w = sensor resistance
 T = air temperature
 T_w = sensor temperature
 U_E = effective velocity
 A_2, B_2 = empirical constants

The constants A_2 and B_2 were determined for each sensor from a least-squares fit of the data to Equation (3). Next, using a pitching fixture, pitch angle versus voltage data were obtained with the probes rotated from $+20^\circ$ to -20° in steps of 5° . The center of pitch coincided with the intersection of the wires of the x. Pitch sensitivity data were obtained for three jet velocities, 50, 80 and 100 ft/sec. The angular sensitivity of the wires was assumed to conform to Champagne's k^2 law (Ref. 7),

$$U_E^2(\phi) = U_E^2(\phi=0) (\cos^2 \phi + k^2 \sin^2 \phi) \quad (4)$$

where ϕ = angle between wire and direction normal to the flow ($\pm 45^\circ$
 with wall probe stem normal to the flow)
 U_E = effective velocity

Using a least-squares routine to find a best fit of the pitch-voltage data to Champagne's equation, optimum values of k were determined for each sensor.

In summary, the temperature-resistance, mean velocity and pitch calibrations were used to determine the following calibration constants.

- (1) R_{32} - sensor resistance at 32°F
- (2) α - temperature-resistance coefficient
- (3) A_2 and B_2 - empirical constants (Eq. 3)
- (4) k - empirical constant (Eq. 4).

3. Description of the Data System

For all test cases, both for isothermal flows and for flows with wall heating, the multi-element hot-wires were driven by Thermo Systems, Inc. (TSI) Model 1050 constant temperature anemometers. Signals from the anemometers were first passed through a wide band amplifier (Preston Model 8300 XWB) and then digitized using a TSI Model 1075 Multichannel Digitizer. A feature of this particular analog-to-digital converter which is important to this application is that the various

channels are sampled and held simultaneously. This simultaneous sample-hold feature permits cross-products of the various fluctuating quantities to be computed. Storage restrictions of the main memory of the minicomputer limited the total number of samples taken in a continuous stream to 18,432. The anemometer signals were sampled at 3906 Hz (6144 total samples) per channel or 2604 Hz (9216 total samples) per channel for 2 or 3 wire applications, respectively. The sampling rates resulted in total continuous sample periods of 2.36 sec for both 2 and 3 wire applications. The digitized voltage samples were stored on magnetic disks using a DEC Model RX02 floppy disk recorder.

The RX02 is a "double density" system and can record up to 512 K bytes of information on a single floppy disk. Reduction of the voltage-time records to either velocity-time records (isothermal flow - 2 wires) or velocity-temperature-time records (flows with wall heating - 3 wires) was accomplished off-line using an LSI 11-03 minicomputer. The reduced temperature-velocity-time or velocity-time results were written onto double-density magnetic disks and copied onto magnetic tape for purposes of plotting and tabulation.

4. Data Analysis Techniques

The digitized voltage vs. time records from the multi-wire probes were reduced to turbulence quantities using an LSI 11-03 minicomputer. For this reduction step the digitized data were read into the computer from the RX02 unit while the following constants for each sensor were input through a terminal.

- R_{32} - sensor resistance at 32°F
- Radiabatic - sensor resistance in flow with no overheat
- R_{hot} - sensor resistance at operating temperature
- R_s - probe, cable and anemometer (40 Ω for TSI-1050 sets) series resistance
- α - temperature-resistance coefficient
- A_2, B_2 - calibration constants from Eq. 3
- k - calibration constant from Eq. 4

4.1 Isothermal Flows (2 Wire Probes)

Solution for the velocity components (u and v for the vertical wire arrays, u and w for the horizontal arrays) for each time step proceeded as follows. First, using the adiabatic resistances (no sensor overheat) measured for the sensors in the test flow and Eq. 1, the temperature (T) of the flow was computed. The hot sensor temperatures (T_w) were then computed from R_{hot} and Eq. 1. For each time step the voltages for each of the sensors were input to Eq. 3 to determine the sensor effective velocity (U_E). Next, assuming that the wires of the x array were perpendicular to each other and at $\pm 45^\circ$ to the mainstream flow direction, the simultaneously measured effective sensor velocities were combined using Eq. 4 to find either u and v (vertical array) or u and w (horizontal arrays). As a check on the accuracy of the assumption that the wires were at exactly $\pm 45^\circ$ to the mainstream one of the probes was also calibrated using the "wire effective angle" method of Refs. 14 and 15.

Voltage vs. time records were reduced to fluctuating velocity components using these two different calibration-reduction techniques and the results were in very close agreement. Once the velocity component vs. time record was generated it remained a straightforward matter to compute any desired statistical quantities for the entire time record. The following turbulence quantities were computed for the u-v (vertical array) components. Similar quantities with the transverse velocity component (w) substituted for the vertical component (v) were computed for the horizontal probe arrays.

- $\overline{u}, \overline{u'^2}, \overline{u'^3}, \overline{u'^4}$ - first through the fourth moments of the streamwise fluctuating velocity
- $\overline{v}, \overline{v'^2}, \overline{v'^3}, \overline{v'^4}$ - first through the fourth moments of the normal fluctuating velocity
- $\overline{u'v'}, \overline{u'^2v'}, \overline{u'v'^2}$ - double and triple cross-products (and their correlation coefficients)
- S_u, S_v, F_u, F_v - skewness and flatness of both velocity components

4.2 Flows with Wall Heating (3 Wire Probes)

For the 3 wire probes employed for these measurements the two parallel wires of the array were operated at different overheats ($R_{w-hot}/R_{adiabatic} = 1.5$ and 1.2). The data reduction technique used for these measurements was based upon the assumption that during any time step the effective velocities over the two parallel wires were equal (for velocity scales equal to or larger than the separation distance between the wires). The solution technique proceeded by first finding the fluid temperature (T) for a given time step. Using the voltages (E_w) from the two parallel sensors and assuming that U_e was equal for both wires, Eq. 3 was iteratively solved for T. Once T was known the solution for the velocity components (u and v) for each step proceeded as in 4.1. In addition to computing the turbulence quantities listed in section 4.1, the following items were determined for the cases with wall heating.

- $\overline{t}, \overline{t'^2}, \overline{t'^3}, \overline{t'^4}$ - first through the fourth moments of the fluctuating temperature
- $\overline{v't'}, \overline{v't'^2}$ - velocity-temperature cross-products (and their correlation coefficients)
- S_T, F_T - skewness and flatness of temperature

4.3 Reynolds Stress and Turbulent Heat Flux Corrections for Sensor Separation

The accuracy of cross-products of correlated turbulent quantities is directly influenced by the spacing between the sensors used to measure these quantities (Ref. 13). The contributions of the smallest scales of the turbulence (smaller than the transverse sensor spacing) are excluded from the correlated products. As examples of the impact of this effect Refs. 9, 10, 11, 12 and 14 all present Reynolds stress measurements ($-\overline{u'v'}$) which are about 30 percent lower than expected. Unfortunately this effect cannot be eliminated completely because a minimum limit for sensor separation is reached when sensor "cross-talk" errors become significant. As discussed in Section 2.1, the probes used for the present program were specifically designed to minimize these effects.

Correction factors for the cross-product terms measured in this program were determined by the following technique. Using the parallel wires of the 3 wire probes, the transverse spatial correlation coefficient (ψ_{parallel}) was determined as a function of position (y/δ) in the test boundary layers. Wire separation distances (r) for each of the probes were accurately measured using a Nikon Model II toolmaker's microscope. By assuming that the correlation coefficient fell with the square of the separation distance (r^2) (Ref. 16) an appropriate spatial correlation coefficient could then be calculated for any x-type probe/boundary layer location combination. Next, assuming that the contributions to the cross-products were directly proportional to the spatial correlation coefficient, a correction factor for the probe/location combination was determined:

$$\beta = (1 - \psi_{\text{parallel}}) \left[\frac{r(\text{x probe})}{r(\text{parallel})} \right]^2 \quad (5)$$

As an example the correction procedure for a measured Reynolds stress was as follows:

$$(\overline{u'v'})_{\text{corrected}} = \frac{(\overline{u'v'})_{\text{measured}}}{1 - \beta} \quad (6)$$

Typical correction factors (β) for the various probes, quantities and locations ranged from 0.12 to 0.2. A journal article documenting the development of this correction technique is currently in preparation.

EXPERIMENTAL DATA

1. Experimental Test Program

Measurements were obtained for three test flow conditions of incompressible, zero pressure gradient flow along a flat, uniform heat flux, test wall. The three test cases of this program reproduced conditions employed for an earlier AFOSR Contract (Ref. 2). For all test cases the free-stream velocity was 100 ft/sec and the test surface boundary layer passed through natural transition, i.e., no artificial trips were employed to promote boundary layer transition. Data were obtained for three levels of free-stream turbulence, (1) at the tunnel minimum turbulence level and (2) and (3) at higher levels of free-stream turbulence generated with bi-plane grids. Using the nomenclature of Refs. 1 and 2, the free-stream turbulence levels of this program are designated as follows

- (1) No grid-low free-stream turbulence (Grid 0) - $T_e \approx \frac{1}{2}$ percent
- (2) Grid number 2 ($\frac{1}{2}$ in. bars) - $T_{enom} = 2$ percent
- (3) Grid number 4 (2 in. bars) - $T_{enom} = 6$ percent

A complete documentation of the multi-component turbulence decay, integral length scale growth and spectral distributions generated by these particular test grids is available in Refs. 1 and 2.

For each of these flow conditions experimental boundary layer profile data were obtained at three streamwise locations ($x = 52, 68$ and 84 inches) for both an adiabatic test surface (no wall heating) and with a uniform surface heat flux condition. With no wall heating the following data were measured:

Type of Data	Instrumentation	Measurement Stations Per Profile
Profiles of streamwise velocity (mean and fluctuating)	Single, horizontal, linearized hot wire	30
Profiles of streamwise and normal velocities	Vertical x-type wires with analog-digital data system	17
Profiles of streamwise and transverse velocities (mean and fluctuating)	Horizontal x-type wires with analog-digital data system	17

With the uniform wall heat flux conditions the following data were measured:

Type of Data	Instrumentation	Measurement Stations Per Profile
Surface Stanton Number distribution	Thermocouple instrumentation incorporated into uniform heat flux test surface	210 surface locations
Profiles of streamwise mean velocity	Miniature boundary layer pitot probes	90
Profiles of mean temperature	Miniature boundary layer thermocouple probes	90
Profiles of temperatures and streamwise and normal velocities (mean and fluctuating)	3-Wire probes with analog-digital data system	17

In summary, for each of the three flow conditions surface heat transfer distributions and three stations of profile data were measured. In total (3 conditions) x (3 profiles) x (6 types of profile data) = 54 profile surveys were documented.

2. Boundary Layer Profile Data Format

The mean and fluctuating quantities measured for the various flow conditions and profile locations have been assembled in both graphical and tabular form. Comparisons of these results for the various flow conditions and with similar results from other experiments will be presented in the Analysis of Results section below. The compiled data for all the measurements stations are given in Appendix B - Experimental Data. As a guide to the format of the presentation and results, the data for a single sample profile are given in Figs. 4 through 5E and in Tables 1 through 3B. These particular sample profile data were obtained at the "middle" free-stream turbulence level (Grid 2, $T_e = 1.6\%$) at $X = 68$ in. The mean profile (total pressure and thermocouple probe) data for the sample set are presented in graphical form in Fig. 4 and in tabular form in Table 1. Table 2 presents a compilation of the test flow conditions and values computed from the mean profile data. These mean profile data are presented both in the form of velocity and temperature ratios versus y/δ and in the coordinates of the universal velocity and temperature "laws of the wall". As discussed in the Data Analysis Techniques section, the digitized data reduction system made possible the computation of any desired moments and cross-products of the various measured fluctuating quantities. A total of 38 quantities were selected for presentation on the grounds that they met either or both of the following criterion: (1) the quantity is employed in some existing boundary layer turbulence modeling method or (2) the quantity serves as a diagnostic of the characteristics of the turbulence, e.g.,

intermittency. These various quantities were both plotted and tabulated for each profile station (see Appendix B). The results for the sample profile are presented in Figs. 5A through E and in Table 3A and B. The distribution of a series of turbulence quantities computed from the fluctuating velocity data are presented in Fig. 5A. Starting in the upper left-hand corner of the figure, the distributions of the individual components of the turbulence are compared with the results of Klebanoff (obtained for near-zero free-stream turbulence). Moving clockwise, the next figure presents the measured distributions of the Reynolds stress nondimensionalized by the friction velocity (U_τ was determined independently from the mean profile data) and the distribution of the shear stress correlation coefficient. Also included in this plot is the distribution of shear stress computed from the mean profile data using the technique of Ref. 17. The lower right-hand corner plot of Fig. 5A presents the transport velocities of turbulent shear stress and kinetic energy defined as follows

$$V_\tau = \frac{\overline{u'v'^2}}{\overline{u'v'}} \quad (7)$$

$$V_q = \frac{\overline{v'(u'^2 + v'^2)}}{\overline{u'^2 + v'^2}} \quad (8)$$

See Ref. 14, pp. 220-239, and Ref. 18 for the development of these terms. (Due to a software error V_τ was not computed for the data of Grid 2 and does not appear for this sample plot.) The remaining plot of Fig. 5A presents the structural coefficient (as defined in Ref. 19) distributions for this case.

Turbulence quantities computed from the fluctuating velocities and temperatures are presented in Fig. 5B. Distributions of the turbulent heat flux and its correlation coefficient are given for the plot in the upper left-hand corner. The turbulent heat flux distribution is shown nondimensionalized by the independently measured wall heat flux. Also shown in this plot is the distribution of heat flux through the boundary layer as computed from the mean velocity and temperature profile data (see Ref. 17). The upper right-hand corner plot of Fig. 5B presents the fluctuating temperature distributions in two forms: (1) nondimensionalized by the friction temperature and (2) nondimensionalized by the temperature difference between the wall and free-stream. The lower two plots of Fig. 5B give the distributions of the turbulent Prandtl number, Pr_t , and two structural coefficients, $a_{1,\theta}$ and $G_{1,\theta}$ (see Ref. 19).

$$Pr_t = \frac{\overline{-u'v'} \frac{\partial T}{\partial y}}{\overline{v't'} \frac{\partial U}{\partial y}} \quad (9)$$

$$a_{1,\theta} = \frac{\overline{v't'}}{\overline{t' \sqrt{-u'v'}}} \quad (10)$$

$$G_{1,\theta} = \frac{\overline{v'w'^2}}{2\overline{v'^2}U_T} \quad (11)$$

Triple product distributions of the fluctuating velocity components are given in Fig. 5C. Streamwise-transverse ($u'w'$) products are grouped on the left-hand plot while streamwise-normal ($u'v'$) products appear in the right.

For Fig. 5D the left-hand figure presents the skewness factor distributions for the fluctuating temperatures and velocities. Note that skewness factor distributions of the streamwise component (u') were determined both from the data from the vertical x probes (S_{uv}) and the horizontal x probes (S_{uh}). The correlation coefficients for the triple products of Fig. 5C are given in the right-hand plot of Fig. 5D.

Flatness factor distributions for the fluctuating temperatures and velocities are given in Fig. 5E. As with the skewness factors of Fig. 5D flatness factor distributions of the streamwise component are given for both the data for the vertical x (F_{uv}) and horizontal x (F_{uh}) probes. To avoid crowding on the figure the flatness of the temperature fluctuations was plotted after dividing by 2.

Tabulated values of these fluctuating quantities are given in Table 3A and 3B.

ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

The present experimental test program was designed to examine, in detail, the effects of free-stream turbulence on the heat transfer through turbulent boundary layers. The test conditions for the present program were intended to reproduce cases for which other experimental data had been obtained previously under an earlier AFOSR contract (Ref. 2).

1. Comparisons of Present Results with Results of Ref. 2

A number of the measurements reported in Ref. 2 were repeated during the present program providing a measure of consistency for the two sets of data. Note that these various measurements were obtained in the same test facility and on the same test surface but about three years apart.

1.1 Free-Stream Turbulence Data

Measurements of the components of the free-stream turbulence (outside the boundary layer) were generally in excellent agreement (absolute levels of individual components agreed within 0.3 percent) with the measurements of Ref. 2. The exceptions to this rule were the transverse (w') fluctuation levels measured for Grid 4. These data were consistently higher (relatively 15% higher) than those measured for the same flow condition of Ref. 2. This discrepancy will be discussed in more detail in a following section.

1.2 Heat Transfer Distributions

For all three test conditions the agreement between the Stanton numbers measured for the present program and for Ref. 2 was excellent ($\pm 1\%$). The heat transfer distributions for the no grid (Grid 0), Grid 2 and Grid 4 cases were virtually identical with those presented in Ref. 2 in Figs. 41, 49 and 57, respectively and are not repeated here.

1.3 Boundary Layer Transition Location

For the Grid 2 and 4 test cases the agreement between the present transition location data and the similar data of Ref. 2 was within ± 3 percent. For the no-grid case, however, the transition Reynolds number increased from $Re_x = 1.2 \times 10^6$ to $Re_x = 1.35 \times 10^6$. This change in observed transition location was related to the three dimensional character of the transition process for the no-grid case. As discussed in Refs. 1 and 2, test section corner flows contaminate the flat test wall laminar boundary layer for the low free-stream turbulence case and produce premature transition along the tunnel centerline. This sidewall contamination was not important for the higher levels of free-stream turbulence because two-dimensional natural transition resulted well upstream of these effects. For the present no-grid test conditions the leading edge scoop adjustment was improved over the setting of the

tests of Ref. 2 producing reduced secondary corner flows and an increased transition Reynolds number. The transition Reynolds number (Re_{θ}) for the present tests was in excellent agreement with classic two-dimensional transition vs. turbulence correlations. The turbulent boundary layers which developed downstream of transition for both the present test and the test of Ref. 2 both exhibited the classic characteristics for zero-pressure gradient, low free-stream turbulence, two-dimensional flow.

1.4 Mean Profile Data

Integral thicknesses (δ^* and θ) computed from the profile data for the Grid 2 and 4 cases agreed within 2 percent with the results from Ref. 2 at the respective locations. For the no-grid case the integral thicknesses were about 12 percent reduced from those computed for Ref. 2 at similar stations. This reduction in boundary layer thickness resulted from the increased length of laminar flow upstream of transition for the present no-grid data.

If comparisons are made only for profiles with equal Re_{θ} the results for all the grids (0, 2 and 4) are practically identical to the respective cases in Ref. 2. When plotted in U^+ or T^+ vs. Y^+ coordinates the mean velocity and temperature profiles exhibit significant regions ($30 < Y^+ < 300$) of logarithmic behavior. Both the velocity and temperature wakes showed significant reduction with increasing free-stream turbulence as did the similar data of Ref. 2. Skin friction coefficients computed from fits of the mean velocity data to the "law-of-the-wall" were in excellent agreement with the results of Ref. 2.

1.5 Comparison with Earlier Data - Conclusion

The conclusion reached from the free-stream turbulence, heat transfer and mean profile data was that the test conditions of Ref. 2 were closely duplicated for the present series of measurements. In effect these present measurements can be considered as an additional set of data for the same test conditions as Ref. 2.

2. Profile Data with Low Free-Stream Turbulence

A number of comparisons have been made between the data obtained for the present no-grid (low free-stream turbulence) profiles and measurements from other experiments. These comparisons are intended to provide a measure of the accuracy and consistency of the present boundary layer turbulence data.

The distributions of the u' and v' components of the turbulence profiles were in very good agreement with the classic results of Klebanoff (Ref. 20), see for example Appendix B—Fig. B-4A. The transverse component (w') measurements, however, were typically about 15 percent reduced from Klebanoff's results with w' only slightly greater than v' . These present w' distributions are thought to be accurate as they are in close agreement (as were the u' and v' distributions) with the recent results of Ref. 14. The turbulent shear stress distributions measured for these low free-stream turbulence cases were in excellent agreement with the shear stress

distributions computed from the mean profiles, Fig. B-4A. The accuracy of these particular measurements is also supported by the fact that for all cases the $u'v'$ correlation coefficient was near the widely accepted value of 0.44 (Ref. 21) across most of the boundary layer. The measured distributions of the "structural" coefficients were in good agreement with the widely accepted constants, $a_1 = u'v'/q^2 = 0.15$, $a_2 = u'^2/q^2 = 0.5$, $a_3 = v'^2/q^2 = 0.2$.

A number of the turbulence quantities computed from the present data were also determined for a similar zero-pressure gradient, low free-stream turbulence flow in the work of Ref. 14. The present distributions of transport velocity of turbulent shear stress (V_τ), transport velocity of turbulent kinetic energy (V_q) (Fig. B-4A), $u'v'$ and $u'w'$ triple products (Fig. B-4C), skewness factors (Fig. B-4D) and flatness factors (Fig. B-4E) were all in good agreement with the respective data of Ref. 14.

The turbulent heat flux distribution measurements were in reasonably close agreement with the distributions inferred from the mean profiles (Fig. B-4B). The accuracy of these mean profile distributions is unclear because of extreme sensitivity to uncertainties in the mean temperature profiles. The fluctuating temperature distributions agreed very closely with the distributions measured in Ref. 21 (Fig. B-4B). The values of the thermal coefficient a_{Te} were about 30 percent greater than those determined in Ref. 21 with the cause of the difference uncertain. The authors were unaware of any other measurements of G_{Te} to which the present data could be compared. Finally the turbulent Prandtl number distributions measured for the low free-stream turbulence cases were in excellent agreement with the proposed distribution of Rotta (Ref. 22).

There were, then, a large number of experimentally determined turbulence quantities in the present program which agreed very closely with the results of other studies. The conclusions reached from this result are that one can have a high level of confidence in the present data acquisition and reduction technique and that the turbulence quantities reported here can be expected to be both accurate and self-consistent.

3. Effects of High Free-Stream Turbulence on the Fluctuating Velocities

The impact of increased free-stream turbulence on the boundary layer turbulence kinetic energy distribution is shown in Fig. 6. Presented in this figure are experimental data from the present program obtained at stations with nearly equal momentum thickness Reynolds numbers ($Re_\theta \approx 5500 \pm 100$) for Grids 0, 2 and 4. Also given in Fig. 6 are turbulence kinetic energy distributions measured for similar zero pressure gradient, low speed flows by other investigators (Refs. 12 and 21). Integral thicknesses were not computed for these other data but based upon the stated values of δ it is estimated that for Ref. 12 Re_θ was about 3500 while for Ref. 21 $Re_\theta \approx 700$. Agreement between the present low free-stream turbulence profile case (Grid 0) and the similar data of Ref. 21 is reasonably good except very close to the wall. As discussed earlier this near-wall discrepancy resulted from the

relatively higher values of w' determined in the study of Ref. 21. For the profiles with higher free-stream turbulence there were no cases where the present flow conditions (Re_δ and Te) were identical with those of Ref. 12. Despite this a comparison of these results shows reasonably good agreement for both the trends and absolute magnitudes of the kinetic energy distributions. Both the present data and the independent results from Refs. 12 and 21 indicate a progressive increase in boundary layer turbulence kinetic energy with increasing free-stream turbulence. Increased levels of turbulence kinetic energy were measured across the entire thickness of the boundary layer.

The effects of the free-stream turbulence level on the individual components of the boundary layer turbulence for these same three profiles are shown in Fig. 7. The streamwise (u') component followed the same trends as the turbulence kinetic energy, increasing with free-stream turbulence level over the entire thickness of the boundary layer. The normal component (v'), however, was damped by the presence of the solid wall and showed virtually no change over the lower half of the boundary layer. See Ref. 23 for an in-depth study of the interaction of solid surfaces with turbulent fluctuations. The distribution of w' for $Te = 4.2$ percent showed a large increase over the distributions for the lower turbulence levels. Outside the boundary layer w' was also measured to be about 20 percent higher than u' or v' . On the grounds that earlier independent measurements of the free-stream turbulence for this grid showed the turbulence to be isotropic at this station (Ref. 1) and the unreasonably large "jump" in the w' distribution across the entire boundary layer it has been concluded that these w' measurements are in error. It is thought that there was an error in the calibration for the horizontal x wire probe used for the Grid 4 test cases. The Grid 4 w' data are reported here as measured, that is uncorrected for this probable error. It is estimated that by reducing the measured w' data by 20 percent a reasonably accurate set of distributions of the transverse component for this Grid 4 case would result.

With the Grid 4 w' data reduced by 20 percent the conclusion that can be reached from Fig. 7 is that the u' and w' component of turbulence increased progressively with increasing free-stream turbulence level. Both components increased at all locations in the boundary layer. The vertical component v' , however, was essentially constant and independent of free-stream turbulence level for the lower half of the boundary layer.

Distributions of the boundary layer turbulence structural coefficients (Bradshaw, et al., Ref. 19) are given in Figs. 8A and 8B. As can be seen from an inspection of Fig. 8A the ratio of shear stress to turbulence kinetic energy (a_1) decreased across the entire boundary layer with increasing free-stream turbulence. The observed decrease was most extreme over the outer 60 percent of the boundary layer. Also shown with the present a_1 distribution data are similar results from Refs. 14 and 21. Agreement between these similar (not identical, Re_δ and Te were slightly different) sets of data was very good.

The ratios of the direct stress components to the turbulent kinetic energy (a_2 , a_3 and a_4) are given in the remaining plots of Figs. 8A and 8B. Employing the

previously described 20 percent reduction to the w' component for $T_e = 4.2$ percent (this also reduces q^2 for $T_e = 4.2$ percent), fairings of the corrected structural coefficient distributions for the highest turbulence level are given in the figures. Using the measured results for $T_e = 0.2$ percent and 1.5 percent and the corrected fairings for $T_e = 4.2$ percent the following conclusions were reached. As the free-stream turbulence stress level was increased a_2 (u'^2/q^2) increased slightly above 0.5, the value widely used for low free-stream turbulence boundary layers. The greatest percentage change was observed for the lower half of the boundary layer for a_3 ($a_3 = v'^2/q^2$). This ratio decreased progressively with increasing T_e dropping to about 0.12 (40% reduction from classic value of 0.2) for $T_e = 4.2$ percent. Only very small changes were observed for a_4 ($a_4 = w'^2/q^2$) with the measured values grouping around 0.3 for the lower half of the boundary layer.

A number of previous studies of free-stream turbulence effects on turbulent boundary layers (Refs. 8, 10, 11, 14 and 234) have reported finite turbulent shear stress levels beyond the edge of the velocity boundary layer. This effect was also observed for the present program. A comparison between the present results and those of the previous investigations is given in Fig. 9 where the turbulent shear level at the edge of the boundary layer ($\delta 0.995$) is given as a function of T_e . The data from the present study and the results reported for most of the other experiments are tightly grouped. Taken together, these data indicate an increase of turbulent shear at the boundary edge directly proportional to the free-stream turbulence level. Huffman's results, which are believed (Ref. 2) to contain significant errors due to anisotropy, show much larger levels of turbulent shear than the other studies.

Additional evidence of the impact of free-stream turbulence on the characteristics of the turbulence near the boundary layer edge is provided by the measurements of flatness factor. The flatness factor ($u'^4/(u'^2)^2$) is an indication of the distribution of velocity fluctuations in a set of samples. For a normal Gaussian distribution the flatness factor is equal to 3 with larger values indicating contributions from intermittent turbulent fluctuations. Flatness factor distributions of the streamwise fluctuating velocity component are given in Fig. 10 as a function of position in the boundary layer. An examination of Fig. 10 shows that the intermittent character of the turbulence near the edge of the boundary layer was greatly reduced by increased free-stream turbulence. For a boundary layer beneath a low turbulence mainstream a relatively sharp irregular "edge" of turbulent boundary layer flow results adjacent to the non-turbulent freestream. With higher levels of free-stream turbulence this distinct border appears to have disappeared.

4. Effects of High Free-Stream Turbulence on the Turbulent Prandtl Number

The measured distributions of turbulent shear stress ($\overline{u'v'}$), the turbulent heat flux ($\overline{v't'}$) and the normal derivatives of the mean velocity and temperature were combined to form local turbulent Prandtl numbers.

$$Pr_t = \frac{\epsilon_m}{\epsilon_h} \quad (12)$$

where ϵ_m = eddy diffusivity of mass
 ϵ_h = eddy diffusivity of heat

$$Pr_t = \frac{\overline{-u'v'}}{\overline{v't'}} \frac{\partial T}{\partial y} \quad (9)$$

The distributions of turbulent Prandtl number measured for the various test cases are presented in Fig. 11. The results from all three profile locations ($x = 52, 68$ and 84 inches) for all three free-stream turbulence levels are included in Fig. 11 with an average free-stream turbulence level assigned to each set. For all points above the wall the turbulent Prandtl numbers were determined from the turbulent heat flux and shear stresses measured with the hot wire probes and from the derivatives of the mean profiles measured with the total pressure and thermocouple probes. At the wall the turbulent Prandtl numbers were determined from the mean temperature and velocity profile data by assuming that for at least some small distance the ratio of shear stress to heat flux remains at the wall value.

$$\frac{\tau}{\dot{q}} \approx \frac{\tau_{wall}}{\dot{q}_{wall}} = \frac{\rho_w \overline{u'v'}}{\rho_w c_p \overline{v't'}} \quad (13)$$

$$\frac{\overline{u'v'}}{\overline{v't'}} = \frac{\rho_w c_p U_\tau^2}{\dot{q}_{wall}} \quad (14)$$

$$Pr_t (wall) = \frac{\rho_w c_p U_\tau^2}{\dot{q}_{wall}} \frac{\partial T}{\partial U} \quad (15)$$

Near-wall values of the turbulent Prandtl number were evaluated from Eq. 15 using friction velocities (U_τ) determined from the mean velocity profile fits to the "law-of-the-wall". Values of $\partial T / \partial U$ were determined graphically from the near-wall velocity and temperature profile data.

Errors in the four measured terms of Eq. 9 combined to produce considerable scatter in the data of Fig. 11. This scatter, however, is much less than reported for the similar measurements of Refs. 21 and 25. It is expected that the consistency and absolute accuracy of such local turbulent Prandtl number measurements could be further improved by employing larger samples of the turbulent data.

The turbulent Prandtl number distributions measured for the low free-stream turbulence profiles were in good agreement with the similar data of Ref. 17. (Ref. 17 employed mean profile data only.) In addition, Rotta's (Ref. 22) suggested Pr_t distribution for low free-stream turbulence boundary layers appears to represent the present low turbulence data well.

$$Pr_t = 0.95 - 0.45 (y/\delta)^2 \quad (16)$$

An examination of Fig. 11 indicates that as the free-stream turbulence level was raised the turbulent Prandtl number increased over nearly the entire boundary layer. Values of Pr_t over unity were recorded at $y/\delta \approx 0.3$ for the highest free-stream turbulence level. These increased outer region turbulent Prandtl numbers for high free-stream turbulence levels had not been expected. At the outset of the program the turbulence characteristics of the outer portion of the boundary layer were known to be altered considerably by increased levels of free-stream turbulence. It was also known from the measurements of Ref. 1 that the free-stream turbulence had a large impact on the turbulent heat transfer with the Reynolds analogy factor increasing with increasing turbulence level. It was speculated that the increased Reynolds analogy factor might result from lowered Pr_t levels (relatively greater increase in $v't'$ as compared to $u'v'$) in the outer portions of the boundary layer. The experimental results of Fig. 11 indicate just the opposite effect. As the free-stream turbulence level was increased the outer region Pr_t levels increased while the near-wall values (determined from the mean profile data) indicate a small but progressive decrease. The following expression, a modification of Rotta's (Eq. 16) low free-stream turbulence equation, represents the measured results reasonably well.

$$Pr_t = \left[0.95 - 0.45 (y/\delta)^2 \right] (1 + 2T)^2 - \frac{5T}{\cosh^{10} y/\delta} \quad (17)$$

Equation 17 is shown in Fig. 11 for the three turbulence levels for which the experimental data were obtained. At $T_e = 0.2$ percent, Eq. 17 is practically identical to Rotta's (Eq. 16) expression.

The mean velocity and temperature profile data from both the present program and from Ref. 1 provide additional evidence that the near-wall turbulent Prandtl number decreased with increased free-stream turbulence level. (The arguments for this conclusion will be presented here in a highly abbreviated form. A more in-depth examination of these effects will be conducted during the preparation of a technical journal article on this contract work.) The effects of the free-stream turbulence on the similarity between the mean velocity and temperature profiles was examined by plotting the velocity ratio (U/U_e) versus the temperature ratio ($(T_w - T)/(T_w - T_e)$) across the boundary layers. Plots of these ratios for all profile locations and free-stream turbulence levels are given in Fig. 12. Also given in Fig. 12 are the similar data from the same stations and turbulence levels obtained in Ref. 1. An examination of Fig. 12 indicates that for all cases, independent of the free-stream turbulence level, the mean velocity and temperature profiles remained highly similar. This similarity between the velocity and temperature profiles extends across at least the outer 90 percent of the boundary layer thickness including all the wake and at least some of the logarithmic zone. It follows that the shapes of the velocity and temperature profiles should also be similar when plotted in universal (U^+ or T^+ vs. Y^+) coordinates. It has been observed in virtually every study of free-stream turbulence effects on turbulent boundary layers that the wake strength of the velocity boundary layer was progressively reduced with increasing free-stream turbulence. It was also

observed in Refs. 2 and 26 that for a given turbulence level the temperature wake was reduced by a larger amount than was the velocity wake. Implicit in the formulation of the temperature law-of-the-wall is the assumption that the turbulent Prandtl number is constant across the entire boundary layer. The large thermal wake depressions reported in Refs. 2 and 26 followed from the use of an average boundary layer turbulent Prandtl number for all the profiles. The following interpretation, however, is more consistent with the conclusion from Fig. 12, that the shapes of the outer region velocity and temperature profiles remained similar for all turbulence levels and streamwise locations. If the near-wall turbulent Prandtl numbers were assumed to be reduced with increased T_e (as Fig. 11 indicates) the slope of the temperature law-of-the-wall ($1/\kappa_\theta = Pr_t/\kappa$) would be reduced. With a reduced logarithmic region slope the apparent temperature wake strength, which is the maximum deviation from the log-law, would increase. An examination of the temperature profiles of Ref. 2 (in T^+ vs. Y^+ coordinates) indicated that good fits to the temperature law-of-the-wall could be achieved from $Y^+ \approx 30$ to $Y/\delta = 0.1$ if Π_θ was set equal to Π . For the present data, very good agreement between the thermal and velocity wake strengths resulted from the use of the near-wall turbulent Prandtl numbers of Fig. 11 for the respective profiles.

Finally, with regard to a potential physical mechanism producing the reduced near-wall Pr_t , the diffusion terms of the turbulence kinetic energy transport equation for velocity and temperature (Ref. 19) differ by the contribution of the pressure-velocity fluctuation product. Blom (Ref. 27) has pointed out that the pressure fluctuations serve to transfer energy from the relatively higher u' component of turbulence to the relatively smaller v' and w' components. Blom also argued that the absence of the $p'v'$ term in the temperature diffusion term could explain the reduction of Pr_t below unity. Since the effect of increased T_e was to increase the difference between the u' and v' components of turbulence near the wall the importance of the $p'v'$ term may grow with T_e . In other words, with increasing difference between u' and v' the effect of the $p'v'$ term may be to progressively decrease Pr_t .

The overall impact of free-stream turbulence on boundary layer heat transfer rates is, then, to depress the near-wall turbulent Prandtl number. Since the heat and momentum transport in turbulent boundary layers are dominated by the turbulent eddy contributions the result is that the Reynolds analogy factor rises with increasing free-stream turbulence level. It should be pointed out, however, that the results of Refs. 2 and 14 clearly show that the effects of free-stream turbulence on turbulent boundary layers are not dependent on turbulence intensity alone. For a fixed free-stream intensity the largest impact on a turbulent boundary layer results if the integral scale of the turbulence is about equal to the boundary layer thickness. Turbulence with integral scales significantly smaller or larger than the boundary layer thickness will produce reduced effects.

THEORETICAL ANALYSIS

The experimental data discussed previously in this report was used to assess the capability of a boundary layer analysis for predicting the effect of free-stream turbulence on momentum and thermal boundary layers. Previously, Blair and Werle (Ref. 2) examined the effects of free-stream turbulence on zero pressure gradient flows. They also evaluated the ability of a finite difference code (Ref. 28), which used a turbulence model of McDonald et al. (Refs. 29 and 30), to predict surface heating and skin friction. The present analytical investigation, which is a continuation of the work initiated by Blair and Werle, makes use of a boundary layer analysis (ABLE - Analysis of the Boundary Layer Equations) recently developed by Edwards, Carter and Werle (Ref. 31). This new boundary layer analysis contains the McDonald et al. turbulence model (Refs. 29 and 30) utilized by Blair and Werle's (Ref. 2) previous work. In addition, it was demonstrated in Ref. 31 that results obtained from the ABLE analysis and the boundary layer procedure employed by Blair and Werle were in excellent agreement for zero pressure gradient flows. In the present study, the capability of the ABLE code to accurately predict mean flow velocity, mean flow temperature, Reynolds shear stress and turbulent heat transport profiles is determined. In addition, the turbulent Prandtl number distribution deduced from the experimental measurements discussed earlier in this report is used in the boundary layer analysis and its effect on surface heating is evaluated.

1. Prediction Method

The ABLE boundary-layer code provides a rapid computation of two dimensional or axisymmetric boundary-layer flows subject to a prescribed distribution of edge Mach number, streamwise velocity, or static pressure. At the surface a distribution of either wall temperature or heat flux may be imposed. This analysis is applicable to attached flows which are laminar, transitional, or turbulent. A detailed description of the theory used in the ABLE code is given in Ref. 31 and a flow chart of the code is shown in Fig. 13. An implicit finite-difference technique is used in the ABLE code to solve the boundary-layer equations which are written in nondimensional form for two dimensional flow as follows.

continuity

$$\frac{\partial \rho u}{\partial s} + \frac{\partial \rho v}{\partial n} = 0 \quad (18)$$

momentum

$$\rho u \frac{\partial u}{\partial s} + \rho v \frac{\partial u}{\partial n} = -\frac{\partial p}{\partial s} + \frac{\partial}{\partial n} \left(\mu \frac{\partial u}{\partial n} - \rho \overline{u'v'} \right) \quad (19)$$

energy

$$\rho u \frac{\partial H}{\partial s} + \rho v \frac{\partial H}{\partial n} = \frac{\partial}{\partial n} \left[\mu \left(1 - \frac{1}{Pr} \right) u \frac{\partial u}{\partial n} + \frac{\mu}{Pr} \frac{\partial H}{\partial n} - \overline{\rho h'v'} - \overline{\rho u'v'} \right] \quad (20)$$

In the above equations, s is the coordinate along the surface, n is the coordinate normal to the surface, u is the streamwise velocity, v is the normal velocity, ρ is the static density, P is the static pressure, h is the static enthalpy and H is the total enthalpy where (in non-dimensional form)

$$H = T + \frac{1}{2} u^2 = h + \frac{1}{2} u^2$$

The placement of a bar over several terms is used to denote the time average of various turbulent fluctuating quantities which are generally considered to represent the dominant Reynolds stress terms in the turbulent boundary layer equations.

The ABLE code currently contains two turbulence models, the Cebeci-Smith algebraic model (Ref. 32) and the McDonald et al., one equation turbulence model (Refs. 29 and 30). Both models are based on an eddy viscosity concept in which the Reynolds shear stress is related to the mean flow velocity gradient by

$$-\overline{\rho u'v'} = \mu_T \frac{\partial u}{\partial n} \quad (21)$$

In addition, the turbulent heat transport is related to the Reynolds shear stress and mean flow quantities through a Reynolds analogy type of argument

$$-\overline{\rho h'v'} = \frac{-\overline{\rho u'v'}}{Pr_t} \frac{\frac{\partial h}{\partial n}}{\frac{\partial u}{\partial n}} = \frac{\mu_T}{Pr_t} \frac{\partial h}{\partial n} \quad (22)$$

where Pr_t is the turbulent Prandtl number. This code presently contains two transition models, the first of which is the Dhawan and Narasimha (Ref. 33) forced transition model which requires the specification of the start and length of transition. The second model is a natural transition model developed by McDonald and Fish (Ref. 29) where the prediction of transition is controlled by the integrated form of the turbulence kinetic energy equation. In the present investigation the ABLE code is applied to the experimental flows discussed previously using the one equation turbulence model of McDonald and Kreskovsky (Ref. 30), the details of which are given in the next section.

2. Turbulence Model

The one equation turbulence model of McDonald and Kreskovsky (Ref. 30) permits the effect of free-stream turbulence to be included in the computed boundary layer

analysis. This turbulence model, which accounts for the proper approach of the turbulence level in the outer region of the boundary layer to the local edge value, is based on the integral form of the turbulence kinetic energy equation. This model is an extension of a turbulence model developed earlier by McDonald and Fish (Ref. 29). The eddy viscosity coefficient is expressed in nondimensional form as

$$\left(\frac{\mu_T}{\mu}\right) = \frac{\rho}{\mu} l^2 \frac{\partial u}{\partial n} Re^{1/2} \quad (23)$$

where Re is a reference Reynolds number, and l , the local mixing length, is expressed as a function of the mixing length l_e at the boundary layer edge through the relation

$$l = D l_e \left\{ \tanh\left(\frac{\kappa n}{l_e}\right) + \frac{1}{2} \left(1 - \tanh\left(\frac{\kappa \delta}{l_e}\right)\right) \left[1 - \cos\left(\frac{n\pi}{\delta_r}\right)\right] \right\} \quad (24)$$

and

$$D = \sqrt{\frac{1}{2} \left[1 + \operatorname{erf}\left(\frac{n^+ - 23}{8}\right)\right]} \quad (25)$$

where κ is the von Karman constant, δ is the boundary-layer thickness, and δ_r is the "shear stress" thickness which is defined as the first location from the outer edge of the boundary layer where

$$\frac{\tau}{\tau_{\max}} \geq 0.02 \quad (26)$$

and $\tau_{\max}$ is the maximum shear stress at each streamwise location.

The local value of l_e is obtained through the solution of the integral form of the turbulence kinetic energy equation which is expressed in nondimensional form as

$$\frac{d}{ds} \left[\frac{\rho_e u_e^3}{2 \sigma_1} \phi_1 \right] = \rho_e u_e^3 (\phi_2 - \phi_3) + E \quad (27)$$

where

$$E = \frac{q_e^2}{2} \left[\rho_e u_e \frac{d\delta_r}{ds} - (\rho v)_e \sqrt{Re} \right] \quad (28)$$

$$\phi_1 = \int_0^{\delta_r} \frac{\rho u}{\rho_e u_e} \left[l \frac{\partial}{\partial n} \left(\frac{u}{u_e} \right) + \sigma_1 f(n/\delta_r) \frac{q_e^2}{u_e^2} \right]^2 dn \quad (29)$$

$$\phi_2 = \sqrt{\text{Re}} \int_0^{\delta_\tau} \frac{\rho}{\rho_e} \ell^2 \left[\frac{\partial}{\partial n} \left(\frac{u}{u_e} \right) \right]^3 (1 - \ell/L) \, dn \quad (30)$$

$$\phi_3 = \int_0^{\delta_\tau} \frac{\rho}{\rho_e} \left(\frac{a_2 - a_3}{a_1} \right) \left\{ \left[\ell \frac{\partial}{\partial n} \left(\frac{u}{u_e} \right) \right]^2 + a_1 f \left(\frac{n}{\delta_\tau} \right) \frac{q_e^2}{u_e^2} \right\} \frac{1}{u_e} \frac{du}{ds} \, dn \quad (31)$$

and

$$L = .118 \, \delta \tanh \left[\frac{\kappa n}{.118 \, \delta} \right] \quad (32)$$

$$q_e = \sqrt{(\overline{u'u'} + \overline{v'v'} + \overline{w'w'})}_e \quad (33)$$

$$f \left(\frac{n}{\delta_\tau} \right) = \frac{1}{2} \left[1 - \cos \left(\frac{n\pi}{\delta_\tau} \right) \right] \quad (34)$$

where the subscript e denotes the flow quantities at the boundary-layer edge. The influence of the free-stream turbulence in the one equation model comes through the term, q_e^2 , which acts as a source term in Eq. 27. In the above relation, L is a dissipation length and a_1 , a_2 , and a_3 are structural coefficients that relate the Reynolds shear stress and turbulence intensity components to the turbulent kinetic energy as suggested by Townsend (Ref. 34) and Bradshaw and Ferris (Ref. 19). These coefficients are given by

$$-\overline{u'v'} = a_1 \left\{ \overline{q^2} - f \left(\frac{y}{\delta_\tau} \right) \overline{q_e^2} \right\} \quad (35)$$

$$\overline{u'u'} = a_2 \overline{q^2} \quad (36)$$

$$\overline{v'v'} = a_3 \overline{q^2} \quad (37)$$

$$\overline{w'w'} = (1 - a_2 - a_3) \overline{q^2} \quad (38)$$

where McDonald and Fish (Ref. 29) suggest the values $a_2 = .5$ and $a_3 = .2$ and that a_1 be expressed as follows

$$a_1 = \frac{a_0 \left(\frac{\bar{R}_\theta}{100} \right)}{1 + 6.666 a_0 \left(\frac{\bar{R}_\theta}{100} - 1 \right)} \quad (39)$$

where

$$a_0 = 0.0115$$

and $\bar{R}_\theta$, which is referred to as the Reynolds number based on momentum thickness by Shamroth and McDonald (Ref. 35) but is in fact a correlation given in terms of an integrated turbulent Reynolds number R_T .

$$\bar{R}_\theta = \begin{cases} 100 R_T^{0.22} & R_T \leq 1 \\ 0.0098215 (R_T - 1)^3 + 1.165 (R_T - 1)^2 + 22 (R_T - 1) + 100 & 1 < R_T < 40 \\ 68.26 R_T - 614.33 & R_T \geq 40 \end{cases} \quad (40)$$

and

$$R_T = \frac{\frac{1}{\delta} \int_0^{\delta_T} v_T \, dn}{\frac{1}{\delta_s} \int_0^{\delta_s} v \, dn} \quad (41)$$

where δ_s is an estimate of the inner wall layer. The computational transition process is controlled by the structural coefficient a_1 as it varies from zero in laminar flow to .15 in in fully turbulent flow. For the present analysis, the structural coefficients a_1 , a_2 and a_3 are constant over the boundary layer using the values suggested by McDonald and Fish (Ref. 29). However the experimental structural coefficients were observed to vary across the boundary layer (Figs. 8(a) and 8(b) and the effect of varying the structural coefficients in the analysis should be assessed in the future. A detailed description of the one equation turbulence model is given in Ref. 36.

3. Turbulent Prandtl Number Model

In the present investigation an evaluation is made of the effect of a variable turbulent Prandtl number, Pr_t , across the boundary layer on the ABLE code prediction of the turbulent heat transport and surface heating. Three different functional forms of Pr_t have been applied in this investigation. They are given by

1) McDonald (Ref. 28)

$$Pr_t = .9P \left(\frac{n^+ - 23}{8} \right) / P \left(\frac{n^+ - 23.6}{10} \right) \quad (42)$$

where

$$P(x) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{x}{\sqrt{2}} \right) \right]$$

2) Rotta (Ref. 22)

$$Pr_t = .95 - .45(n/\delta)^2 \quad (43)$$

3) Present experimental investigation

$$Pr_t = \left[.95 - .45(n/\delta)^2 \right] \left[1 + 2 Tu \right]^2 - 5 Tu / \cosh[10n/\delta] \quad (44)$$

where

$$Tu = 1/3 \overline{q} e^2$$

A comparison of these three turbulent Prandtl number distributions are shown in Fig. 14. McDonald's function (Eq. 42) has a maximum value of 1.7 at the wall and decreases rapidly in the laminar sublayer of the turbulent boundary layer but is nearly constant and equal to .9 for $n^+ > 50$. Rotta's function (Eq. 43) has a maximum value of Pr_t of .95 at the wall and decreases linearly with respect of $(n/\delta)^2$ to the edge of the boundary layer to a value of .5. The Pr_t distribution obtained in the experimental portion of the present investigation (Eq. 44) is essentially a modification of Rotta's distribution to account for the effects of free-stream turbulence. An assessment of the accuracy of each of these turbulent Prandtl number formulations is made in the next section using the ABLE code and the experimental results presented above. However, since the turbulent heat transport $\overline{h'v'}$ is modeled in terms of $u'v'$, the turbulent Prandtl number and the normal derivatives of u and h as given in Eq. 22, then all of these quantities are compared with the experimental data before an assessment is made of the effect of Pr_t on the calculation of the turbulent heat transport.

DISCUSSION OF ANALYTICAL RESULTS

A series of calculations have been made with the ABLE code for the flow over a heated flat plate for each of the nominal inlet free-stream turbulence levels of 1%, 2%, 4% and 6% generated by the use of inlet turbulence Grids 1, 2, 3 and 4, respectively. A calculation was not performed for the case of the flow with .25 percent inlet turbulence since it was concluded by Blair and Werle (Ref. 2) that the transition process of this flow is three dimensional and thus the turbulence model of McDonald et al. (Refs. 29 and 30) cannot accurately predict the location and length of the transition region. For each case, a calculation is made with the ABLE code for each of the turbulent Prandtl number formulations discussed in the previous section. The mean flow quantities, Reynolds shear stress and turbulence kinetic energy predicted from the ABLE code were found to be insensitive to the different turbulent Prandtl number formulations; hence, these quantities are presently for only the present Pr_t formulation given in Eq. 44. This result was expected since the experimental flows are low speed and thus the momentum equation (Eq. 19) is essentially uncoupled from the energy equation (Eq. 20).

For all of the test cases analyzed in this investigation with the ABLE code, the gas is assumed to be air with a constant ratio of specific heats, γ , equal to 1.4 and a constant Prandtl number equal to .72. The von Karman constant for turbulent flow is set to .43 as suggested by McDonald and Kreskovsky (Ref. 30). The following flow conditions were used in all test cases

$$\begin{aligned}U_e &= 100 \text{ ft/sec} \\P_{T_e} &= 14.78 \text{ lb/in}^2\end{aligned}$$

and the streamwise variation of the free-stream turbulence for each flow with a specified inlet grid is obtained from the following expression

$$Tu = .78 \left(\frac{2.54x + 132}{b} \right)^{-5/7} \quad (45)$$

where b (grid bar width) = .48, 1.27, 3.81, and 5.08 for Grids 1, 2, 3, and 4, respectively. This relation was shown to be accurate in earlier testing reported in Ref. 2. The measured wall temperature levels are tabulated in Table I of Ref. 2, with the free-stream static temperature set to 530°R ($T_{T_e} = 530.83^\circ\text{R}$) for all calculations. The temperature distributions were numerically smoothed to eliminate spurious variations in the computed wall results due to minor experimental error. The smoothed temperature distributions were used as input to the ABLE code. Comparison of the measured and smoothed temperature distributions for each of the flow cases are shown in Fig. 15. The smoothing procedure is a least squares polynomial curve fit described in Ref. 37.

A computational mesh consisting of 101 grid points in the normal direction and 100 points in the streamwise direction was used in each of the calculations. A grid stretching based on a geometric progression was applied in each direction to insure

that a fine grid distribution was placed in the high gradient regions. The initial profile for the boundary layer calculation is the Blasius profile (Ref. 38) which was imposed at the flat plate leading edge. In addition, two iterations per streamwise station are applied in the computational procedure due to large streamwise temperature gradients which are encountered in the transition region of the flow. The current calculations required approximately 1 minute of CPU time on a UNIVAC 1180 operating system to compute the flow over the 8 foot length of the test section.

In this section comparisons are presented in Figs. 16-27 between the results obtained from the ABLE code with those measured experimentally both in the present investigation and in the previous investigation by Blair and Werle (Ref. 2). These comparisons are made for zero pressure gradient flows for the two cases with inlet turbulence levels of 2 percent and 6 percent. The following quantities are compared:

1. skin friction
2. displacement thickness
3. momentum thickness
4. mean velocity profile
5. mean temperature profile
6. Reynolds shear stress profile
7. turbulent kinetic energy profile
8. profiles of the components of turbulence intensity
9. turbulent Prandtl number profile
10. turbulent heat transport profile

The profile comparisons are shown only at $X = 68$ inches from the leading edge of the test section; similar comparisons were obtained at the other measuring stations.

Figure 16 is a comparison of the computed skin friction coefficient distribution with that obtained experimentally along the flat plate surface for inlet turbulence levels of 2 percent and 6 percent. The theoretical distribution is slightly higher (approximately 5%) than the experimental distribution for the flow with an inlet turbulence of 2 percent while the result obtained for the flow with an inlet turbulence of 6 percent is in excellent agreement with the experimental result. A comparison of the theoretical and experimental displacement and momentum thickness distributions are shown in Figs. 17 and 18, respectively. It is apparent from these figures that the computed integral quantities are in good agreement with the experiment over most of the test section. Figures 19 and 20 are comparisons of the computed mean velocity and temperature profiles with the experimental measurements for inlet turbulence levels of 2 percent and 6 percent. In all profile comparisons, the theoretical boundary layer thickness, δ , was used to nondimensionalize the normal coordinate. It is observed from Figs. 19 and 20 that the computed results are in excellent agreement with the experimental results for both flows. From Figs. 16-20 it is concluded that the ABLE boundary layer analysis with the McDonald and Kreskovsky turbulence model (Ref. 30) produces good agreement with the mean flow quantities of zero pressure gradient flows with various levels of inlet turbulence.

In order to determine how well the boundary layer analysis will predict turbulent fluctuating quantities, comparisons of computed profiles with experimental data

were made of the flows with inlet turbulence levels of 2 percent and 6 percent. Figure 21 is a comparison of the computed Reynolds shear stress profile with that obtained experimentally. Several interesting features are noted in this figure. By using the turbulence modeling (Eqs. 28-32) developed by McDonald and Kreskovsky in the computational procedure, the predicted Reynolds shear stress in the inner layer of the turbulent boundary layer is in excellent agreement with the experimental measurements. The theoretical results exhibit the same shape and level as the experimental results. However, in the outer layer, as the free-stream turbulence increases, the deviation between the computed and experimental results grows significantly as it is observed that the computed $u'v' \rightarrow 0$ whereas the experimental $u'v'$ approaches a finite value. Figure 22 is a comparison of the measured and computed turbulence kinetic energy distributions. It is observed that the computed results are in good agreement with the experimental data for both levels of free-stream turbulence. This result indicates that McDonald and Kreskovsky's modeling of free-stream turbulence in the turbulence kinetic energy equation (Eq. 27) captures the correct shape of the turbulence kinetic energy across the boundary layer for zero pressure gradient flows with different levels of free-stream turbulence. Figures 23-25 are comparisons of the measured and computed components of turbulence intensity, $u'u'$, $v'v'$, $w'w'$. From these figures it is observed that the predicted results are in fair agreement with the experimental data across the boundary layer.

An anomaly appears in the results shown in Figs. 19-25. First, from Figs. 22-25, the computed turbulence kinetic energy and its various components are in relatively good agreement with the experimental results. Secondly, the computed mean velocity (Fig. 19) is in excellent agreement with the experiment. However, the computed Reynolds shear stress (Figs. 21) has a significant deviation from the experimental results in the outer region of the boundary layer as the inlet turbulence level increases. This difference tends to suggest that the eddy viscosity modeling of turbulence (Eq. 21) does not properly model flows with significant levels of free-stream turbulence since by applying this model, the computed Reynolds shear stress is forced to zero at the edge of the boundary layer. The inability of the turbulence model to predict accurate Reynolds shear stress distributions over the entire boundary layer will affect the transition model (Eq. 39) since the transition process is controlled by an integrated form of the turbulent Reynolds number R_T (Eq. 41). An investigation is needed to determine an analytical turbulence model that will properly represent the Reynolds shear stress in the outer region of the turbulent boundary layer for flows with significant levels of free-stream turbulence.

A comparison of McDonald's, Rotta's, and the present turbulent Prandtl number formulation with the experimentally determined distribution is shown in Fig. 26(a) and Fig. 26(b) for flows with 2 percent and 6 percent turbulence levels, respectively. In Fig. 26(a) it is observed that McDonald's distribution, which is essentially constant over the boundary-layer overpredicts the experimental results over most of the boundary layer while Rotta's and the present distribution exhibit the same general shape and level as the experiment distributions. For the high inlet turbulent flow (Fig. 26(b)), the present Pr_t distribution exhibits the same shape and level as the experimental distribution while the relatively constant McDonald distribution does not have the same shape or level as the experimental results.

Also, Rotta's distribution exhibits the best shape of the experimental data but is not at the same level. Figures 27(a) and 26(b) are comparisons of the measured and computed turbulent heat flux distributions for the flows with turbulence levels of 2 percent and 6 percent, respectively. From these figures, it is noted that except near the wall, the computed turbulent heat flux distribution across the boundary layer is essentially the same for each of the three different Pr_t formulations which are used. Figures 27(a) and 27(b) show that the computed results are in reasonable agreement with the experimental results except at the edge of the boundary layer where the theoretical results go to zero and the experimental data does not. Since the turbulent heat flux is determined from Eq. (22) and all the computed quantities in that equation are in reasonable agreement with experimental data except the Reynolds shear stress, this suggests that the inaccuracy of predicting the turbulent heat flux in the outer portion of the boundary layer is due to the modeling of the Reynolds shear stress in the outer region of a turbulent boundary layer with significant levels of free-stream turbulence. Further investigation of this feature of the flow is needed.

In Figure 28, comparisons are presented between measured and computed Stanton number distributions for the flows with inlet turbulence levels of 1, 2, 4 and 6 percent. The following observations about the Stanton number prediction in the fully turbulent region of the flows are made. The predicted Stanton number using McDonald's formulation is in good agreement with the experiment for the flow with an inlet turbulence level of 1 percent; however, as the inlet turbulence level increases, the computational procedure using McDonald's formulation underpredicts the measured Stanton number distribution. The computational procedure using Rotta's formulation overpredicts the Stanton number for the flow with the 1 percent inlet turbulence level. However, as the inlet turbulence level increases the computed results tend to slightly overpredict the measured Stanton number distribution. The present turbulent Prandtl number formulation yields essentially the same results as the computed with Rotta's formulation since the present formulation is a perturbation of Rotta's Pr_t formulation. The results shown in Fig. 28 indicate that the computation using the present distribution shows no marked improvement over the computation using Rotta's distribution. However, for the flows with inlet turbulence of 2 percent or larger, computations using either Rotta's or the present formulation result in predicted Stanton number distributions which are in better agreement with the experimental results than that obtained using McDonald's formulation. A further indication of the advantage of Rotta's or the present formulation is shown in Fig. 29 where the predicted Reynolds analogy factor, $2 St/C_f$, from calculations using the present and McDonald's turbulent Prandtl number distributions are compared to the experimentally deduced Reynolds analogy. In this figure it is observed that the calculation using the present (or Rotta's) formulation predicted Reynolds analogy factors that are in better agreement with the experiment than the computation which uses McDonald's formulation. The overall implication of these results is that the analysis using the McDonald and Kreskovsky turbulence model (Ref. 30) with either Rotta's or the present turbulent Prandtl number formulation can accurately represent the momentum and energy transport mechanisms for zero pressure gradient flows in the wall region of the boundary layer but that there is a severe weakness in its

ability to represent the momentum and energy transport mechanisms in the region near the edge of the boundary layer for flows with significant levels of free-stream turbulence.

CONCLUSIONS

The present program was designed to examine, both experimentally and analytically, the effect of free-stream turbulence on the heat transfer through turbulent boundary layers. The experimental test conditions for the present program were intended to reproduce cases for which numerous other experimental data had been obtained under an earlier AFOSR contract (Ref. 2). Measurements of multi-component free-stream turbulence intensities, test surface Stanton number distributions, transition Reynolds numbers and boundary layer integral thicknesses were in excellent agreement with the respective quantities of the earlier contract. It has been concluded that these present measurements can be viewed as additional data for the same test conditions as were previously studied. A number of comparisons were made between low free-stream turbulence boundary layer turbulence data obtained in the present study and similar results from other investigations. These comparisons showed excellent agreement indicating that the present boundary layer turbulence data are of high quality.

The conclusions reached from the experimental measurements obtained for higher levels of free-stream turbulence were as follows:

1. The present data indicate a progressive increase of boundary layer turbulence kinetic energy with increasing free-stream turbulence. Increased levels of turbulence kinetic energy were measured across the entire thickness of the boundary layer. These results are in agreement with data from other independent studies.
2. Both the u' and w' components of turbulence increased progressively with increasing free-stream turbulence level. The u' component increased more than the w' component. The vertical component (v'), however, was essentially constant and independent of free-stream turbulence level for the inner half of the boundary layer.
3. The ratio of shear stress to turbulence kinetic energy decreased across the entire boundary layer with increasing free-stream turbulence level. The decrease was most extreme over the outer 60 percent of the boundary layer.
4. The effects of free-stream turbulence level on the ratios of the direct stress components to the turbulence kinetic energy were to a) increase $u'u'/q^2$, b) decrease $v'v'/q^2$ and c) leave $w'w'/q^2$ nearly constant.
5. Reynolds stress distribution measurements indicated that at high levels of free-stream turbulence the turbulent shear stresses extend beyond the mean velocity boundary layer. The present data and results from other sources indicate an increase in turbulent shear at the boundary layer edge directly proportional to the free-stream

turbulence level. Flatness factor measurements indicated that as the free-stream turbulence level was increased the "border" between the fluid in the boundary layer and the free-stream fluid became less distinct.

6. Measurements of the boundary layer turbulent Prandtl number distribution for the case of the low free-stream turbulence were in good agreement with a model suggested by Rotta. The present data indicate that as the free-stream turbulence level was increased, the near-wall Pr_t decreased while Pr_t over the outer region of the boundary layer slightly increased. A correlation, $Pr_t(y/\delta, Te)$, which fit the observed data reasonably well was suggested.

The experimental data was used to assess the capability of a boundary-layer computer program, ABLE (Analysis of the Boundary Layer Equations) for predicting the effect of free-stream turbulence on momentum and thermal boundary layers. In addition the turbulent Prandtl number formulation deduced from the experimental measurements was used in the boundary layer analysis and its effect on surface heating was determined. The following conclusions were reached from the theoretical portion of this investigation:

1. The modeling of free-stream turbulence in the one equation turbulence model of McDonald and Kreskovsky captures the correct shape and level of the turbulence kinetic energy.
2. For increased levels of free-stream turbulence, the Reynolds shear stress and turbulent heat flux determined from the turbulence model is significantly smaller than that observed experimentally in the wake region of the turbulent boundary layer. This discrepancy could be due to the eddy viscosity concept used in McDonald and Kreskovsky's model and further investigation of turbulence models is needed.
3. Analytical calculations using either Rotta's turbulent Prandtl number correlation or the correlation of the present investigation predicted Reynolds analogy factors ($2S_t/C_f$) that are in reasonable agreement with experimental measurements and accurately predict the increase in surface heat transfer due to increased free-stream turbulence.

LIST OF SYMBOLS

$a_1, a_2, a_3, a_4, a_1, \dots$	Turbulence structural coefficients
c_p	Specific heat at constant pressure
d	Hot wire sensor diameter
$\mathcal{D}$	Wall damping function in turbulence
Fu_v	Flatness factor (vertical x probe) = $\overline{u'^4}/(\overline{u'^2})^2$
Fu_h	Flatness factor (horizontal x probe) = $\overline{u'^4}/(\overline{u'^2})^2$
Fv_v	Flatness factor (vertical x probe) = $\overline{v'^4}/(\overline{v'^2})^2$
Fw_h	Flatness factor (horizontal x probe) = $\overline{w'^4}/(\overline{w'^2})^2$
FT	Flatness factor (tri-x probe) = $\overline{t'^4}/(\overline{t'^2})^2$
$G_{1,\theta}$	Turbulence structural coefficient (Eq. 11)
h	Height of hot wire sensor array
h	Static enthalpy
$\overline{h'v'}$	Reynolds thermal flux
H	Total enthalpy
ℓ	Active length of hot wire sensor
ℓ	Mixing length function in turbulence model
ℓ_e	Free-stream mixing length
L	Dissipation length scale
n	Distance normal to surface
n^+	Dimensionless normal distance to surface,
Nu	Nusselt number of hot wire sensor
p	Static pressure
Pr_t	Turbulent Prandtl number (Eq. 9)
$\dot{q}$	Heat flux
$\overline{q^2}$	Turbulence kinetic energy
r	Separation distance between hot wire sensors
Re	Reynolds number
Re_θ	Reynolds number based on momentum thickness
R_T	Turbulent Reynolds number
$\tilde{R}_\theta$	McDonald's correlation of Re_θ

s	Coordinate along wall surface
Su_v	Skewness factor (vertical x probe) = $\overline{u'^3}/(\overline{u'^2})^{3/2}$
Su_h	Skewness factor (horizontal x probe) = $\overline{u'^3}/(\overline{u'^2})^{3/2}$
Sv_v	Skewness factor (vertical x probe) = $\overline{v'^3}/(\overline{v'^2})^{3/2}$
Sw_h	Skewness factor (horizontal x probe) = $\overline{w'^3}/(\overline{w'^2})^{3/2}$
S_T	Skewness factor (tri-x probe) = $\overline{t'^3}/(\overline{t'^2})^{3/2}$
T	Mean static temperature
Te	Free-stream turbulence level
T_T	Total temperature
T_τ	Friction temperature = $q_w/\rho_w c_p U_\tau$
T^+	Dimensionless temperature = $(T_w - T)/T_\tau$
t'	Fluctuating temperature
u	Streamwise velocity
U	Mean streamwise velocity
U_τ	Friction velocity
U^+	Dimensionless velocity = U/U_τ
$\overline{u'u'}, \overline{v'v'}, \overline{w'w'}$	Components of turbulent intensity
u', v', w'	Streamwise normal and transverse fluctuating velocities
$-\overline{u'v'}$	Reynolds shear stress
v	Normal velocity
V_q	Transport velocity of turbulence kinetic energy (Eq. 8)
V_τ	Transport velocity of turbulent shear stress (Eq. 7)
x	Distance from plate leading edge
y	Distance from wall
y^+	Dimensionless distance from wall = yU_τ/ν
δ	Boundary layer thickness
δ_τ	Thermal boundary layer thickness
δ_s	Thickness of inner wall region of boundary layer
δ^*	Boundary layer displacement thickness
θ	Boundary layer momentum thickness
κ	von Karman constant for velocity of law-of-the-wall
κ_θ	von Karman constant for temperature law-of-the-wall

μ	Molecular viscosity
μ_T	Eddy viscosity
ν	Kinematic viscosity
Π	Wake strength for velocity boundary layer
Π_θ	Wake strength for temperature boundary layer
ρ	Density
τ	Shear stress
Ψ_{B_V}	Correlation coefficient = $\frac{\overline{u'^2 v'}}{\overline{u'^2}} \sqrt{v'^2}$
Ψ_{B_W}	Correlation coefficient = $\frac{\overline{u'^2 w'}}{\overline{u'^2}} \sqrt{w'^2}$
Ψ_{C_V}	Correlation coefficient = $\frac{\overline{u' v'^2}}{\overline{u'^2}} \sqrt{v'^2}$
Ψ_{C_W}	Correlation coefficient = $\frac{\overline{u' w'^2}}{\overline{u'^2}} \sqrt{w'^2}$

Subscripts

e	Freestream
w	Wall
0.995	where $U = 0.995 U_e$

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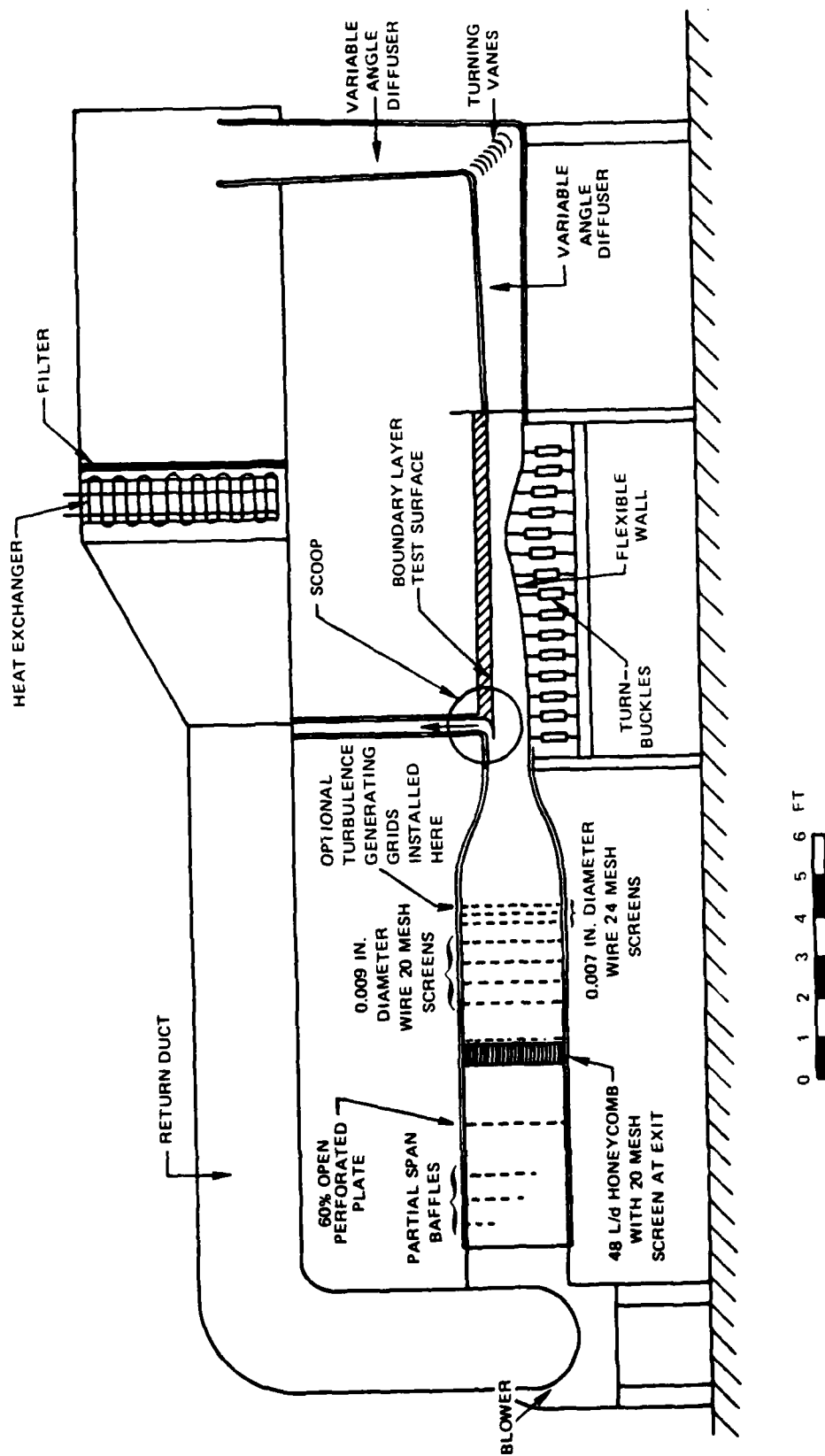


Figure 1. United Technologies Research Center Boundary Layer Wind Tunnel

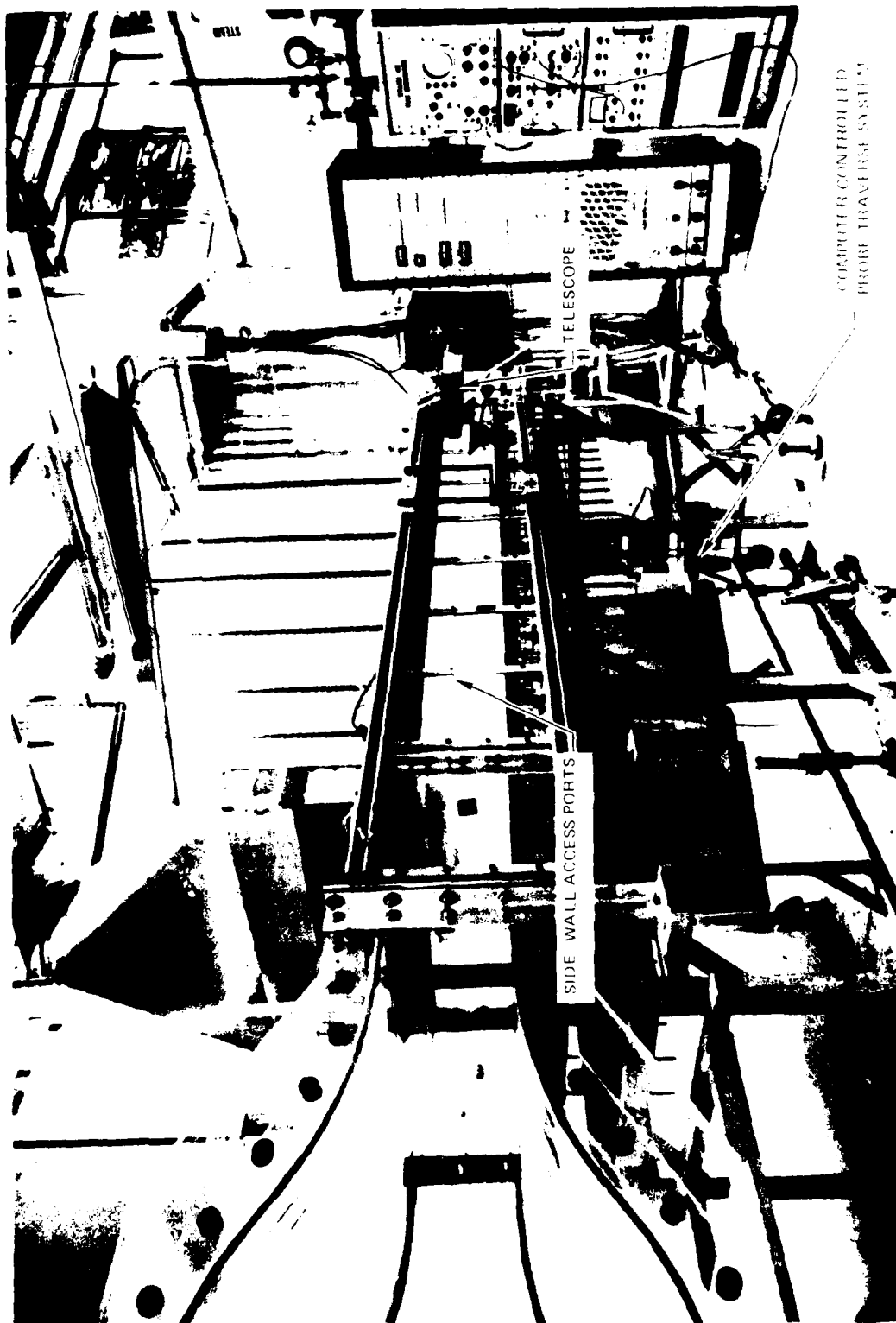


Figure 2. Photograph of UTRC Boundary Layer
Wind Tunnel Test Section

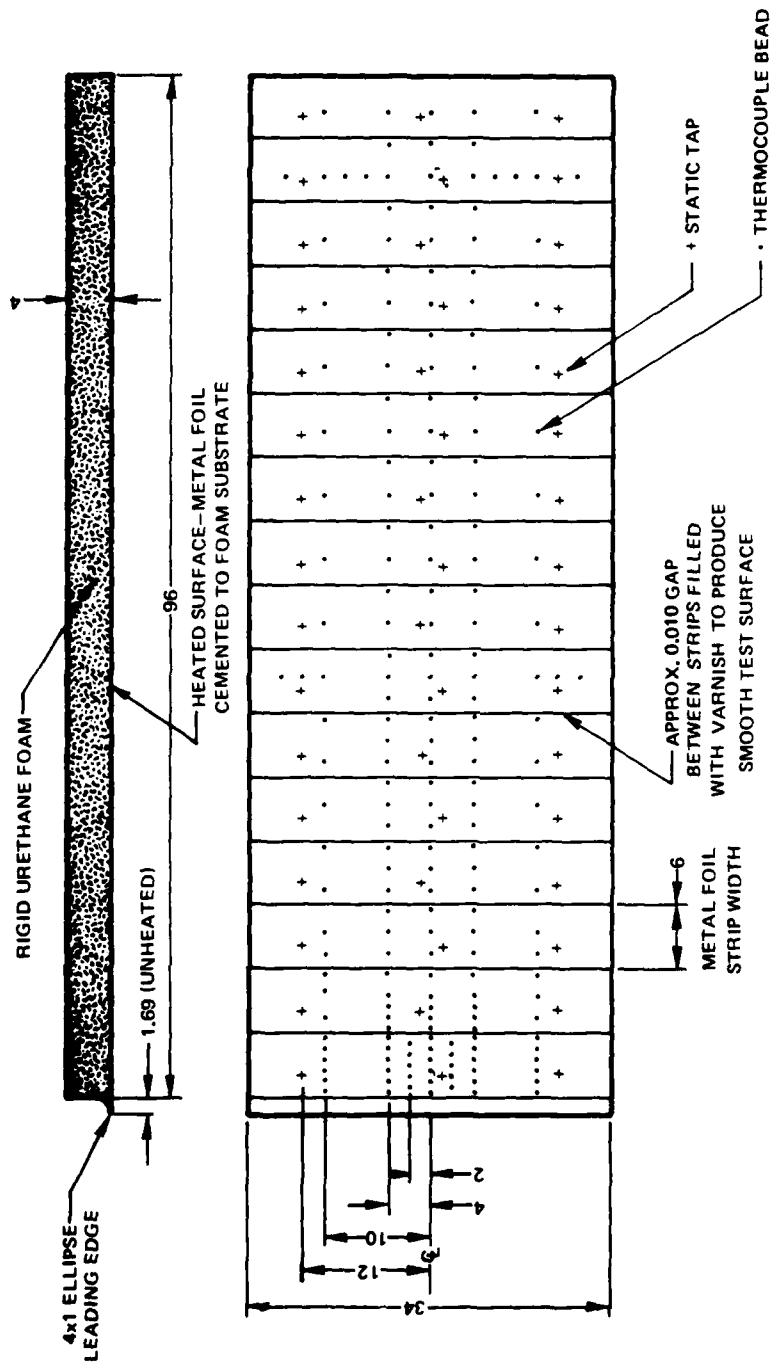


Figure 3. Instrumentation Diagram for the Uniform Heat Flux Flat Wall Model

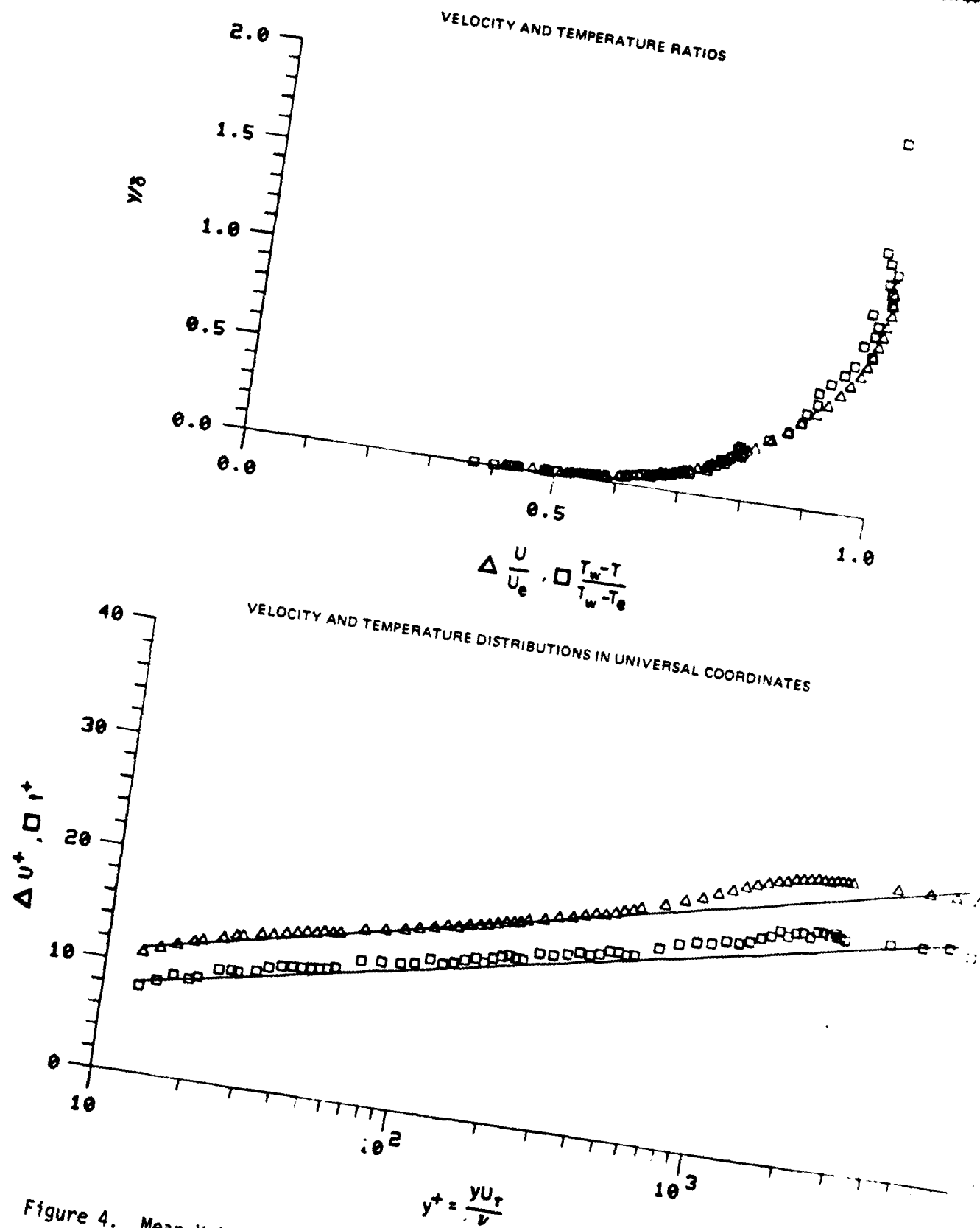


Figure 4. Mean Velocity and Temperature Profiles $x = 68$ in., $Te = 1.6\%$

$$x = 68 \text{ in.}, T_e = 1.6\%$$
Table 1

BOUNDARY LAYER PROPERTIES	LINEAR INTERPOLATION TO WALL	STANDARD SUBLAYER FUNCTION FROM WALL TO $y^+ = 30$
FREF STREAM VELOCITY =	98.170	98.170
FREE STREAM TEMPERATURE =	70.180	
WALL TEMPERATURE =	95.750	
WALL HEAT FLUX =	.07954	
FREE STREAM DENSITY =	.07552	
FREE STREAM KINEMATIC VISCOSITY =	.0001619	
DENSITY OF FLUID AT WALL =	.07204	
KINEMATIC VISCOSITY OF FLUID AT WALL =	.0001760	
WALL/FREE STREAM DENSITY RATIO =	.95396	
LOCATION REYNOLDS NUMBER (REX) =	3435559.84	
INPUT VALUE OF VELOCITY DELTA =	1.30000	
INPUT VALUE OF TEMPERATURE DELTA =	1.30000	
CALCULATED DELTA =		1.12046
DELTA 99.5% INPUT =	.00300	
DISPLACEMENT THICKNESS (DELSTAR) =	.15429	.15443
MOMENTUM THICKNESS (THETA) =	.10938	.10967
ENERGY-DISSIPATION THICKNESS =	.19539	.19556
ENTHALPY THICKNESS =	.00597	.00598
SHAPE FACTOR 12 (DELSTAR/THETA) =	1.41057	1.40819
SHAPE FACTOR 32 (ENERGY/THETA) =	1.78634	1.76327
MOMENTUM THICKNESS REYNOLDS NUMBER =	5526.16	5540.66
DISPLACEMENT THICKNESS REYNOLDS NUMBER =	7795.01	7602.27
SKIN FRICTION COEFFICIENT =	.002865	
FRICTION VELOCITY =	3.81748	
LAW OF THE WALL CONSTANT (K) =	.41000	
LAW OF THE WALL CONSTANT (C) =	5.00000	
WAKE STRENGTH =		.44004
CLAUSERS 'DELTA' INTEGRAL =	-3.62559	-3.91767
CLAUSEPS 'G' INTEGRAL =	24.97566	24.86843
DISPLACEMENT THICKNESS - CONSTANT DENSITY =	.14465	.14845
MOMENTUM THICKNESS - CONSTANT DENSITY =	.11055	.11085
SHAPE FACTOR 12 - CONSTANT DENSITY =	1.30848	1.33924
LOCATION -X-	68.00000	
Te = 1.6%		

Table 2

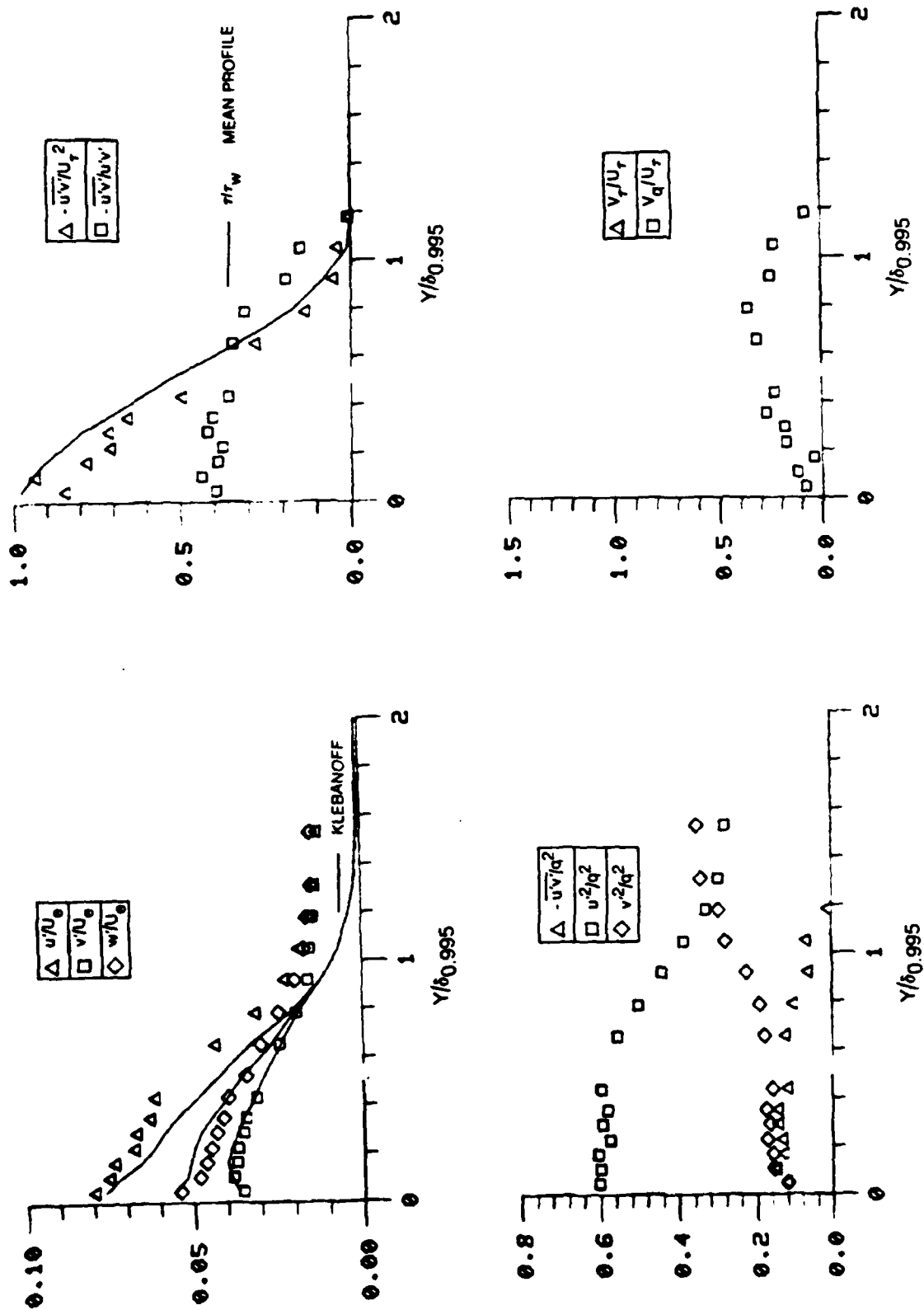


Figure 5A. Boundary Layer Turbulence Quantities $x = 68$ in, $T_e = 1.6\%$

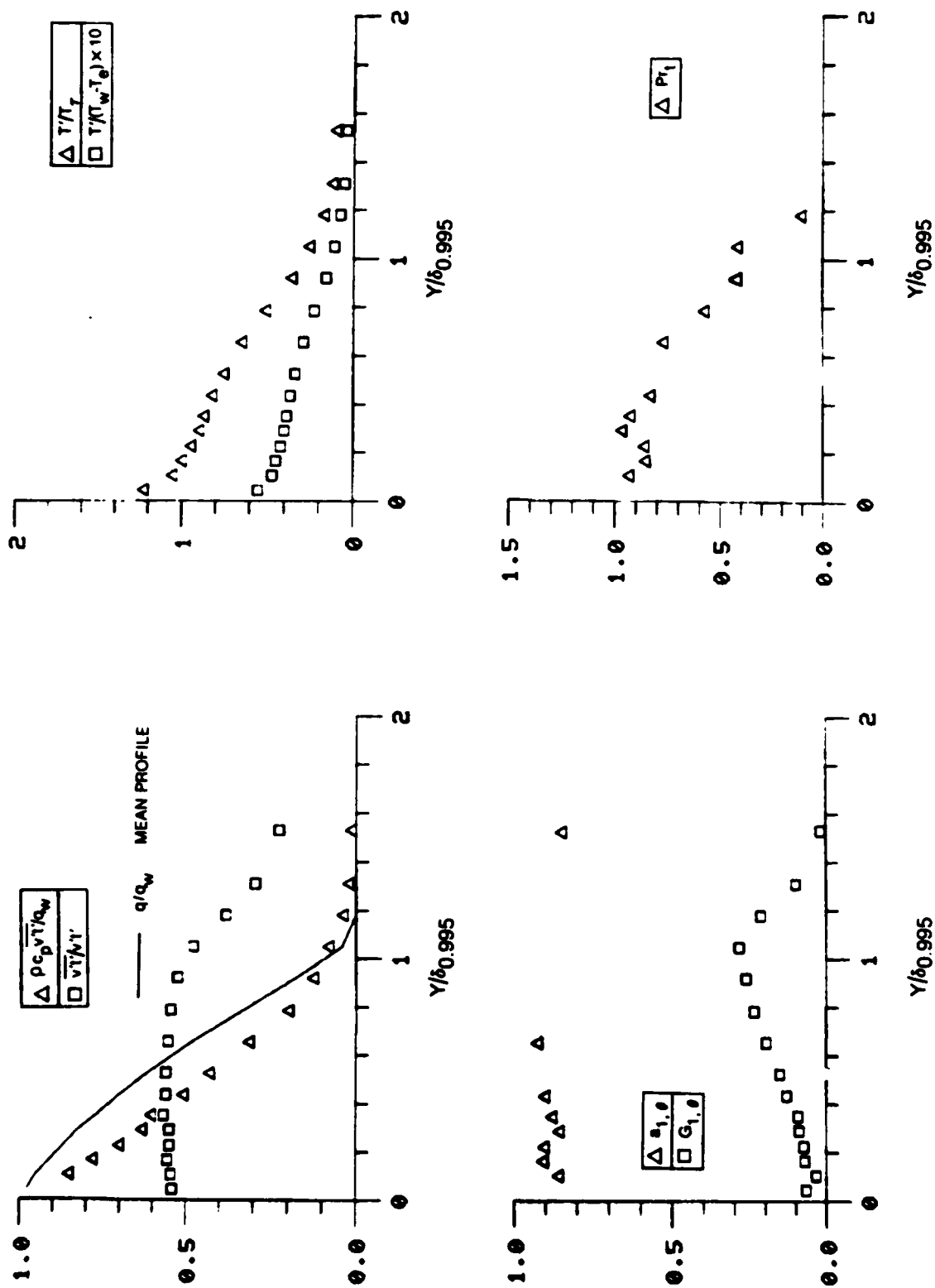


Figure 58. Boundary Layer Turbulence Quantities $x = 68$ in, $T_e = 1.6\%$

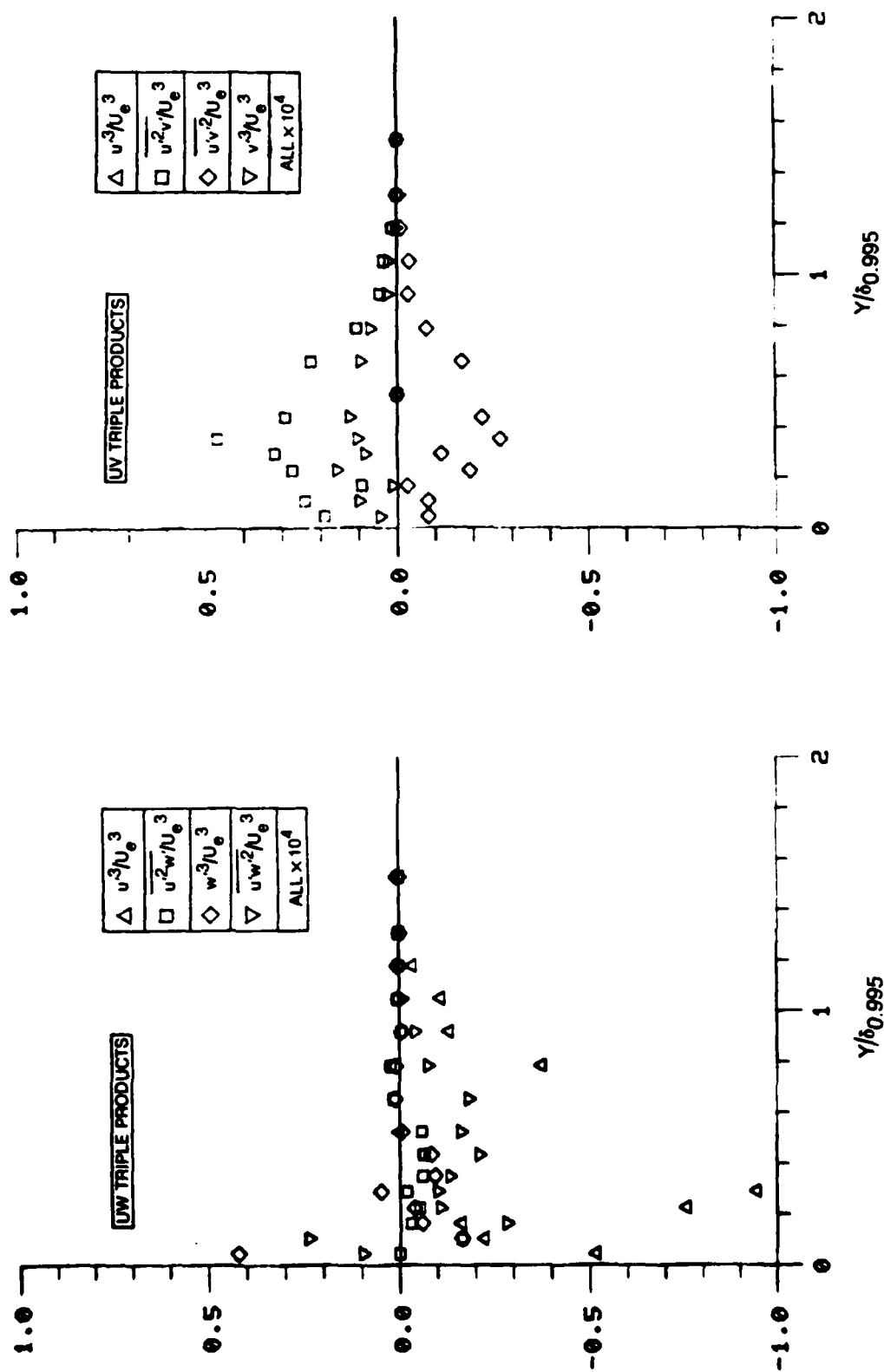


Figure 5C. Boundary Layer Triple Product Distributions $x = 68$ in, $T_e = 1.6\%$

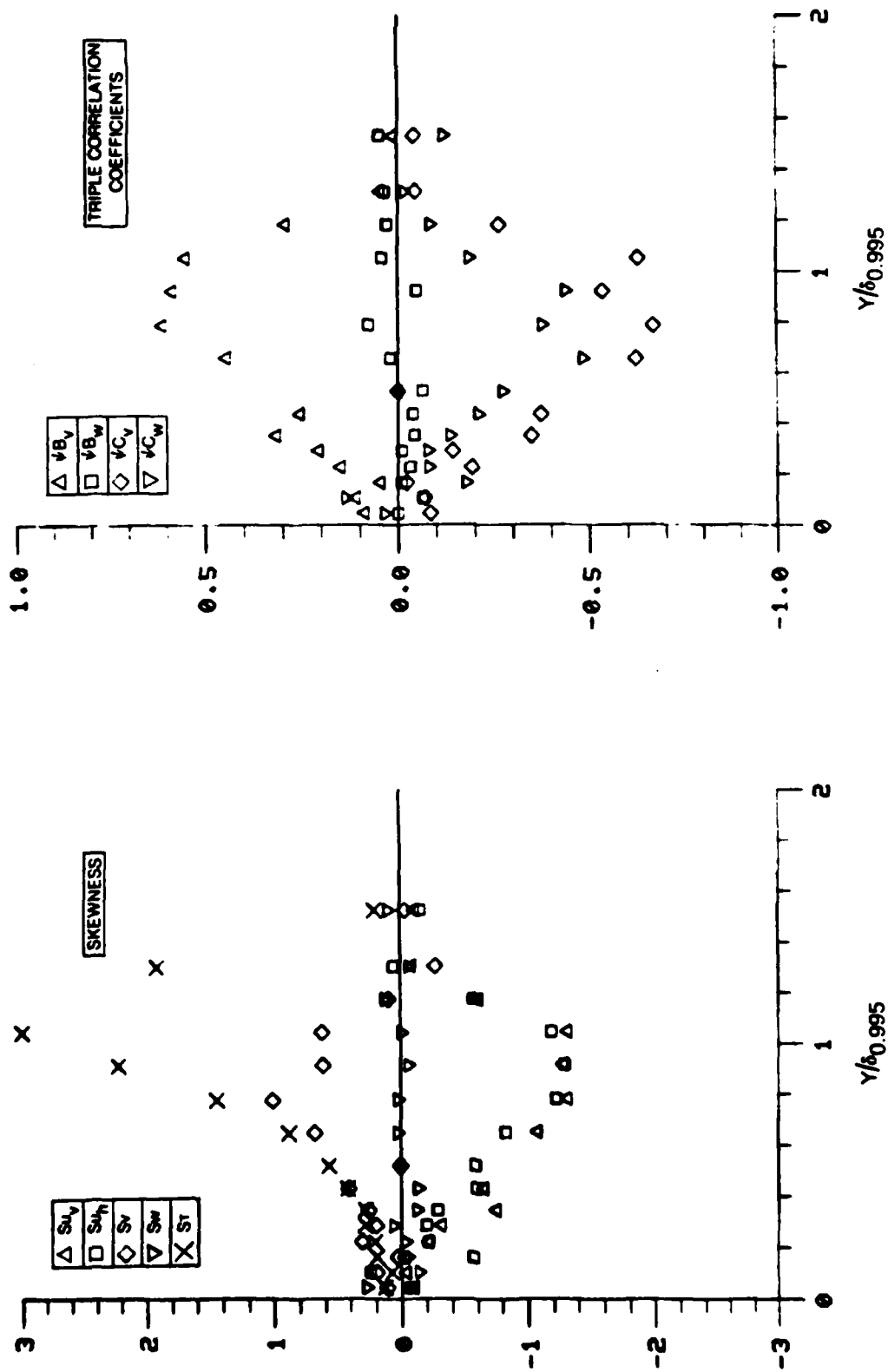


Figure 50. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 68$ in, $T_e = 1.6\%$

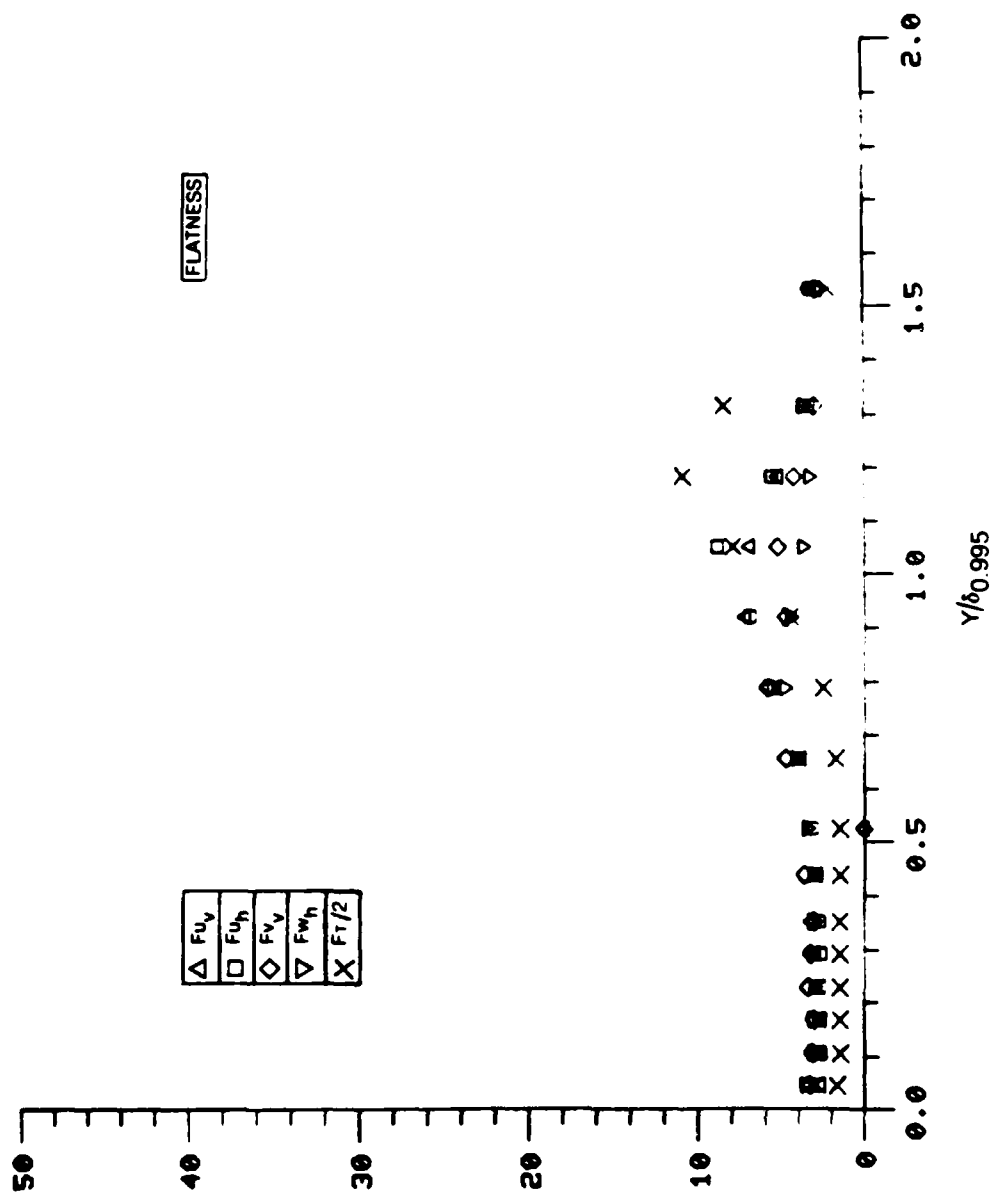


Figure 5E. Boundary Layer Flatness Distributions $x = 68$ in, $Te = 1.6\%$

$$x = 68 \text{ in, } T_e = 1.6\%$$
Table 3A

Fluctuating Profile Data

x = 68 in., Te = 1.6%

N INCHES	Y/ DELTA	U ³ /UE ³ x 10000	U ³ /UE ³ x 10000	U ³ /UE ³ x 10000	U ³ /UE ³ x 10000	U ³ /UE ³ x 10000	U ³ /UE ³ x 10000	U ³ /UE ³ x 10000
1	1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6	6
7	7	7	7	7	7	7	7	7
8	8	8	8	8	8	8	8	8
9	9	9	9	9	9	9	9	9
10	10	10	10	10	10	10	10	10
11	11	11	11	11	11	11	11	11
12	12	12	12	12	12	12	12	12
13	13	13	13	13	13	13	13	13
14	14	14	14	14	14	14	14	14
15	15	15	15	15	15	15	15	15
16	16	16	16	16	16	16	16	16
17	17	17	17	17	17	17	17	17
18	18	18	18	18	18	18	18	18
19	19	19	19	19	19	19	19	19
20	20	20	20	20	20	20	20	20
21	21	21	21	21	21	21	21	21
22	22	22	22	22	22	22	22	22
23	23	23	23	23	23	23	23	23
24	24	24	24	24	24	24	24	24
25	25	25	25	25	25	25	25	25
26	26	26	26	26	26	26	26	26
27	27	27	27	27	27	27	27	27
28	28	28	28	28	28	28	28	28
29	29	29	29	29	29	29	29	29
30	30	30	30	30	30	30	30	30
31	31	31	31	31	31	31	31	31
32	32	32	32	32	32	32	32	32
33	33	33	33	33	33	33	33	33
34	34	34	34	34	34	34	34	34
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36	36	36	36	36	36	36	36	36
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38	38	38	38	38	38	38	38	38
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43	43	43	43	43	43	43	43	43
44	44	44	44	44	44	44	44	44
45	45	45	45	45	45	45	45	45
46	46	46	46	46	46	46	46	46
47	47	47	47	47	47	47	47	47
48	48	48	48	48	48	48	48	48
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50	50	50	50	50	50	50	50	50
51	51	51	51	51	51	51	51	51
52	52	52	52	52	52	52	52	52
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62	62	62	62	62	62	62	62	62
63	63	63	63	63	63	63	63	63
64	64	64	64	64	64	64	64	64
65	65	65	65	65	65	65	65	65
66	66	66	66	66	66	66	66	66
67	67	67	67	67	67	67	67	67
68	68	68	68	68	68	68	68	68
69	69	69	69	69	69	69	69	69
70	70	70	70	70	70	70	70	70
71	71	71	71	71	71	71	71	71
72	72	72	72	72	72	72	72	72
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75	75	75	75	75	75	75	75	75
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77	77	77	77	77	77	77	77	77
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81	81	81	81	81	81	81	81	81
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84	84	84	84	84	84	84	84	84
85	85	85	85	85	85	85	85	85
86	86	86	86	86	86	86	86	86
87	87	87	87	87	87	87	87	87
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89	89	89	89	89	89	89	89	89
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92	92	92	92	92	92	92	92	92
93	93	93	93	93	93	93	93	93
94	94	94	94	94	94	94	94	94
95	95	95	95	95	95	95	95	95
96	96	96	96	96	96	96	96	96
97	97	97	97	97	97	97	97	97
98	98	98	98	98	98	98	98	98
99	99	99	99	99	99	99	99	99
100	100	100	100	100	100	100	100	100

Table 38

KEY		
SYMBOL	SOURCE	T_e %
○	PRESENT	0.2
□	PRESENT	1.5
△	PRESENT	4.2
---	REF 20	0.1
—	REF 12	AS SHOWN

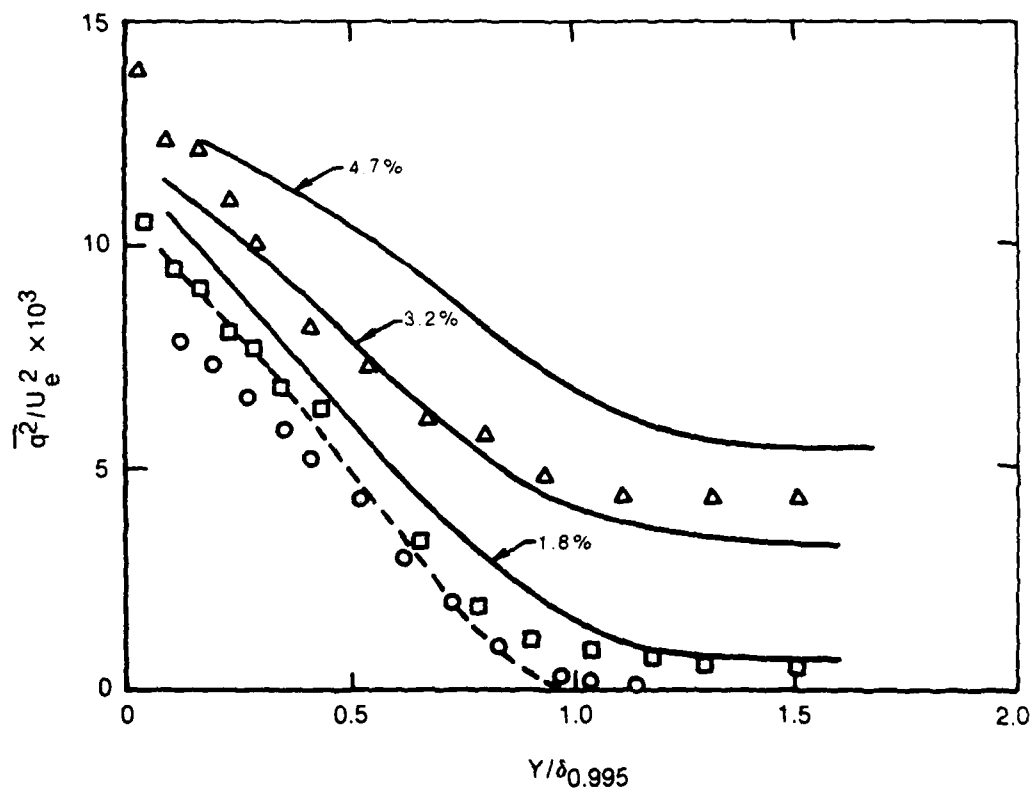


Figure 6. Boundary Layer Turbulent Kinetic Energy Distribution

SYM	FAIRING	T_e %
○	—	0.2
□	- · - · -	1.5
△	- - -	4.2

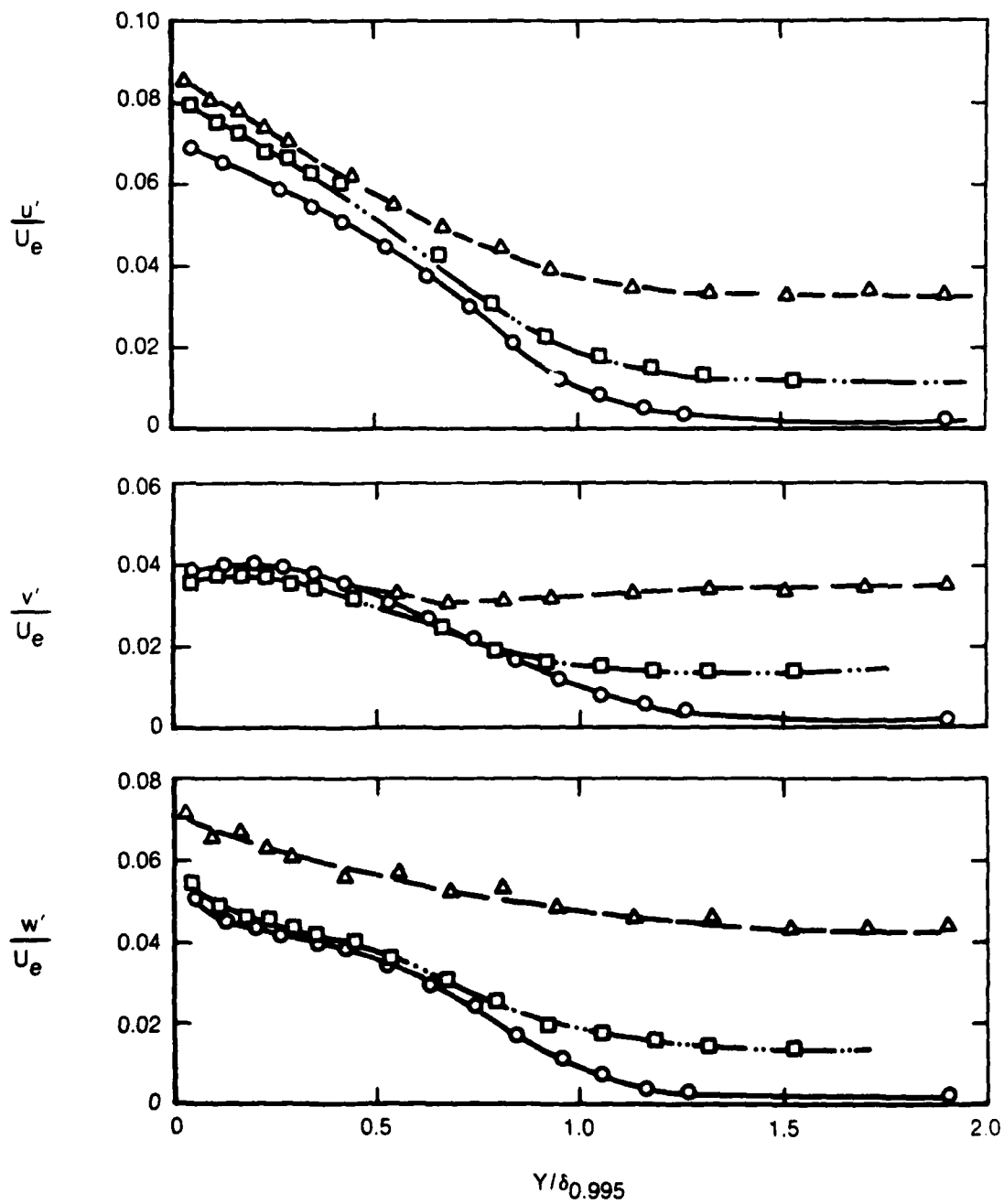


Figure 7. Distribution of the Components of Boundary Layer Turbulence

SYMBOL	T_e %
○	0.2
□	1.5
△	4.2

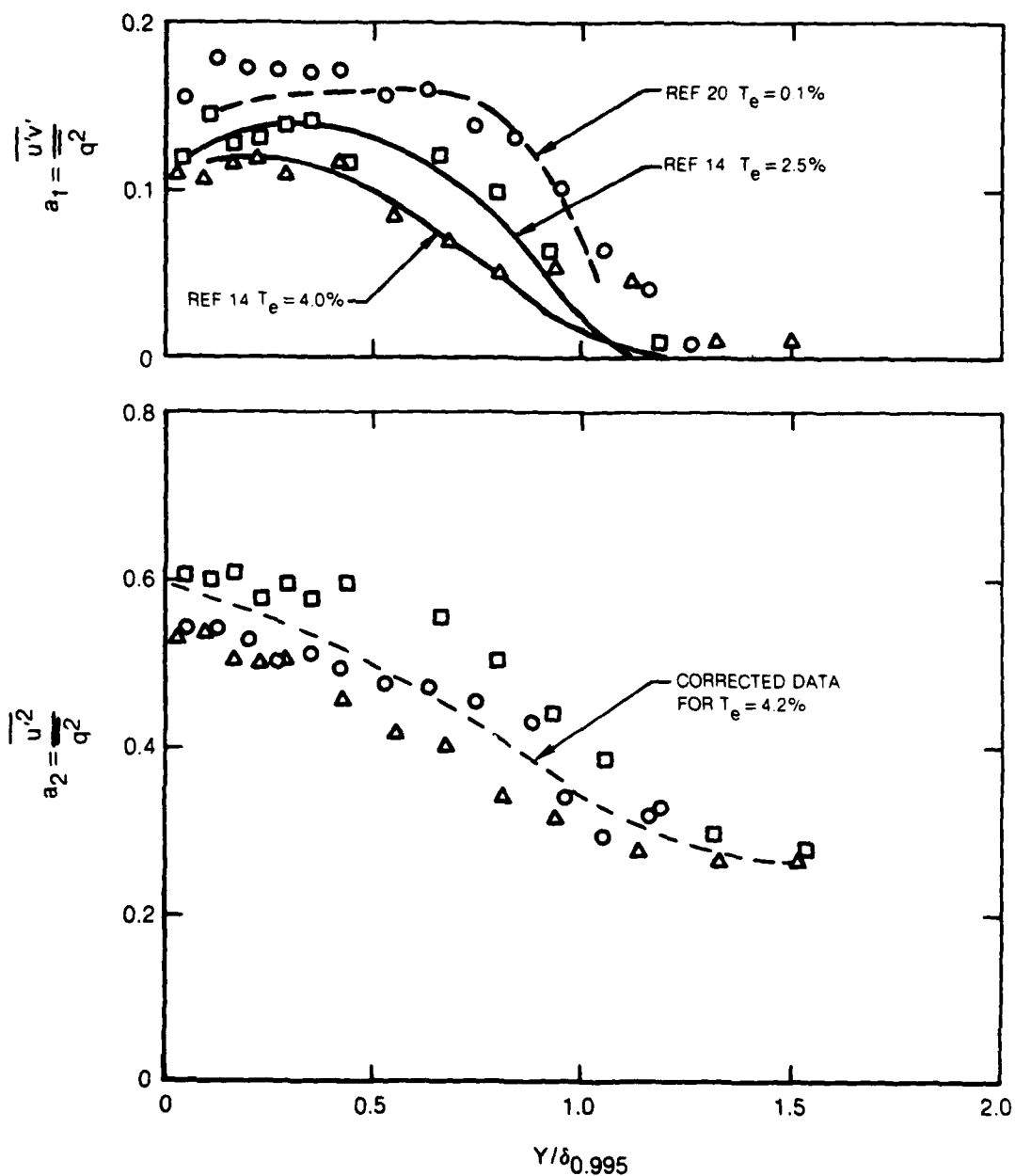


Figure 8A. Distribution of the Turbulence Structural Coefficients a_1 and a_2 Across the Boundary Layer

SYMBOL	T_e %
○	0.2
□	1.5
△	4.2

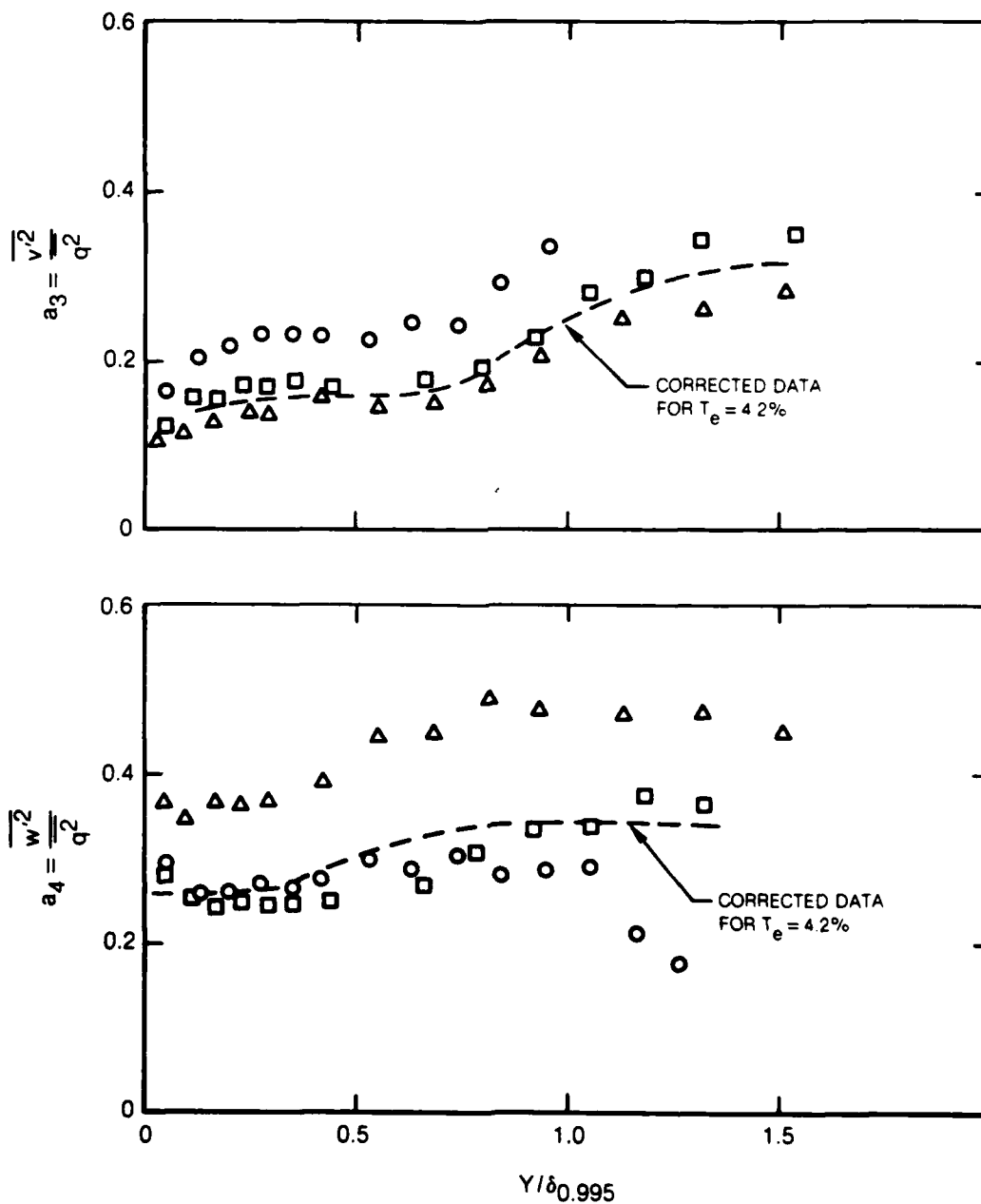


Figure 8B. Distribution of the Turbulence Structural Coefficients a_3 and a_4 Across the Boundary Layer

KEY	
SYM	SOURCE
●	PRESENT DATA
△	CHARNAY, et al (10)
▽	CHARNAY, et al (12)
□	HANCOCK (14)
◇	HUFFMAN (11)
○	EVANS (24)

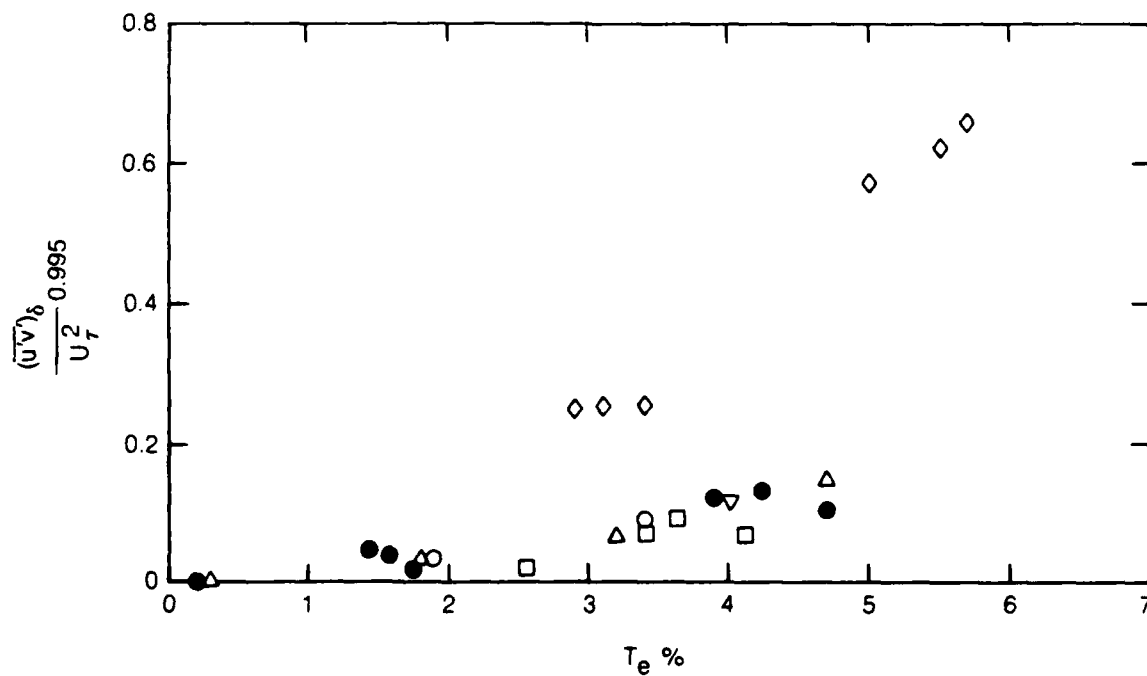


Figure 9. Influence of Free-Stream Turbulence on the Turbulent Shear Stress at $\delta_{0.995}$

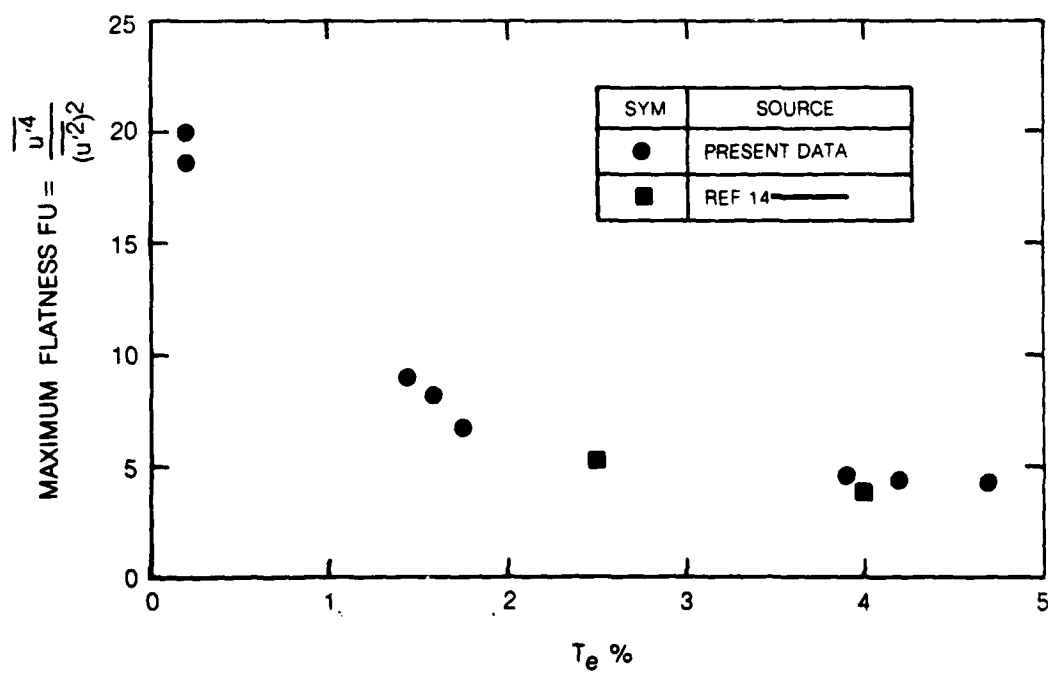
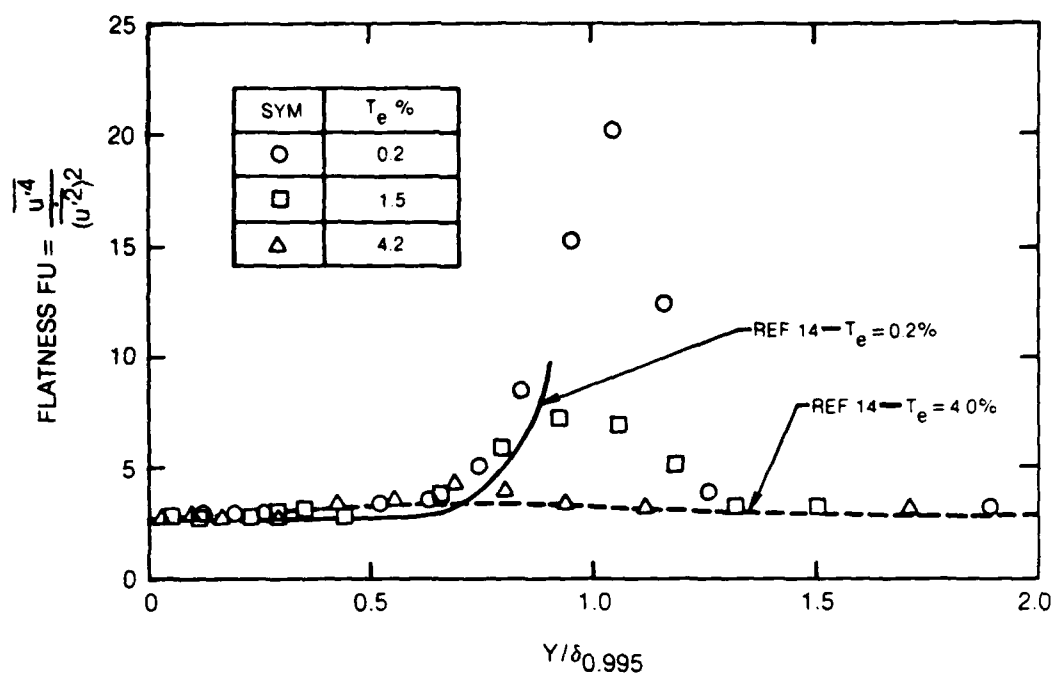


Figure 10. Effect of Free-Stream Turbulence on the u' Flatness Factor Distributions

SYMBOL CODE		
DATA	EQ 17	T_e %
○	—	0.2
▲	- - -	1.4
□	- · - ·	4.0

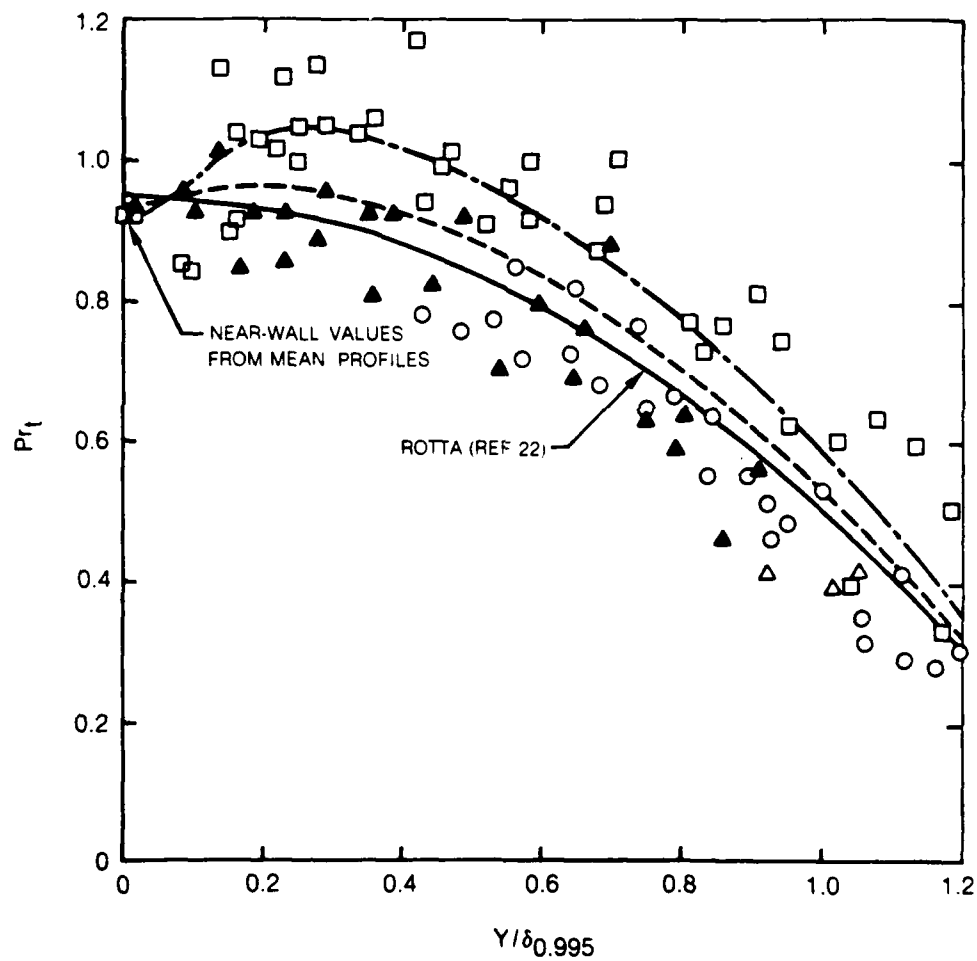


Figure 11. Effect of Free-Stream Turbulence on the Turbulent Prandtl Number Distribution

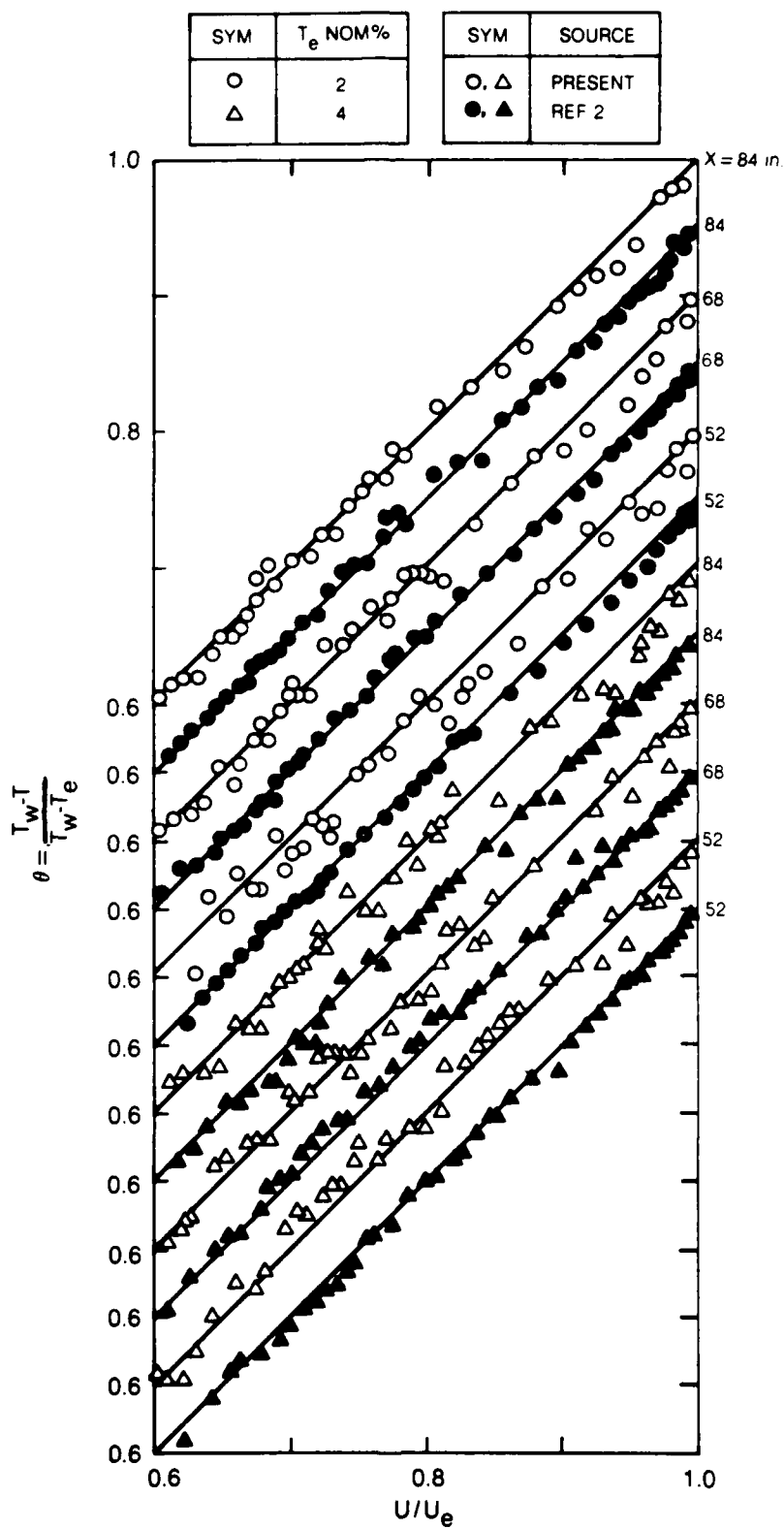


Figure 12. Mean Velocity and Temperature Profiles
for Various Free-Stream Turbulence Levels

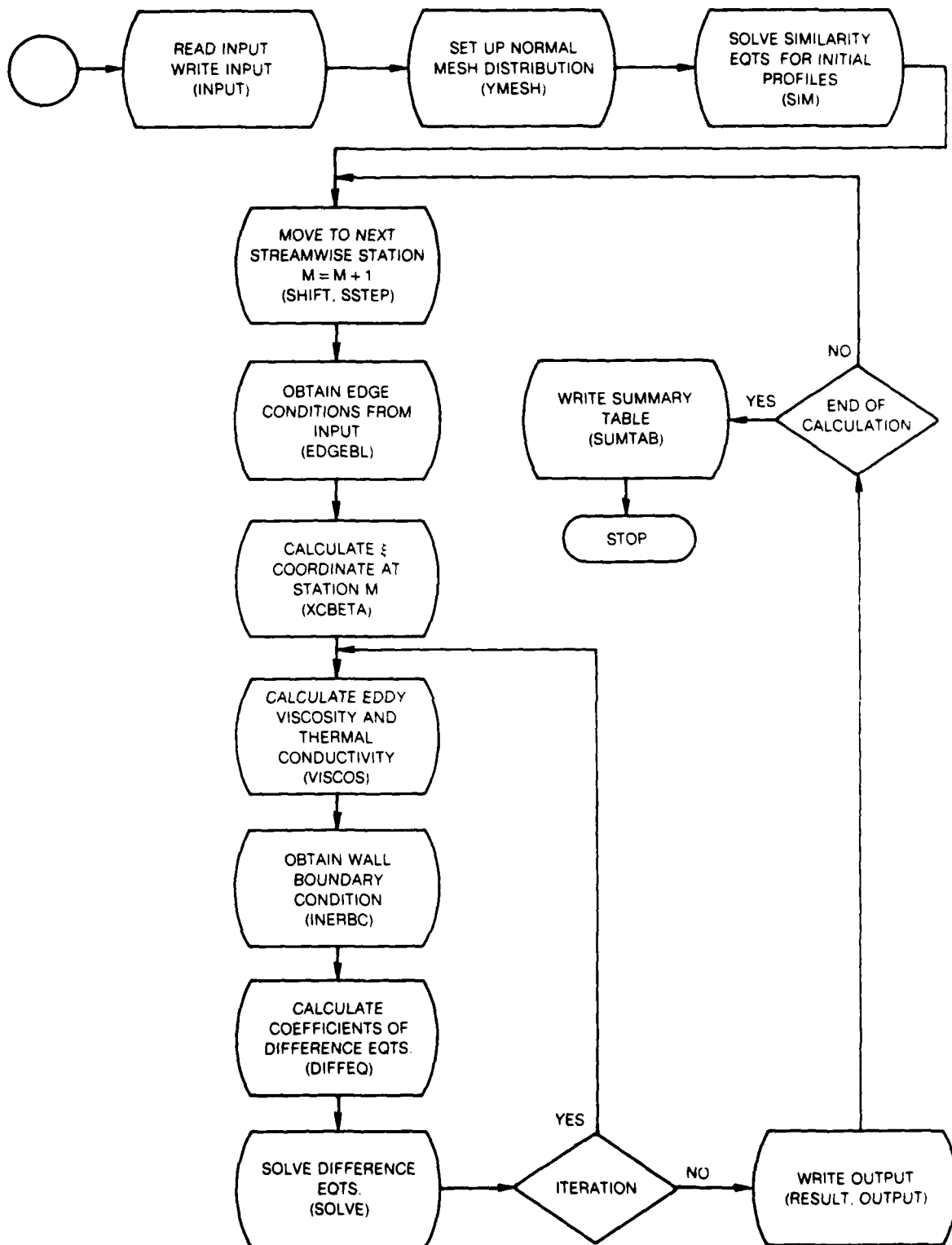


Figure 13. Flow Chart for ABLE Code - Module MAIN

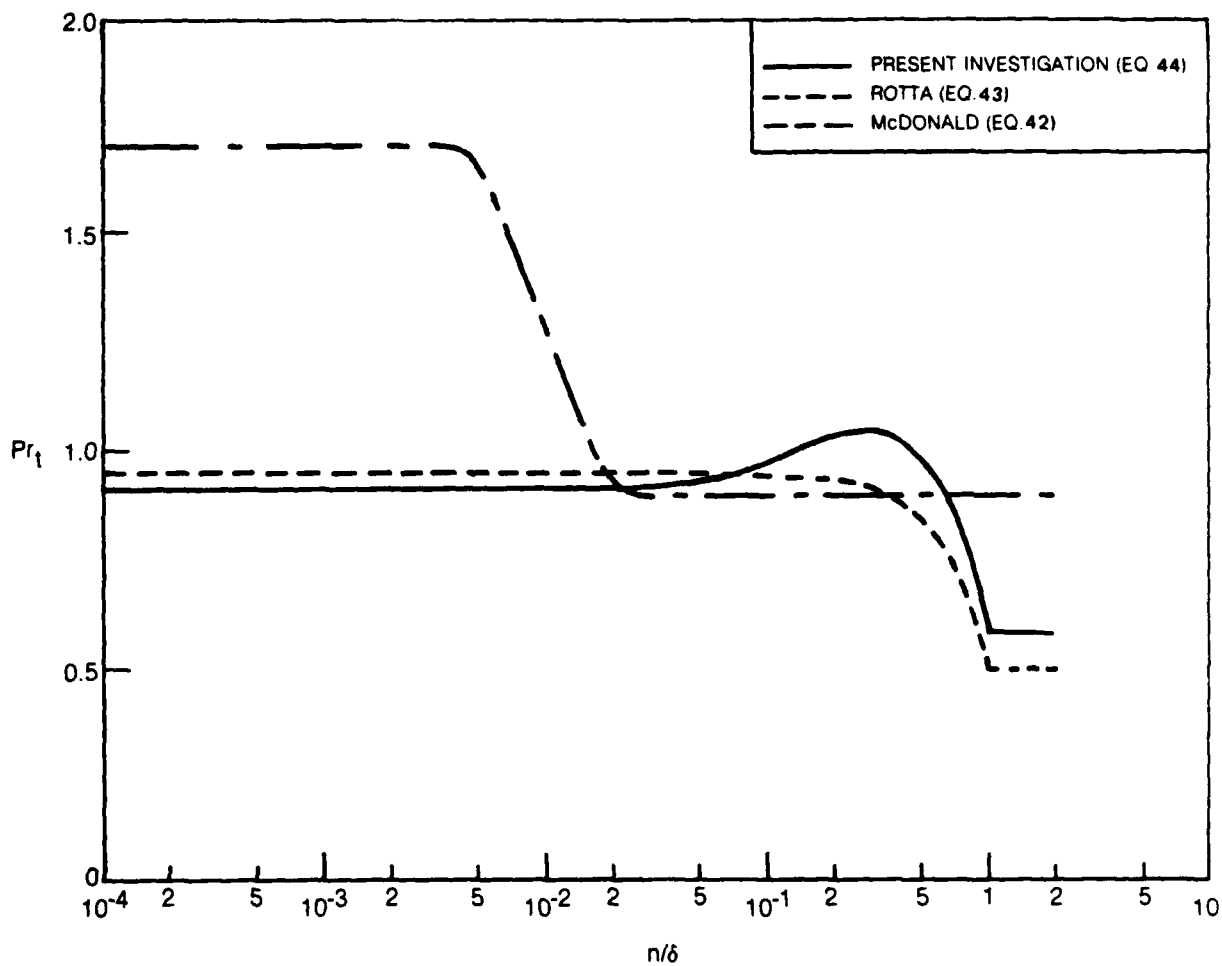


Figure 14. Comparison of Turbulent Prandtl Number Distributions for Flow with 2% Freestream Turbulence

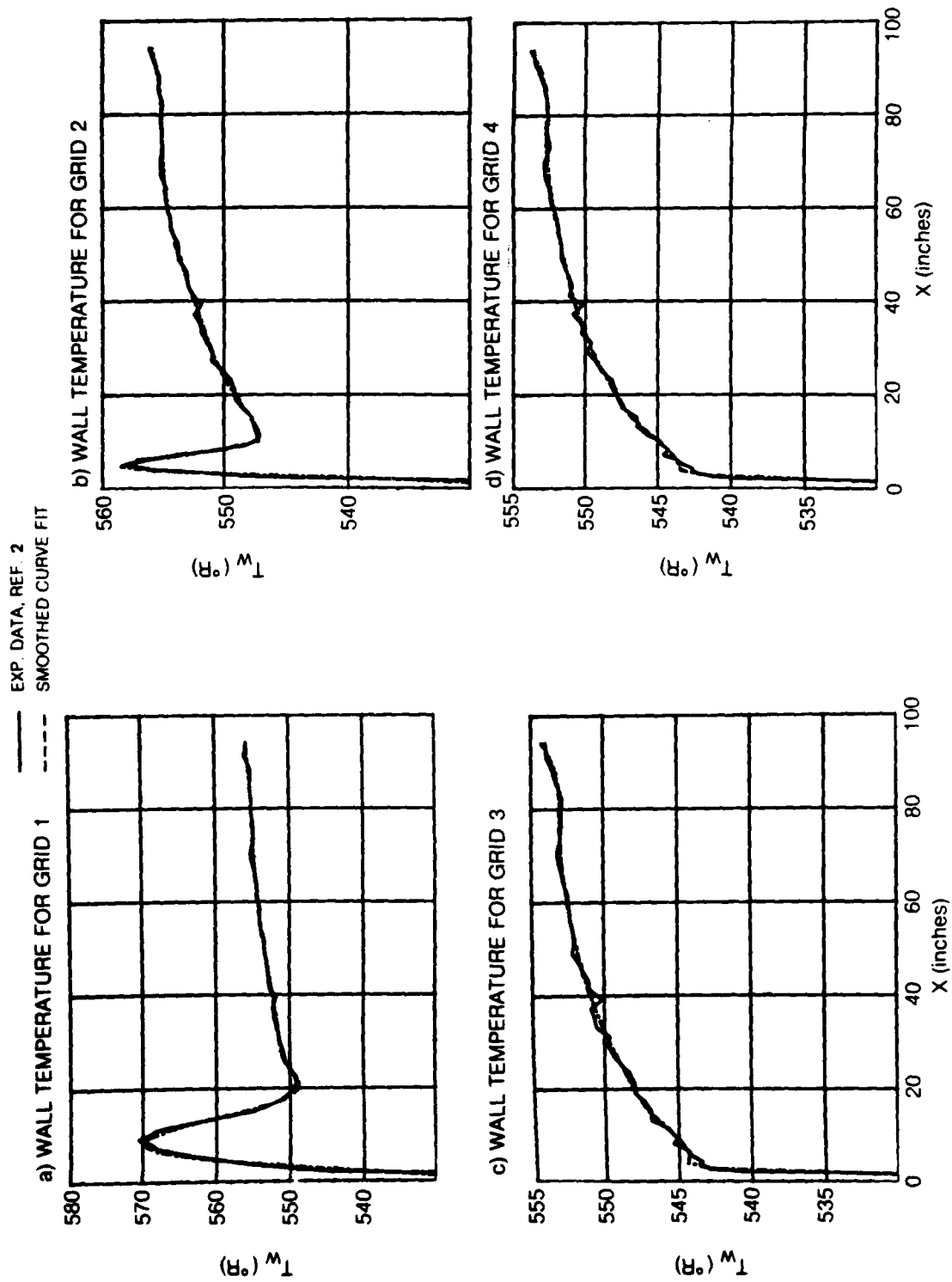


Figure 15. Numerically Smoothed Experimental Wall Temperature Distribution

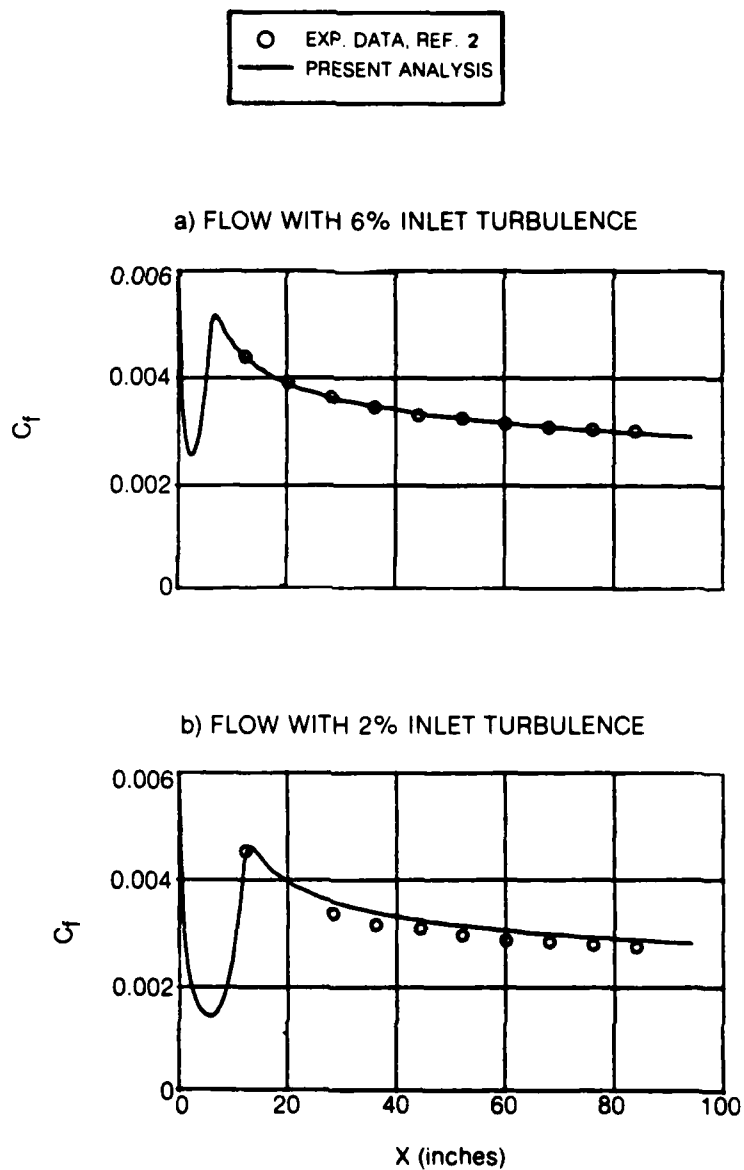


Figure 16. Comparison of Theoretical Skin Friction with Experimental Data for Different Inlet Turbulence Levels

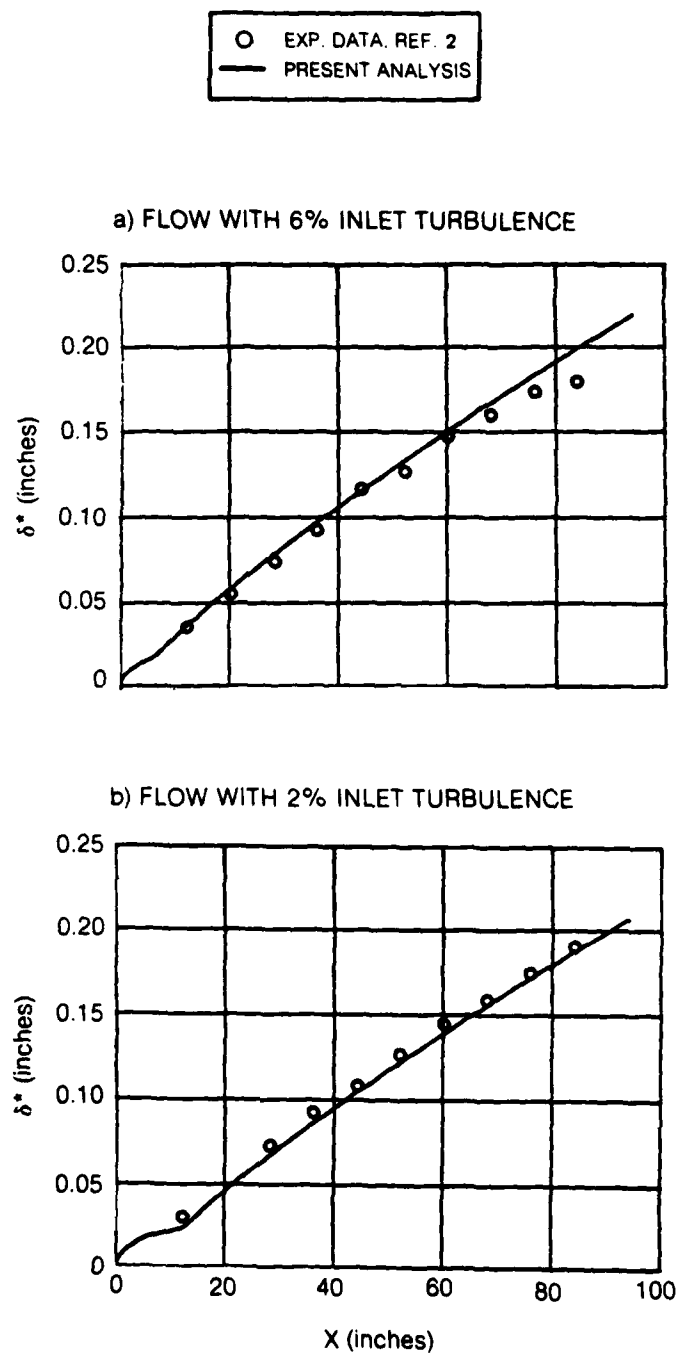


Figure 17. Comparison of Theoretical Displacement Thickness with Experimental Data for Different Inlet Turbulence Levels

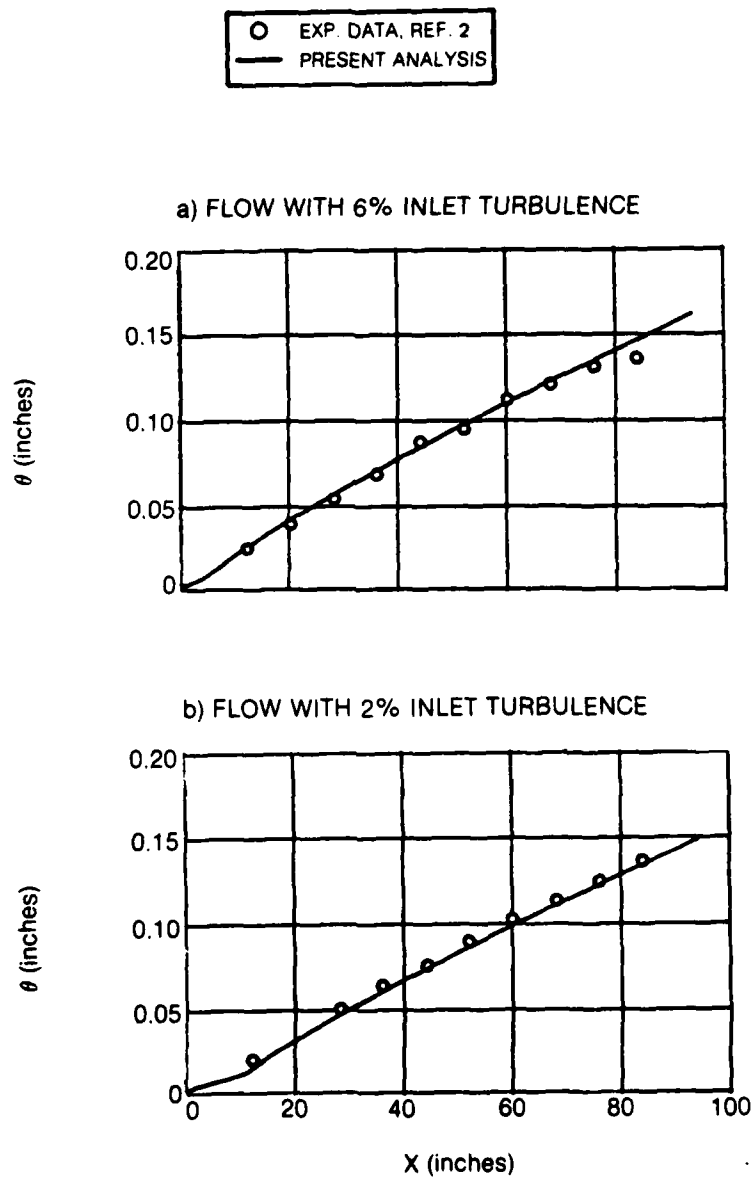


Figure 18. Comparison of Theoretical Momentum Thickness with Experimental Data for Different Inlet Turbulence Levels

INLET TURBULENCE	δ (inches)	
6%	1.256	□ EXP. DATA, REF. 2
2%	1.055	— PRESENT ANALYSIS

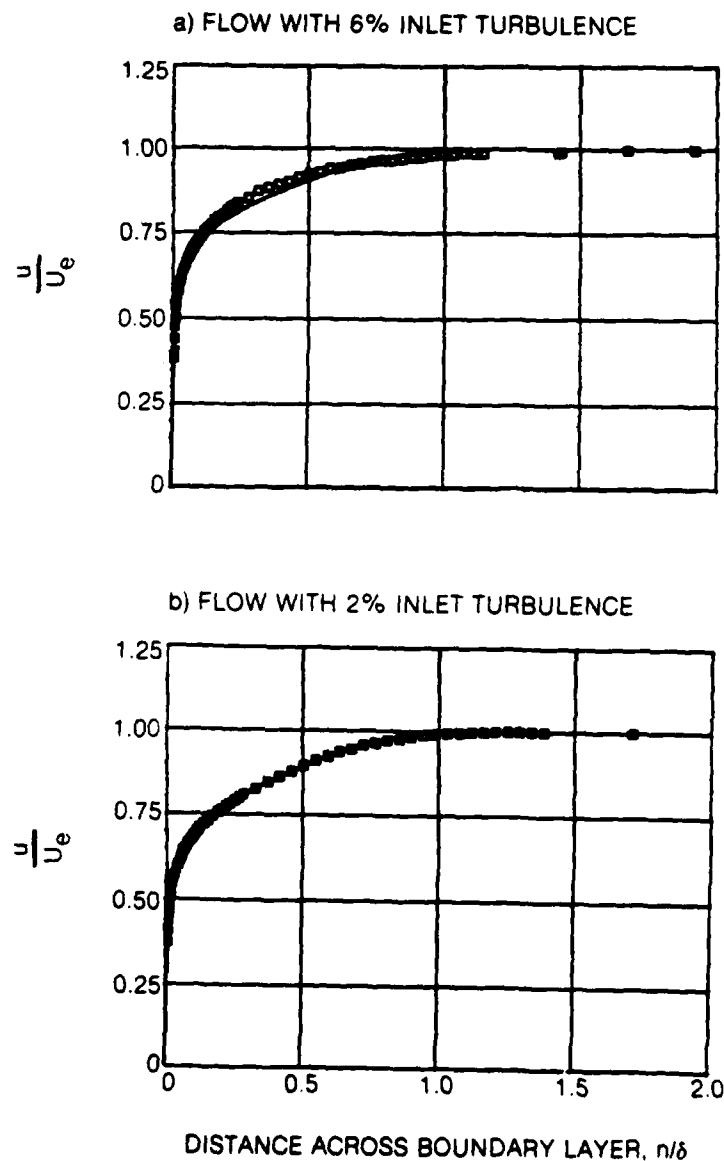
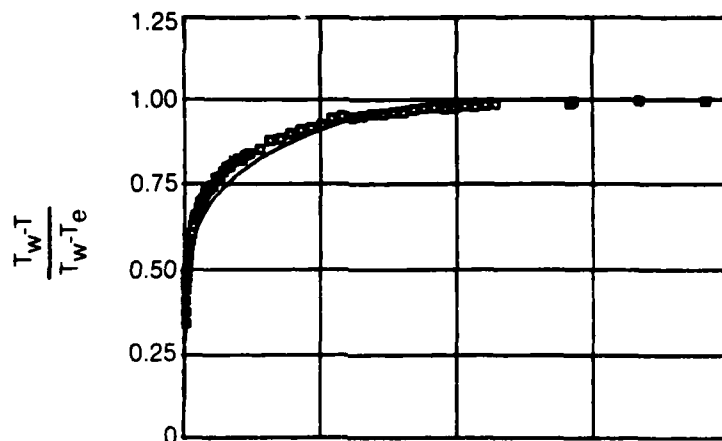


Figure 19. Comparison of Theoretical Mean Velocity With Experimental Data at $X = 68$ inches for Different Inlet Turbulence Levels

INLET TURBULENCE	δ (inches)	□ EXP. DATA, REF. 2 — PRESENT ANALYSIS
6%	1.256	
2%	1.055	

a) FLOW WITH 6% INLET TURBULENCE



b) FLOW WITH 2% INLET TURBULENCE

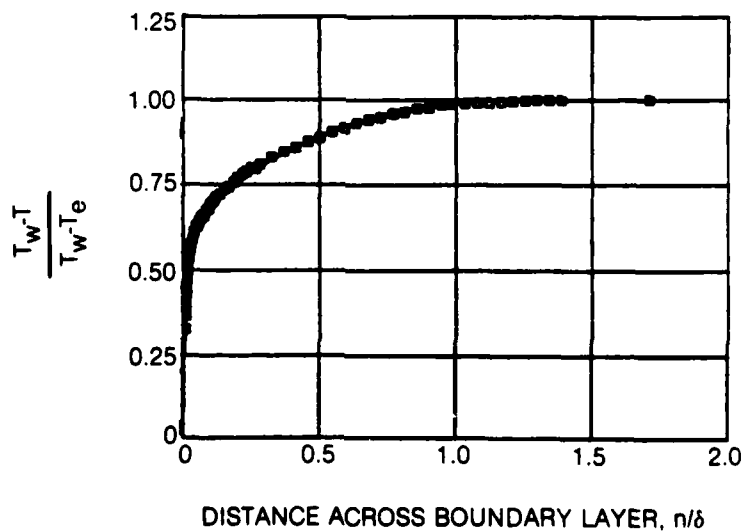


Figure 20. Comparison of Theoretical Mean Temperature with Experimental Data at $X = 68$ inches for Different Inlet Turbulence Levels

INLET TURBULENCE	δ (inches)	
6%	1.256	$\square$ EXP. DATA
2%	1.055	— PRESENT ANALYSIS

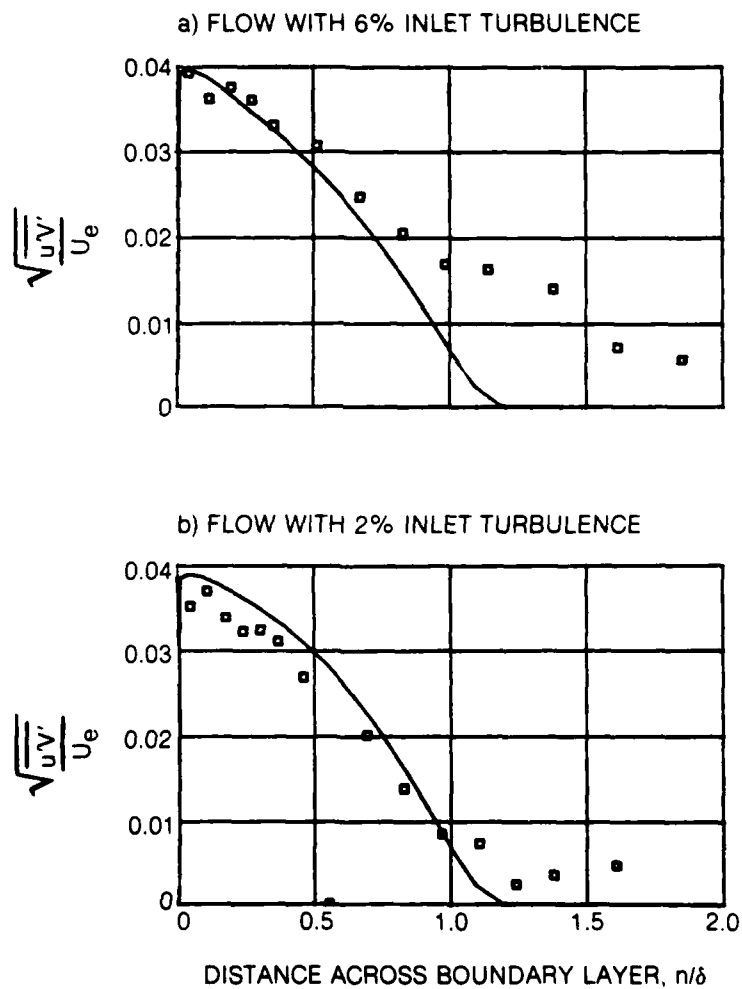


Figure 21. Comparison of Theoretical Reynolds Shear Stress with Experimental Data at $X = 68$ inches for Different Inlet Turbulence Levels

INLET TURBULENCE	δ (inches)	
6%	1.256	$\square$ EXP DATA
2%	1.055	— PRESENT ANALYSIS

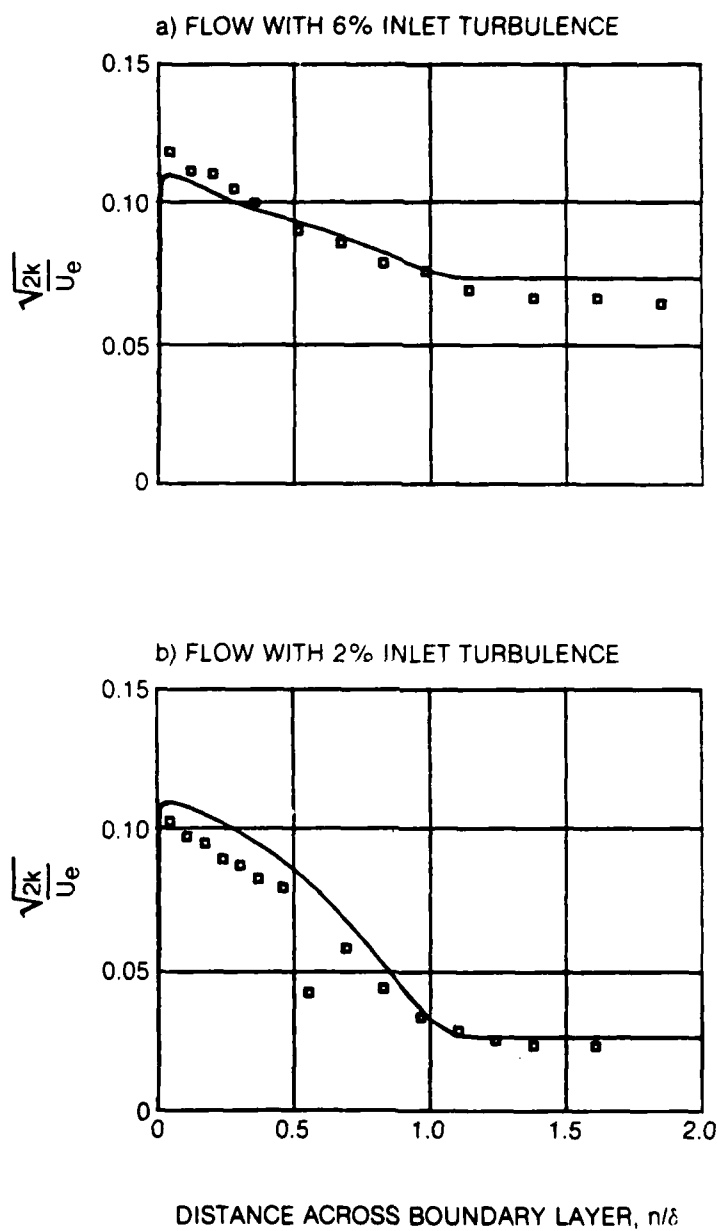


Figure 22. Comparison of Theoretical Turbulent Kinetic Energy with Experimental Data at $X = 68$ inches for Different Inlet Turbulence Levels

INLET TURBULENCE	δ (inches)	EXP. DATA	PRESENT ANALYSIS
6%	1.256		
2%	1.055		

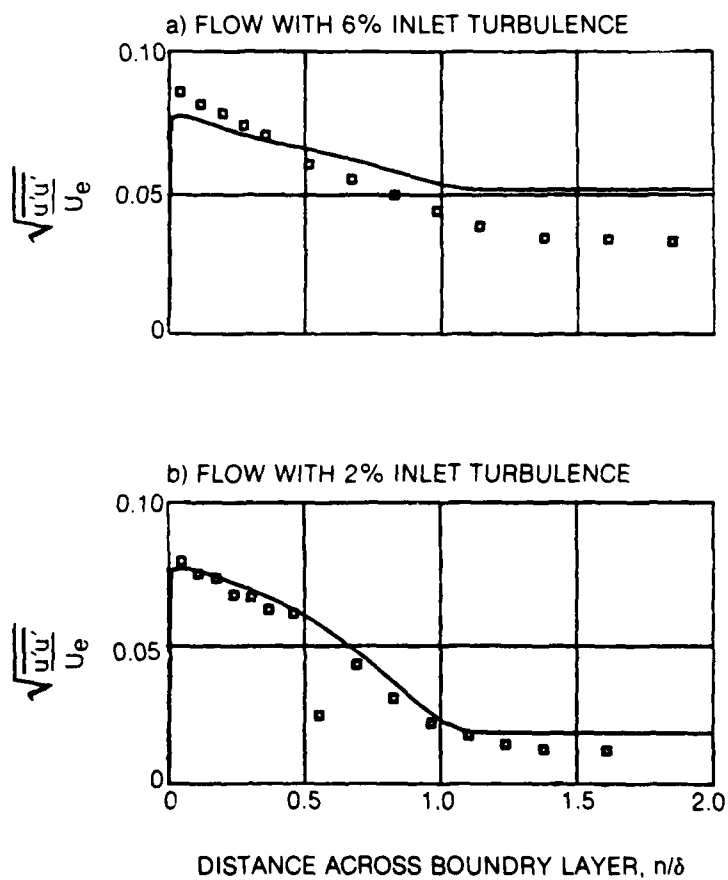


Figure 23. Comparison of Theoretical Component of Turbulent Intensity, $\sqrt{u'u'}$, with Experimental Data at $X = 68$ inches for Different Inlet Turbulence Levels

INLET TURBULENCE	δ (inches)	□ EXP. DATA — PRESENT ANALYSIS
6%	1.256	
2%	1.055	

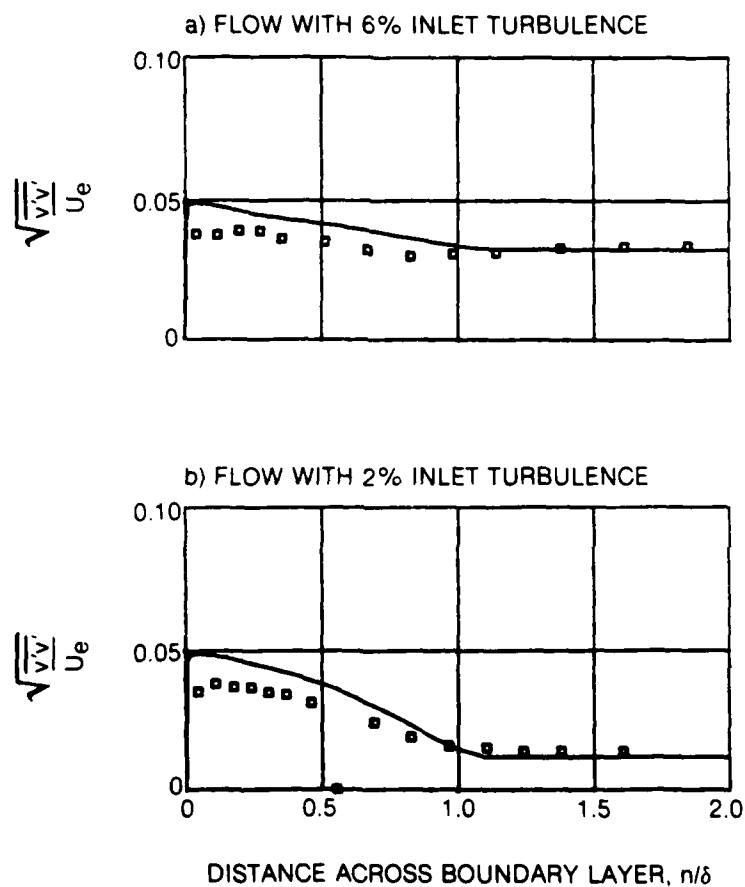


Figure 24. Comparison of Theoretical Component of Turbulent Intensity, $\sqrt{v'v'}$, with Experimental Data at $X = 68$ inches for Different Inlet Turbulence Levels

INLET TURBULENCE	δ (inches)	EXP. DATA
6%	1.256	— PRESENT ANALYSIS
2%	1.055	

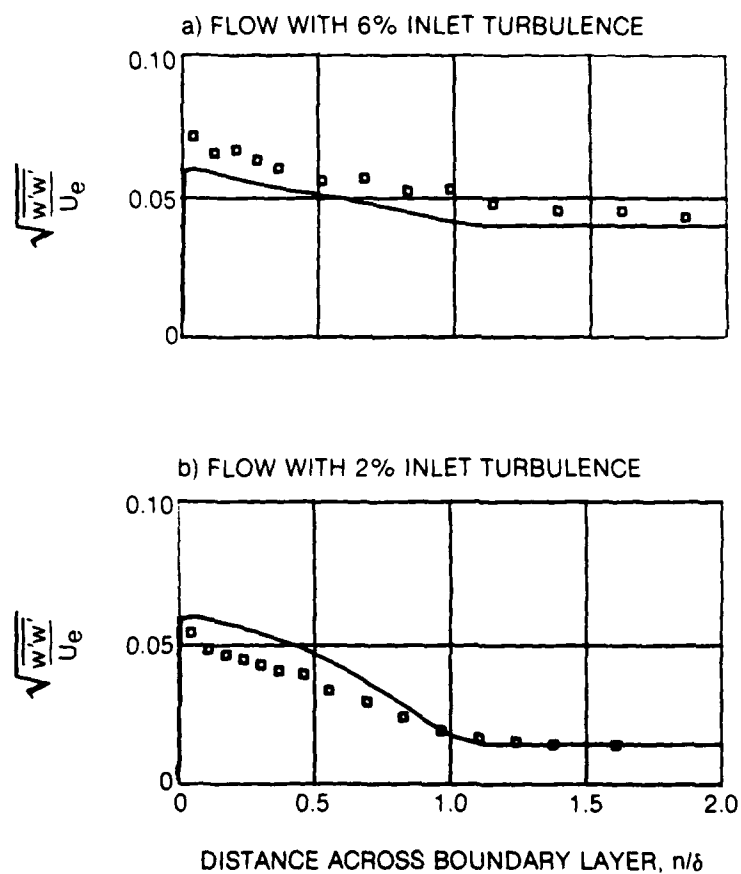


Figure 25. Comparison of Theoretical Component of Turbulent Intensity, $\sqrt{\overline{w'w'}}$, with Experimental Data at $X = 68$ inches for Different Turbulence Levels

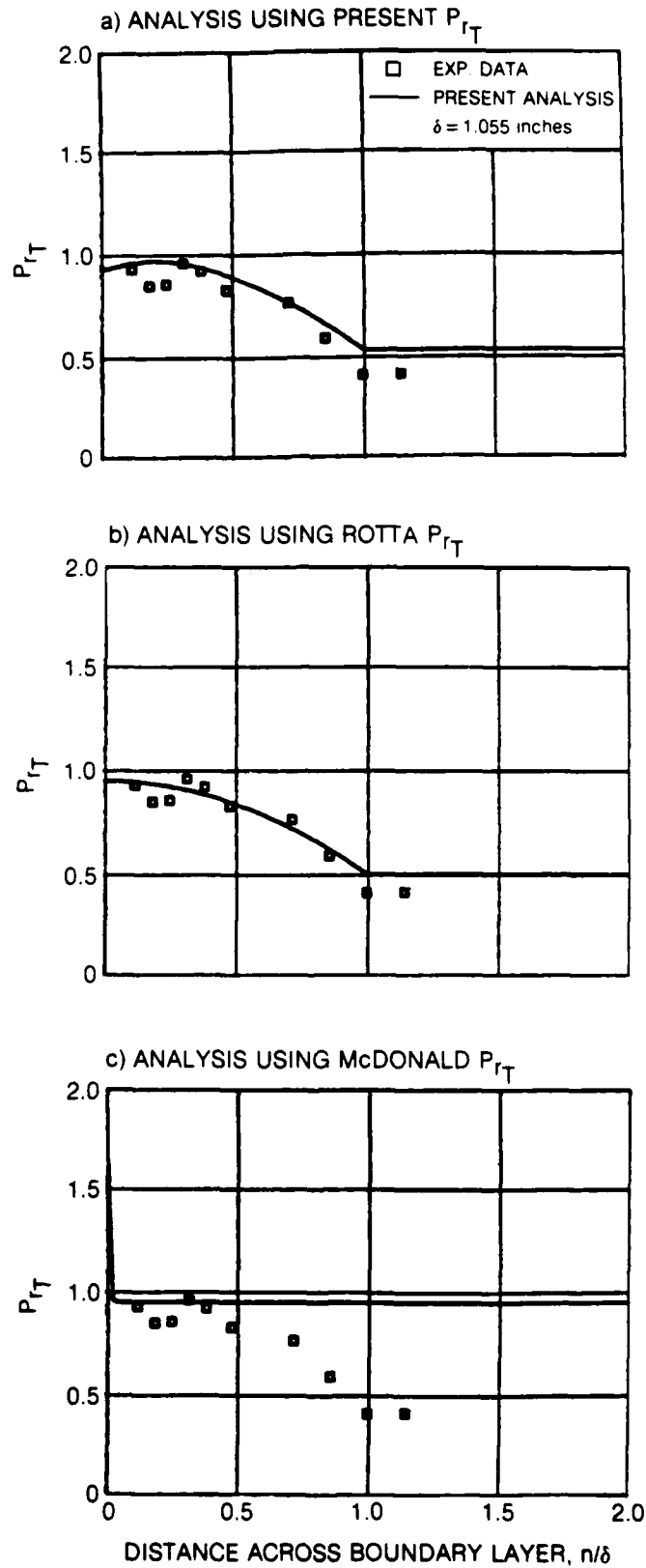


Figure 26a. Comparison of Theoretical Turbulent Prandtl Number with Experimental Data at $X = 68$ inches for 2% Inlet Turbulence Level

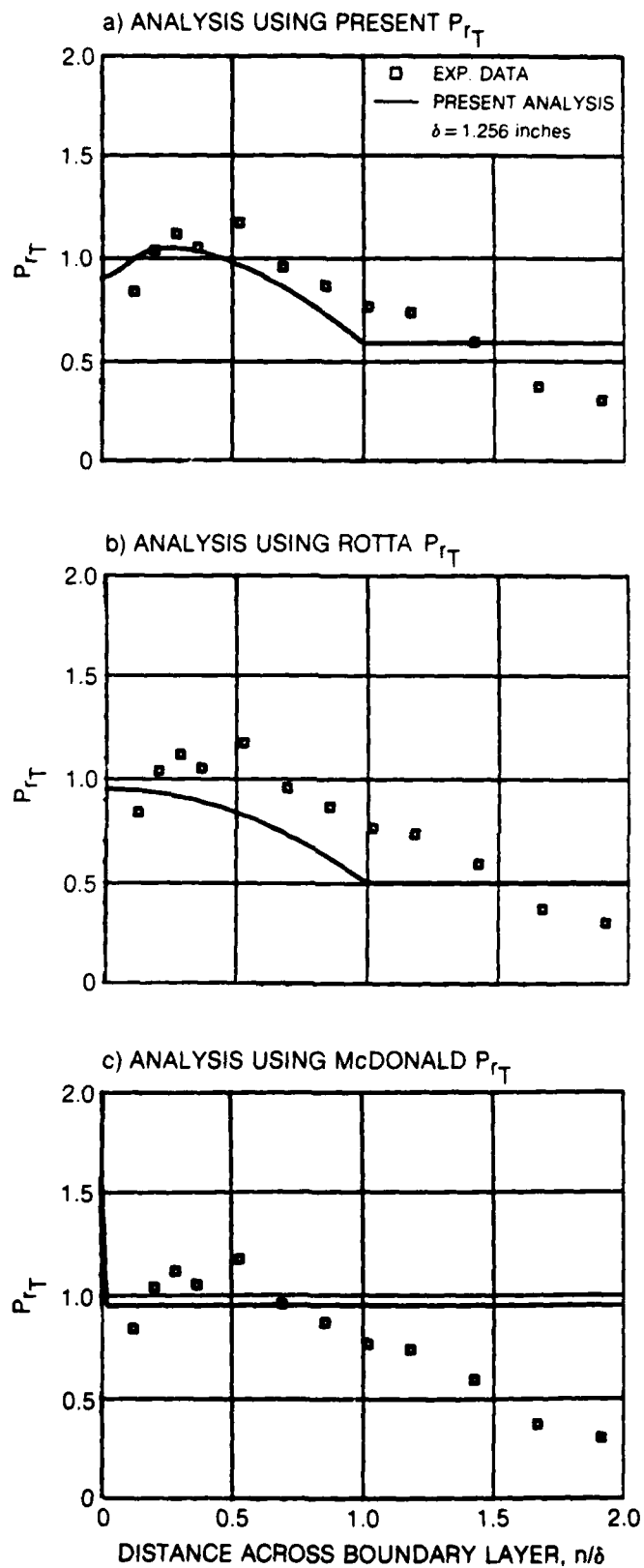


Figure 26b. Comparison of Theoretical Turbulent Prandtl Number with Experimental Data at $X = 68$ inches for 6% Inlet Turbulence Level

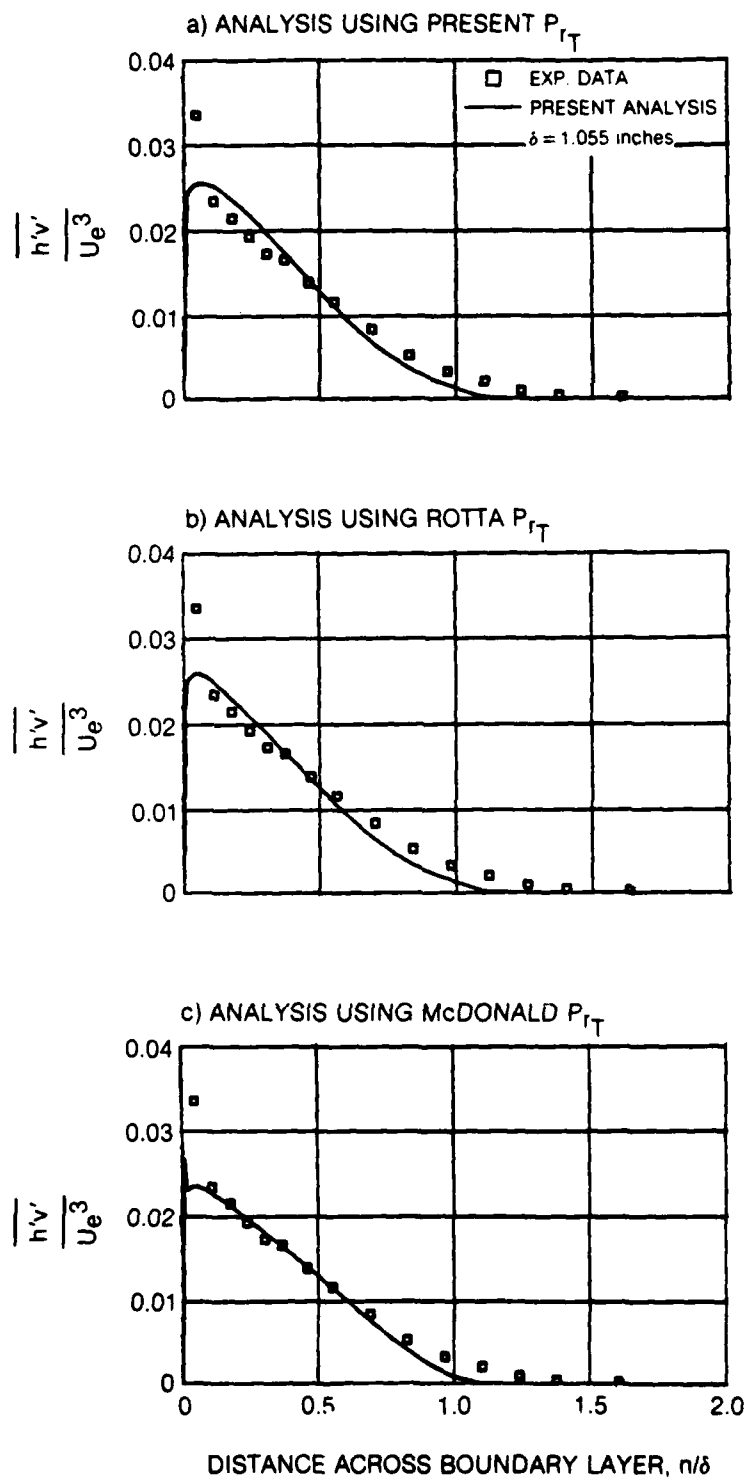


Figure 27a. Comparison of Theoretical Thermal Heat Flux with Experimental Data at $X = 68$ inches for a 2% Inlet Turbulence Level

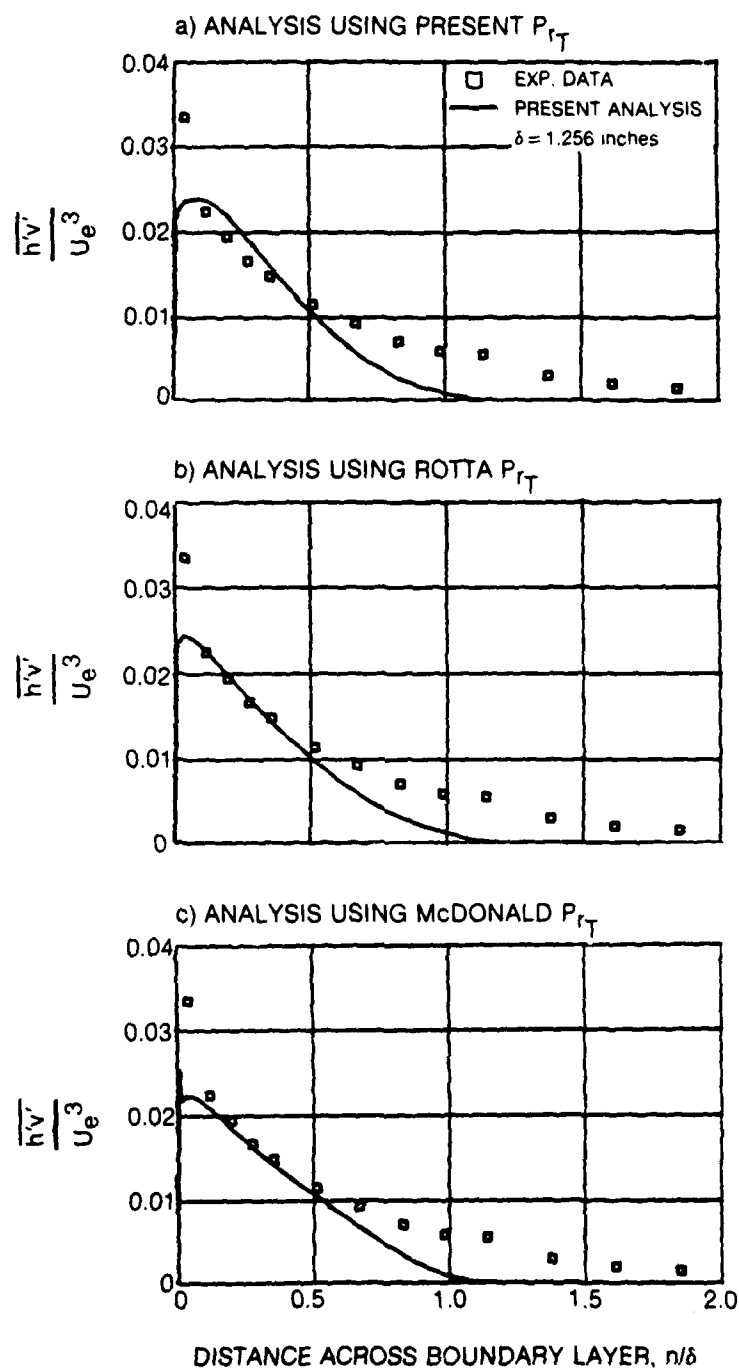


Figure 27b. Comparison of Theoretical Thermal Heat Flux with Experimental Data at $X = 68$ inches for a 6% Inlet Turbulence Level

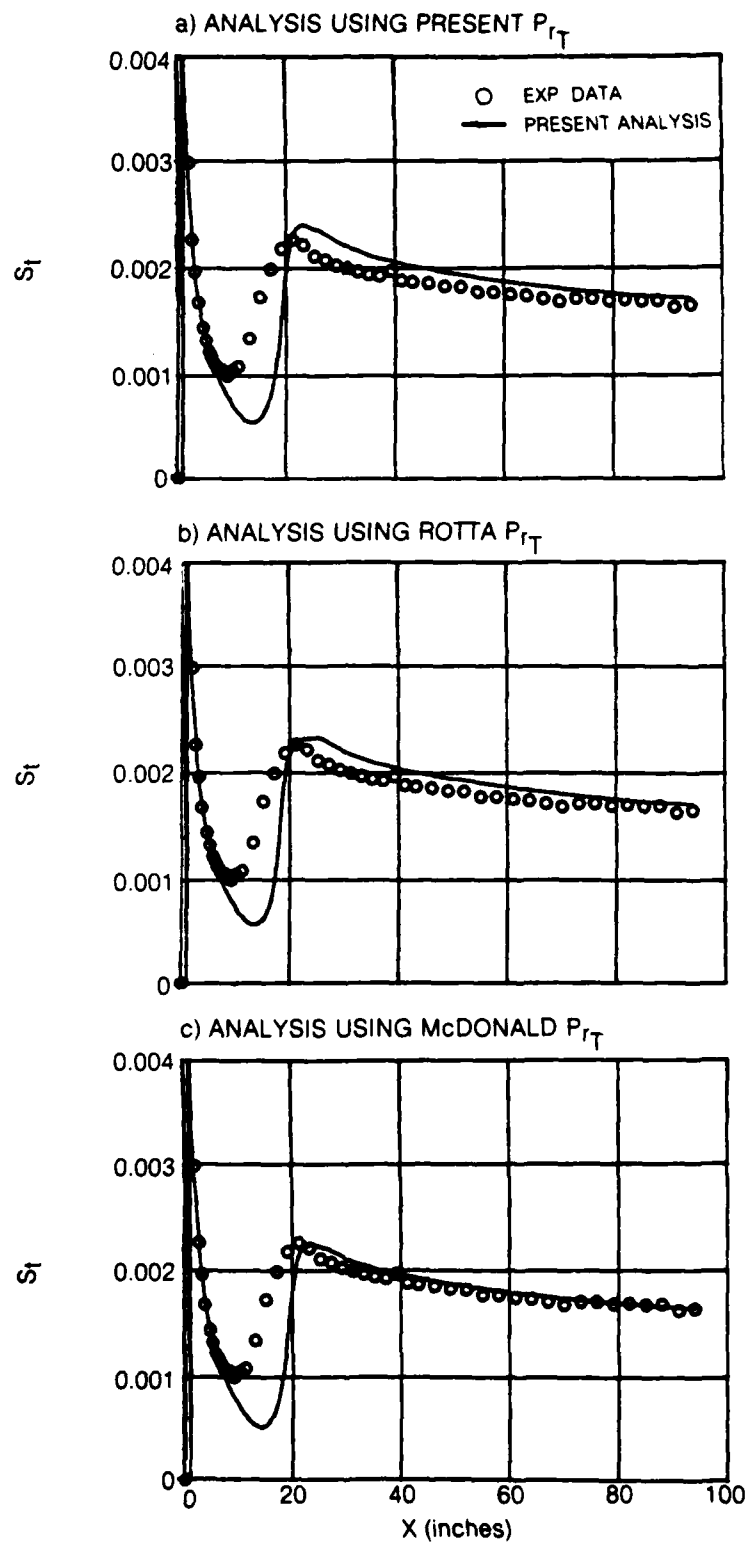


Figure 28a. Comparison of Theoretical Stanton Number with Experimental Data for 1% Inlet Turbulence Level

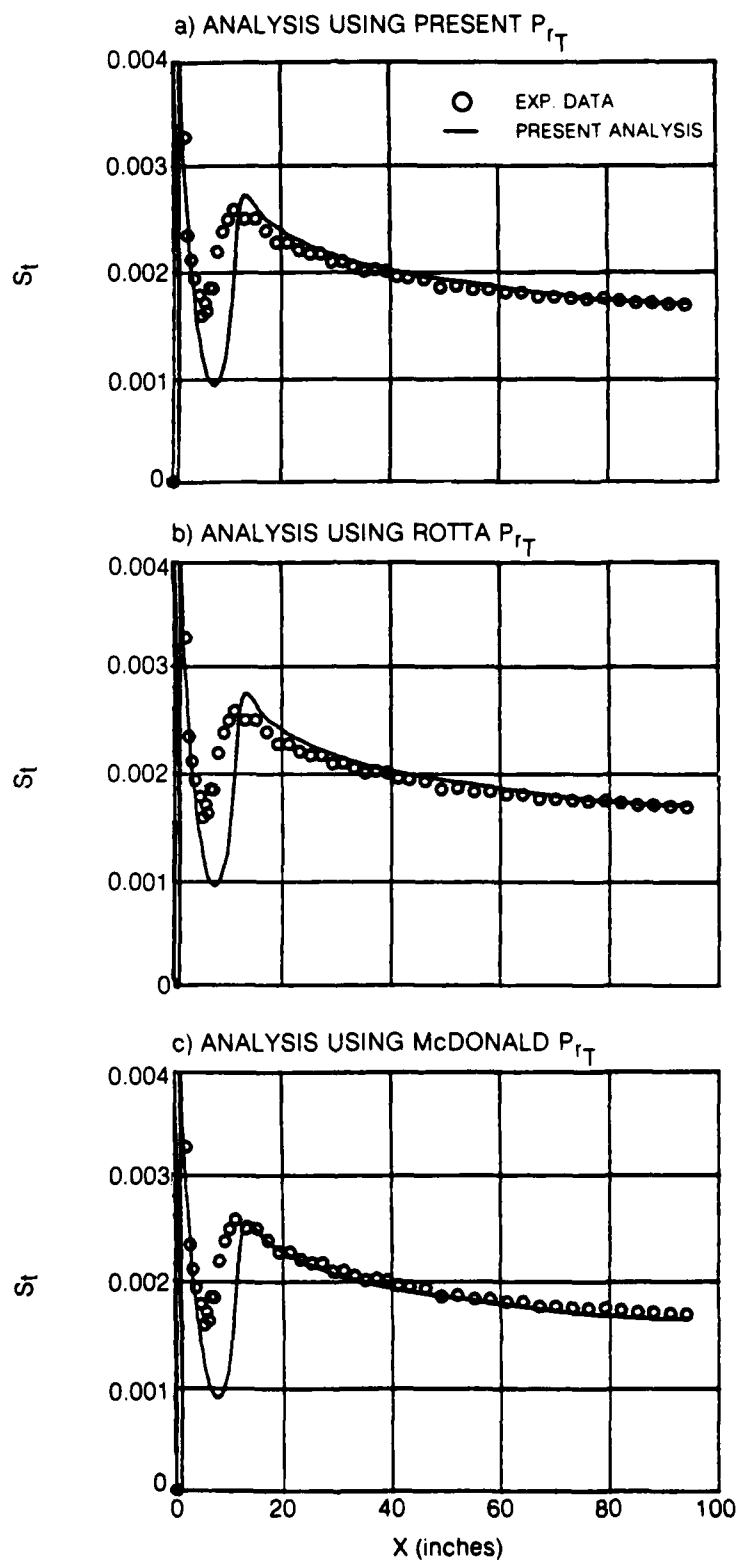


Figure 28b. Comparison of Theoretical Stanton Number with Experimental Data for 2% Inlet Turbulence Level

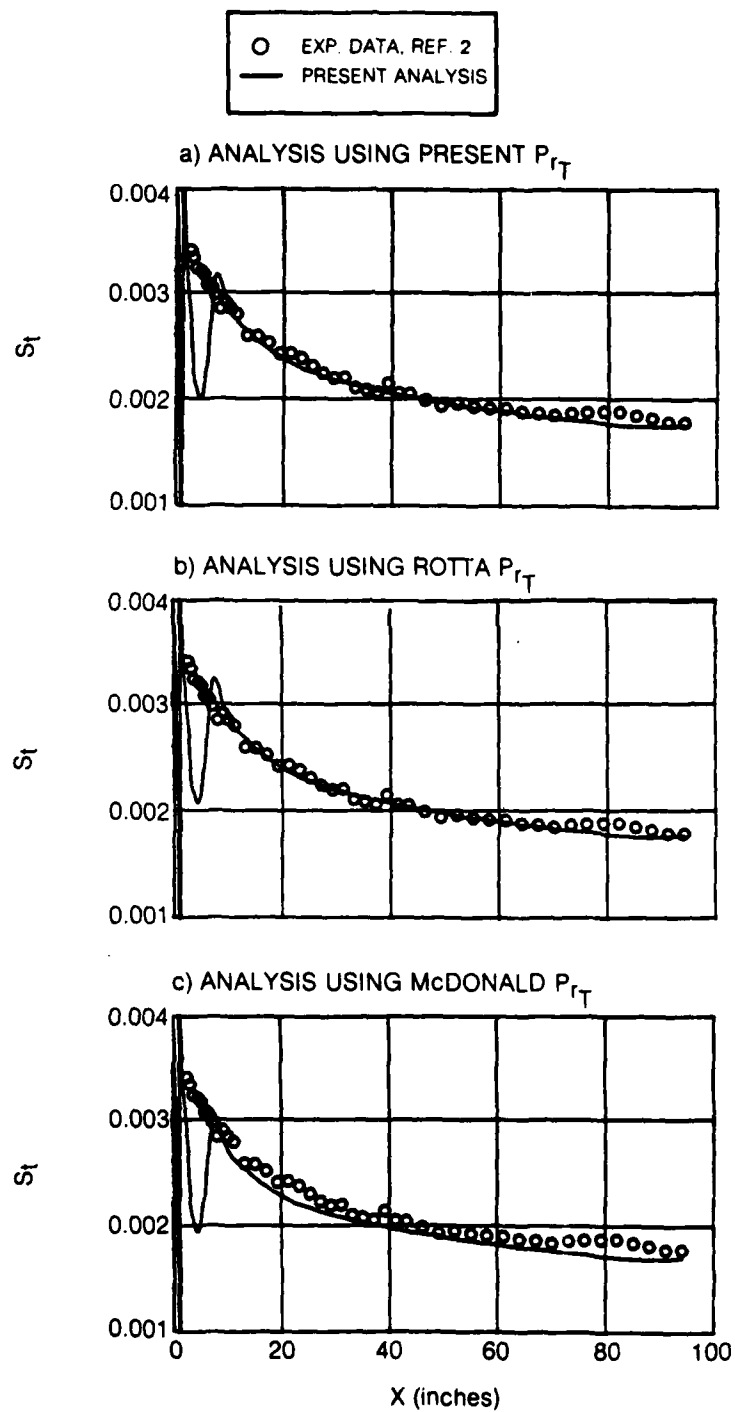


Figure 28c. Comparison of Theoretical Stanton Number with Experimental Data for 4% Inlet Turbulence Level

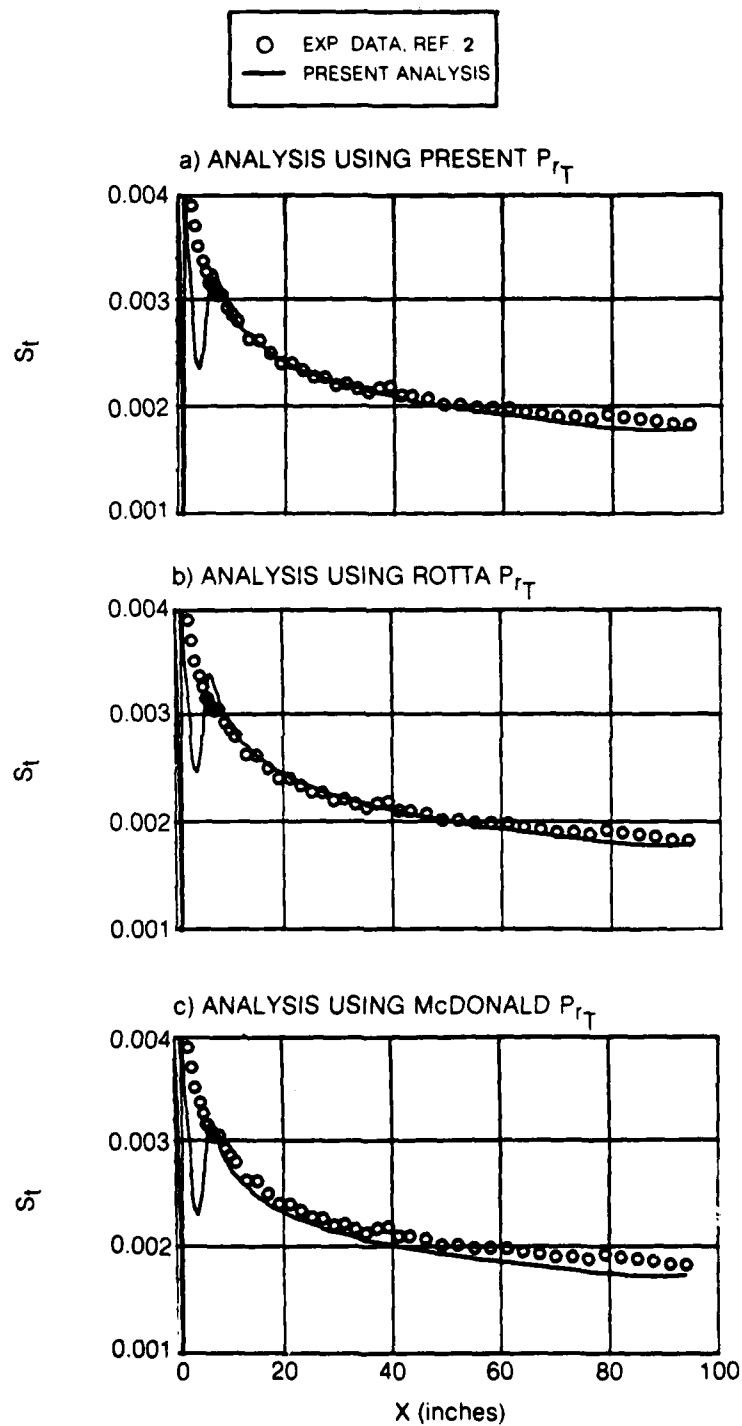


Figure 28d. Comparison of Theoretical Stanton Number with Experimental Data for 6% Inlet Turbulence Level

● ○ ▽ △	EXP. DATA, REF. 2
————	PRESENT ANALYSIS USING PRESENT P_{rT}
— · — ·	PRESENT ANALYSIS USING McDONALD P_{rT}

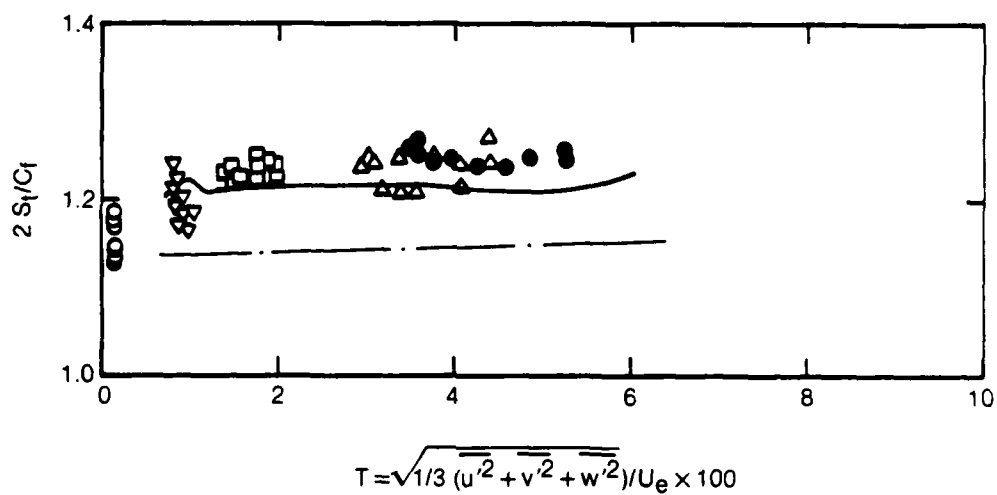


Figure 29. Theoretical Prediction of Reynolds Analogy Factor - Varying Edge Turbulence Levels

APPENDIX A - ERROR ANALYSIS

In this program mean velocity (U) profiles were determined by means of Pitot, single wire, x wire and 3 sensor hot wire probes. Mean temperatures (T) were measured by both 3 sensor hot wire and thermocouple probes. Fluctuating velocities and Reynolds stress distributions (u' , v' , w' , $u'v'$) were determined both with x wire and 3 wire techniques.

Assessment of absolute errors for the analog signals measured in this program would be a relatively straightforward matter. For example, the possible errors in measured pressures from the pitot probes or the recorded, digitized voltages from the hot-wire anemometer can be computed from the individual expected uncertainties. Computation of the absolute errors of the measured physical quantities (e.g., u' , v' , t'), however, is practically impossible because the true accuracy of factors such as Pitot probe wall proximity corrections, Pitot probe turbulence corrections, hot wire wall radiation effects, high turbulence sensor cross-talk, etc. are unknown. For this reason the uncertainties for the various quantities measured for this program will be assessed by (1) comparing the measured quantities with independently determined or computed results or (2) comparisons of like quantities measured using different probes and instrumentation techniques.

Mean velocity and temperature profile data obtained with different measurement techniques (four techniques for velocity, two techniques for temperature) are presented in Fig. A-1. These profile data were all obtained at $X = 84$ inches at three levels of free-stream turbulence. In-depth descriptions of the Pitot and thermocouple probes and data systems used for the mean velocity and temperature profiles are provided in Ref. 2. These probes were designed and constructed specifically for these types of boundary layer flows and a number of well established near-wall correction terms (see Ref. 2) were applied to the data. In addition, a number of comparison checks (see Refs. 1 and 2) showed that these mean profile data were very accurate. For these reasons the mean velocity profiles from the Pitot probe and the mean temperature profiles from the thermocouple probe were selected as the "true" respective profiles. For the data of Fig. A-1 all the other velocity profile measurements were compared to the Pitot probe data while the triple sensor temperature data were compared to the temperature profiles from the thermocouple probe.

An examination of the mean velocity profile data of Fig. A-1 indicates that 85 percent of all the measurements fell within ± 3 percent of the "true" Pitot profile. Only one set of data, the vertical x probe results for $Te = 0.2$ percent, had any discrepancies larger than 5 percent. Discrepancies in the mean temperature profile measurements were slightly larger than those for the velocity measurements with only 70 percent of the measurements falling within ± 5 percent of the thermocouple probe profile. The 3 sensor probe temperature data also showed a clear bias to read slightly lower temperatures than the thermocouple probe. The relatively larger errors for the temperature profiles as compared to the velocity profiles is not surprising. Because of the relatively large size of the 3 sensor probes they span a gradient of both velocity and temperature in the boundary layer flow. The data reduction system

is forced to assume that a single effective velocity and flow temperature apply over the entire probe.

Plots of the average bias $\overline{(x_i - \bar{x})}$ and standard error $\sqrt{\overline{(x_i - \bar{x})^2}}$ (x_i is the measured quantity and $\bar{x}$ is the "true" quantity at a given profile location) for the various profiles are given in Fig. A-2. These results are plotted as a function of the ratio between the overall boundary layer thickness and the probe sensor height (h). The overall profile errors are plotted in Fig. A-2, were largest for the thinnest boundary layers (with the relatively steepest velocity and temperature gradients). In addition, the largest local bias errors of Fig. A-1 were located near the wall where the steepest gradients exist. This result has led to the conclusion that the local gradients across the sensor arrays were a significant cause of the discrepancies between the x-type probe mean data and the "true" profiles.

Distributions of the various measurements of the streamwise and vertical velocity fluctuations and the Reynolds stress distributions are given in Figs. A-3 and A-4. No "true" or best distributions of these quantities are known for these profiles and so the data at a given location in a profile were compared with the average of all the like data taken at that location. The plots of Figs. A-3 and A-4, then, show distributions of the inconsistencies between the various measurement techniques for the various profiles. The agreement between the separate measurements for u'/U_e and v'/U_e were generally very good ($\pm \approx 1/2$ percent for u'/U_e and $\pm \approx 1/5$ percent for v'/U_e). If the average levels of u'/U_e and v'/U_e are approximated as 0.06 and 0.04 respectively the above inconsistencies are equivalent to ± 8 percent and ± 5 percent uncertainties in the fluctuating velocities (u' and v') themselves. Note that for the u'/U_e plot of Fig. A-3 data were included for a "single horizontal wire". These particular data were obtained with an analog data system consisting of a polynomial linearizer and a true RMS voltmeter. All the other data of Fig. A-3 were obtained with the previously described analog-digital system. The consistency between the measurements for these two very different techniques is excellent. The largest inconsistencies were observed for the Reynolds stress distributions of Fig. A-4. This is not at all surprising as it is far more difficult to measure correlated than single fluctuating quantities. For these Reynolds stress data a ± 15 percent inconsistency band encompasses nearly all the measurements.

Plots of the average "bias" and "standard error" for the fluctuating quantities of Fig. II-3 and II-4 are presented in Fig. A-5. The overall profile errors for the stress measurements were clearly much larger than the errors for the individual velocity fluctuations. Unlike the mean profile results of Fig. A-2 the uncertainties of the fluctuating quantities for the various boundary layer thicknesses were nearly constant.

TYPE PROBE	SINGLE HORIZ	TRI-X	X-H	X-V	T_e %	02	14	39
SYMBOL	○	□	▽	△	SYMBOLS	OPEN	HALF FILLED	SOLID

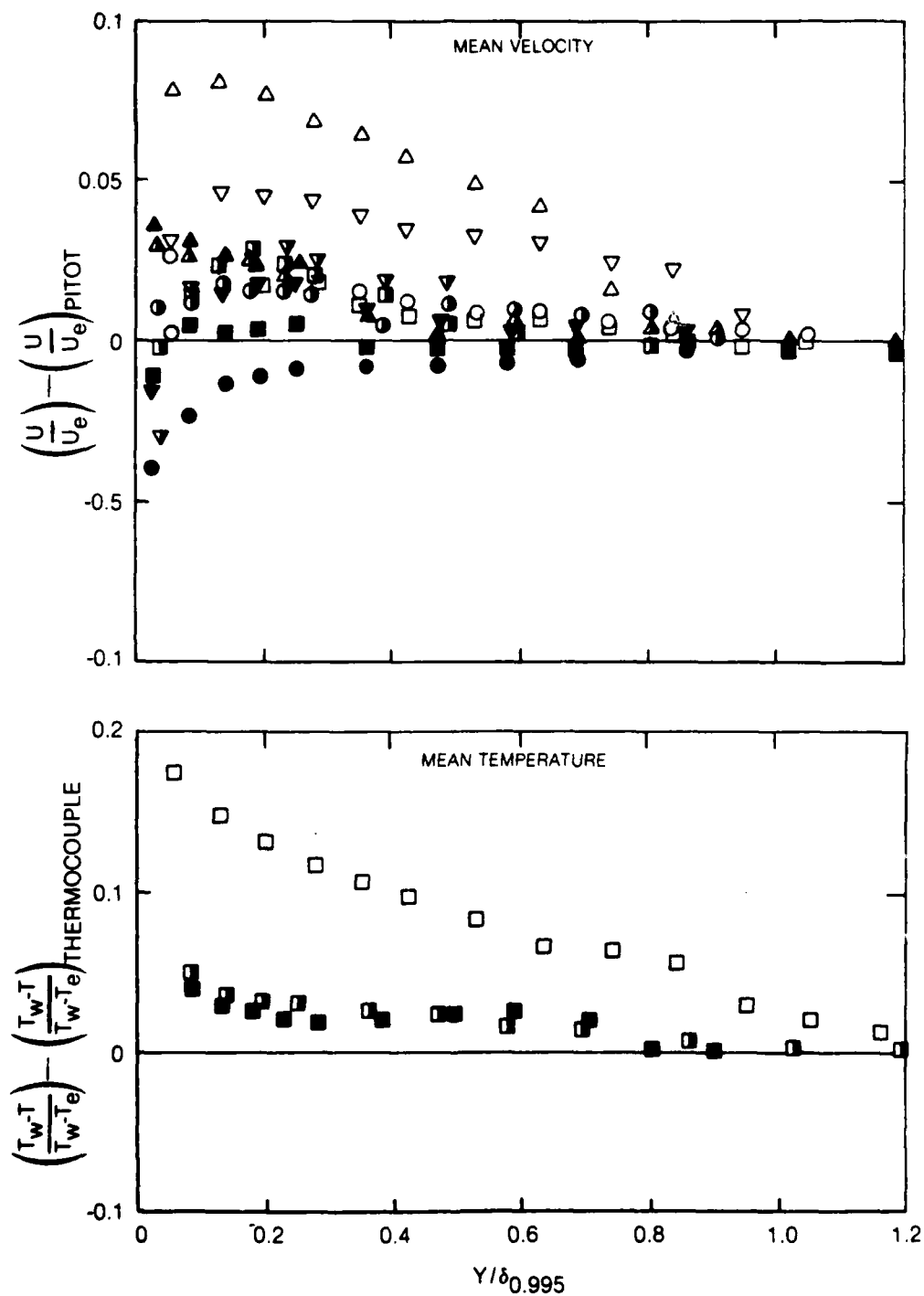


Figure A-1. Discrepancies Between Various Local Measurements of Mean Velocity and Temperature Profile Data

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THE EFFECTS OF FREE-STREAM TURBULENCE ON THE TURBULENCE
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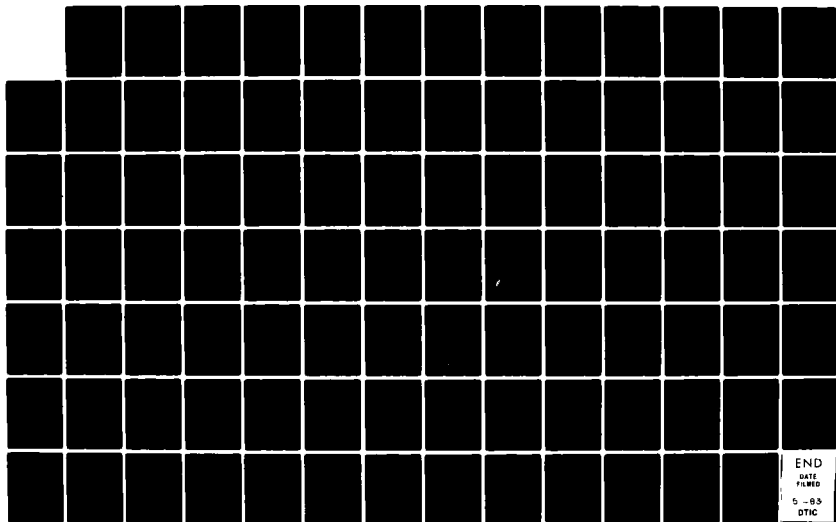
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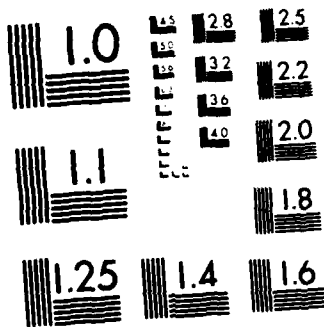
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NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

MEASURED QUANTITY	U/U_e			T_w-T/T_w-T_e
TYPE PROBE	TRI-X	X-H	X-V	TRI-X
SYMBOL	□	▽	△	◇

T_e %	0.2	1.4	3.9
SYMBOLS	OPEN	HALF FILLED	SOLID

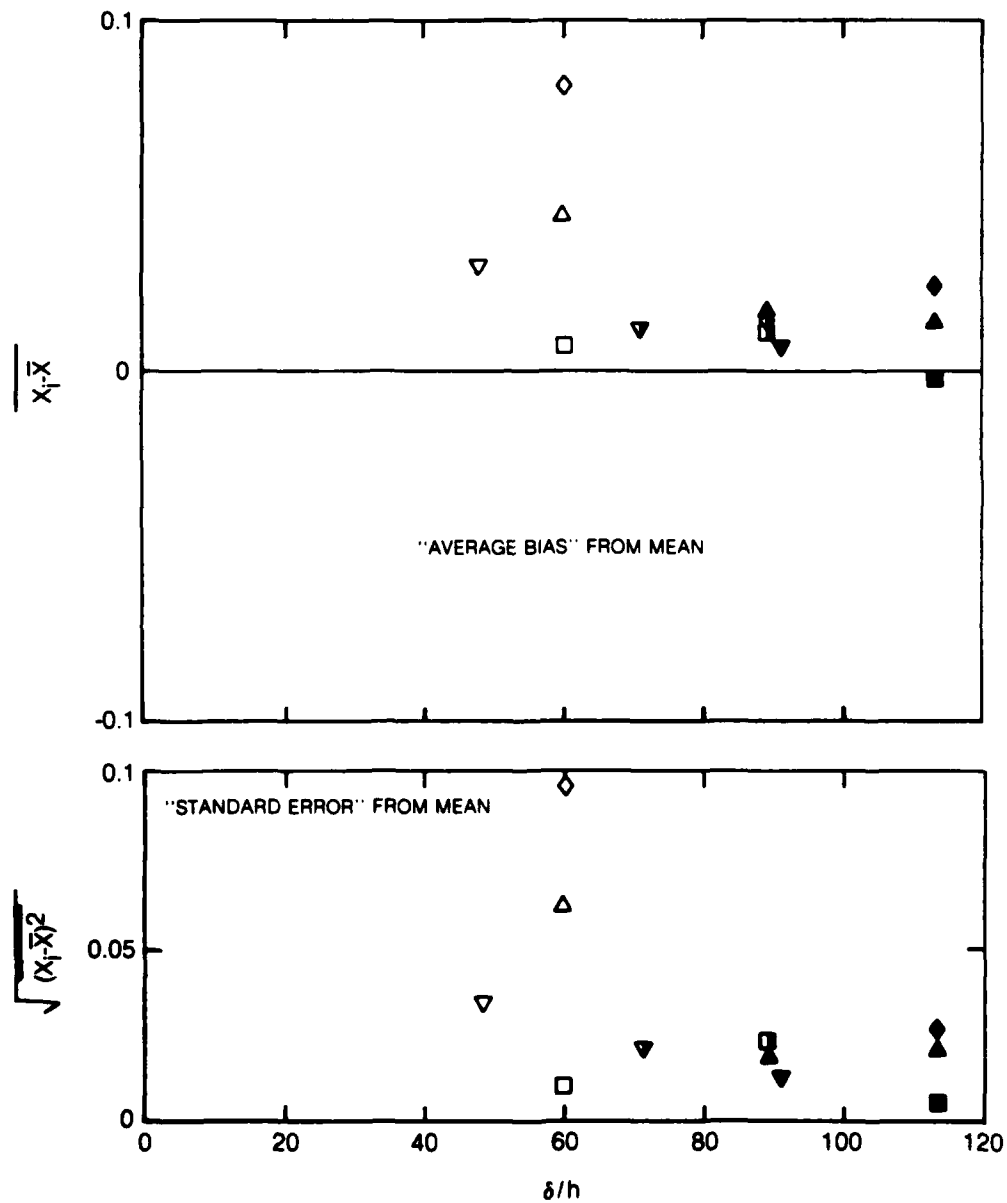


Figure A-2. Overall Discrepancies Between Different Mean Measurement Techniques for Various Profiles

TYPE PROBE	SINGLE HORIZ	TRI-X	X-H	X-V ₁	X-V ₂
SYMBOL	○	□	▽	△	▲

T _e %	0.2	1.4	3.9
SYMBOL	OPEN	HALF FILLED	SOLID

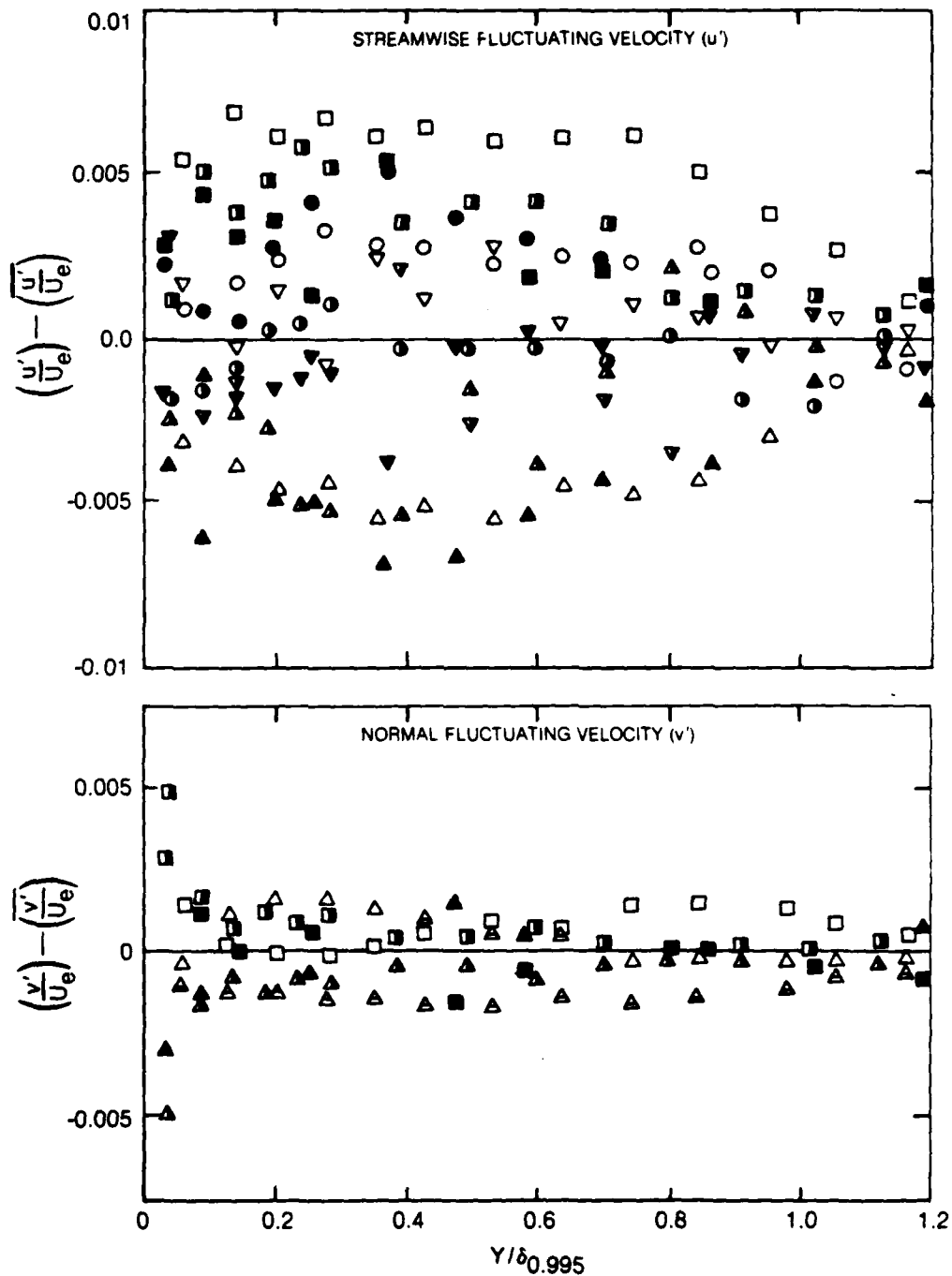


Figure A-3. Discrepancies Between Various Local Measurements of Fluctuating Velocity Components

TYPE PROBE	TR-X	X-V ₁	X-V ₂
SYMBOL	○	△	▲

T _e %	0.2	0.14	3.9
SYMBOL	OPEN	HALF FILLED	SOLID

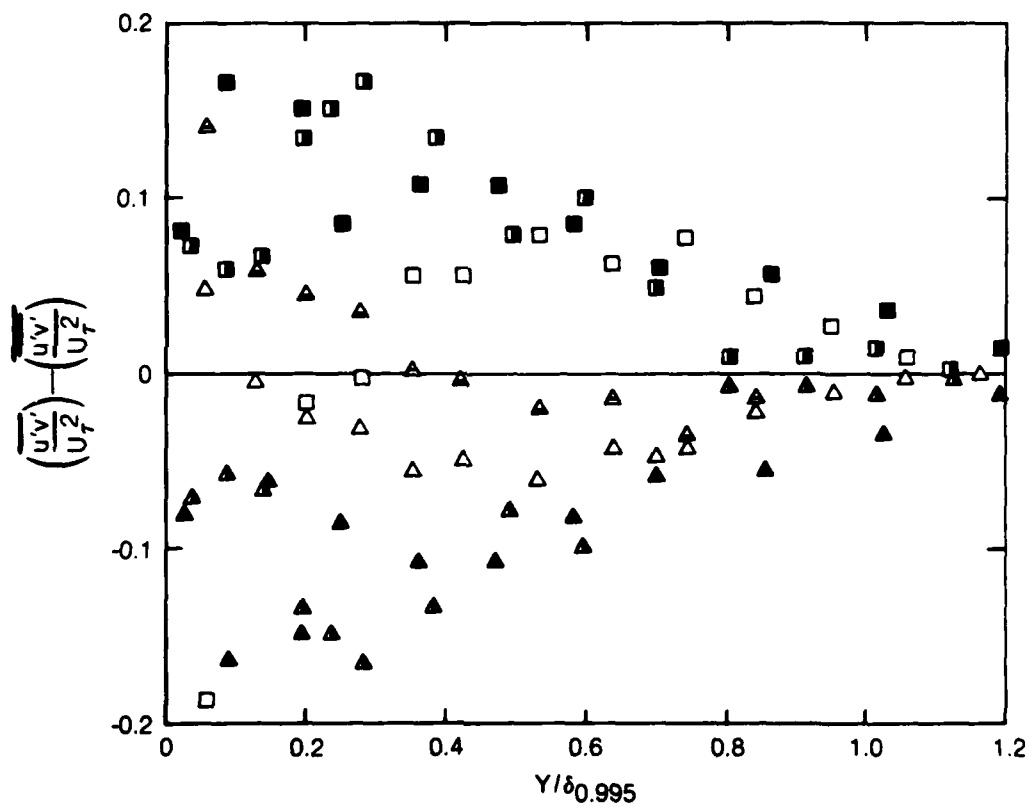


Figure A-4. Discrepancies Between Various Local Turbulent Shear Stress Measurements

MEASURED QUANTITY	u'/U_e			v'/U_e		$\overline{u'v'}/U_e^2$	
TYPE PROBE	TRI-X	X-H	X-V	TRI-X	X-V	TRI-X	
SYMBOL	$\square$	∇	$\triangle$	$\diamond$	$\triangledown$	∇	$\circ$

T_e %	0.2	1.4	3.9
SYMBOLS	OPEN	HALF FILLED	SOLID

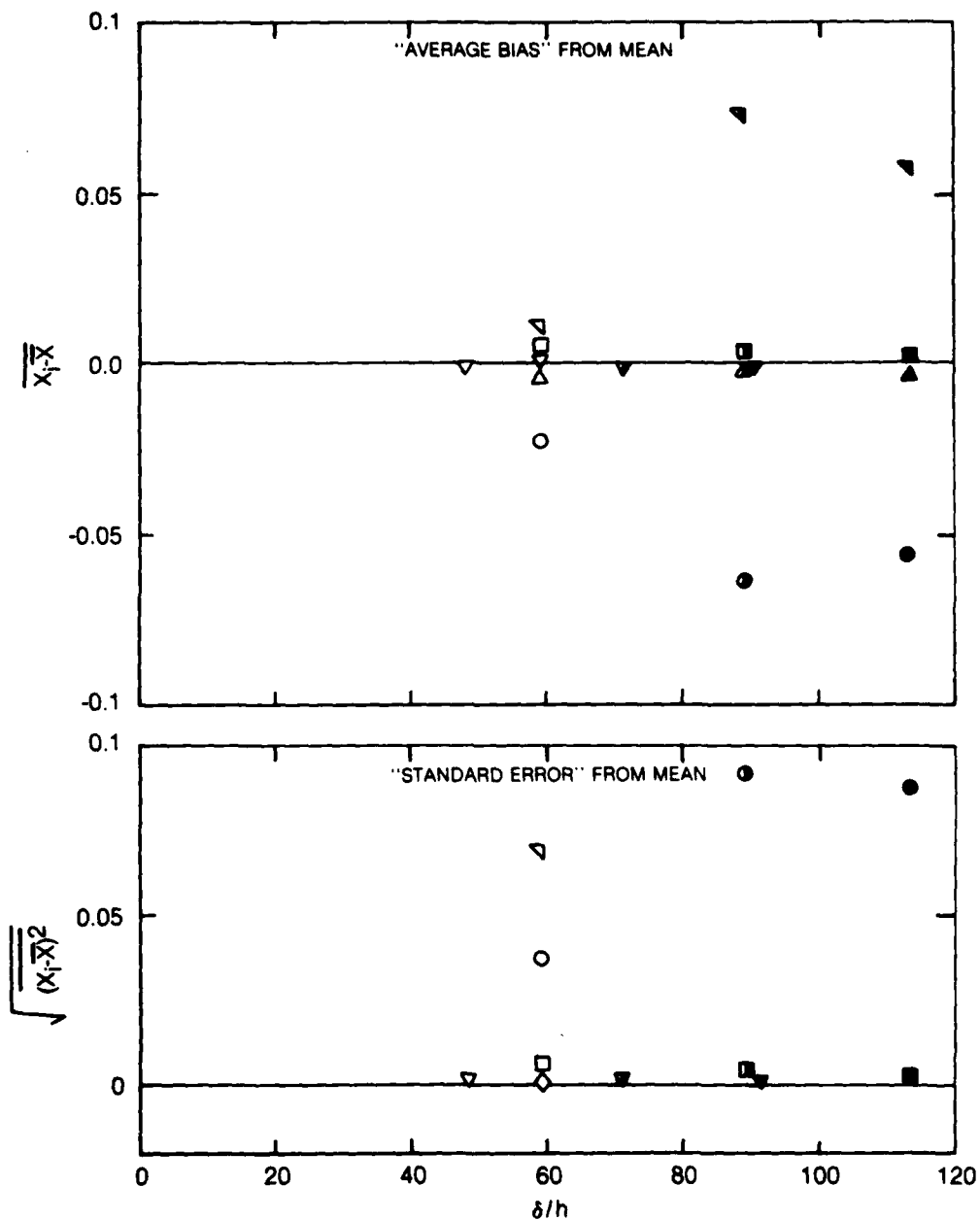


Figure A-5. Overall Discrepancies Between Different Fluctuating Measurement Techniques for Various Profiles

APPENDIX B - EXPERIMENTAL PROFILE DATA

All data for each profile are grouped together as follows:

- a) mean profile data
- b) mean profile data tabulation
- c) boundary layer property tabulation
- d) fluctuating profile plots (A-E)
- e) fluctuating profile data tabulation (A-B).

The profile data are presented in the following order:

	<u>X</u>	<u>Te%</u>
1	52	0.2
2	68	0.2
3	84	0.2
4	52	1.8
5	68	1.6
6	84	1.4
7	52	4.7
8	68	4.2
9	84	3.9

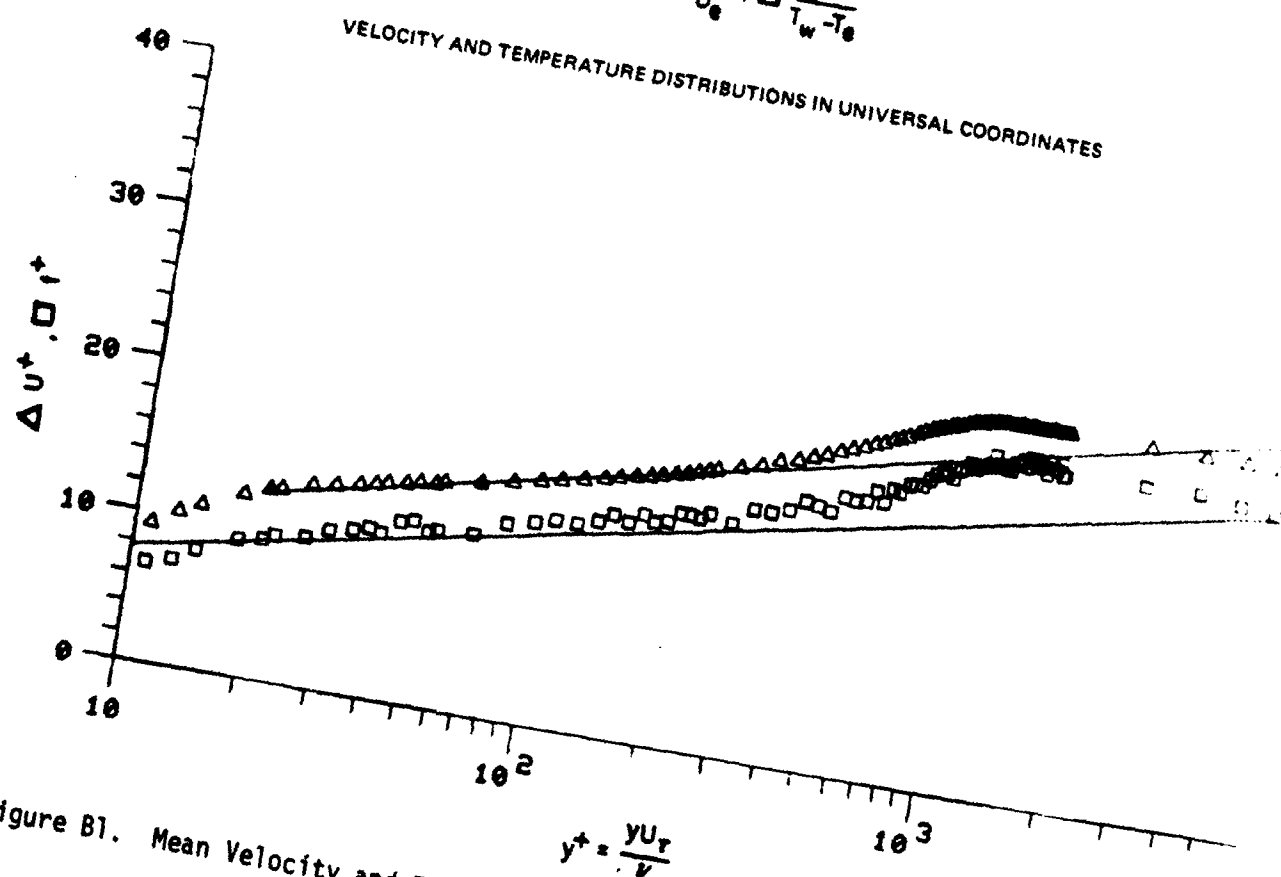
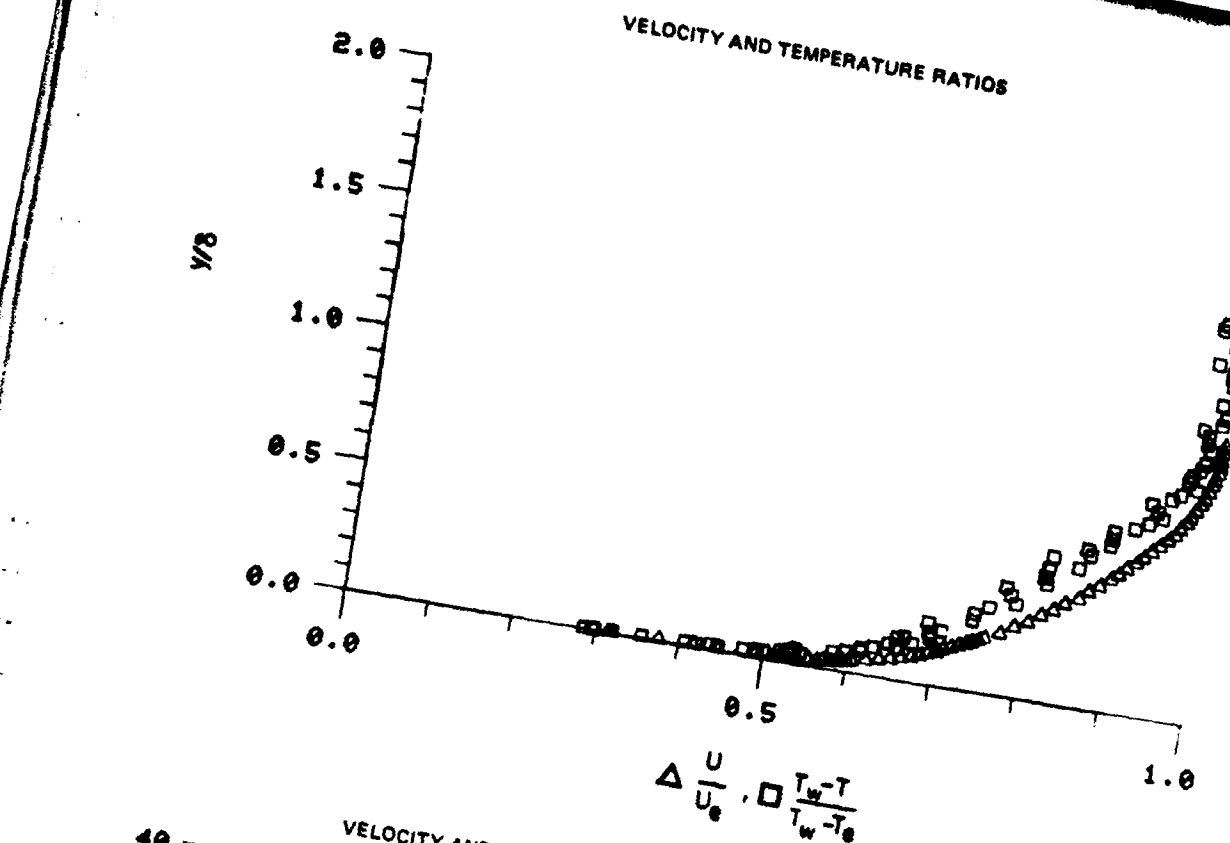


Figure B1. Mean Velocity and Temperature Profiles $x = 52$ in., $Te = 0.2\%$

Mean Profile Data

x = 52 in., Te = 0.2%

N	Y	Y/T	U	T	U/UE	THETA	L-UE	U(1)	T(1)	Y(1)
1	1	1	1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6	6	6	6
7	7	7	7	7	7	7	7	7	7	7
8	8	8	8	8	8	8	8	8	8	8
9	9	9	9	9	9	9	9	9	9	9
10	10	10	10	10	10	10	10	10	10	10
11	11	11	11	11	11	11	11	11	11	11
12	12	12	12	12	12	12	12	12	12	12
13	13	13	13	13	13	13	13	13	13	13
14	14	14	14	14	14	14	14	14	14	14
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37	37	37	37	37	37	37	37	37	37	37
38	38	38	38	38	38	38	38	38	38	38
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40	40	40	40	40	40	40	40	40	40	40
41	41	41	41	41	41	41	41	41	41	41
42	42	42	42	42	42	42	42	42	42	42
43	43	43	43	43	43	43	43	43	43	43
44	44	44	44	44	44	44	44	44	44	44
45	45	45	45	45	45	45	45	45	45	45
46	46	46	46	46	46	46	46	46	46	46
47	47	47	47	47	47	47	47	47	47	47
48	48	48	48	48	48	48	48	48	48	48
49	49	49	49	49	49	49	49	49	49	49
50	50	50	50	50	50	50	50	50	50	50
51	51	51	51	51	51	51	51	51	51	51
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71	71	71	71	71	71	71	71	71	71	71
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74	74	74	74	74	74	74	74	74	74	74
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82	82	82	82	82	82	82	82	82	82	82
83	83	83	83	83	83	83	83	83	83	83
84	84	84	84	84	84	84	84	84	84	84
85	85	85	85	85	85	85	85	85	85	85
86	86	86	86	86	86	86	86	86	86	86

Table B1

RUN NO. 3. POINT 3.
 BOLNDARY LAYER PROPERTIES

	LINEAR INTERPOLATION TO WALL	STANDARD SUBLAYER FUNCTION FROM WALL TO $Y^+=35$
FREE STREAM VELOCITY	98.922	98.922
FREE STREAM TEMPERATURE	71.150	
WALL TEMPERATURE	87.410	
WALL HEAT FLUX	.05120	
FREE STREAM DENSITY	.07523	
FREE STREAM KINEMATIC VISCOSITY	.0001628	
DENSITY OF FLUID AT WALL	.07300	
KINEMATIC VISCOSITY OF FLUID AT WALL	.0001717	
WALL/FREE STREAM DENSITY RATIO	.97028	
LOCATION REYNOLDS NUMBER (REX)	2633499.75	
INPUT VALUE OF VELOCITY DELTA	.61000	
INPUT VALUE OF TEMPERATURE DELTA	.67000	
CALCULATED DELTA		.60504
DELTA 99.5% INPUT	.00000	
DISPLACEMENT THICKNESS (DELSTAR)	.09026	.09063
MOMENTUM THICKNESS (THETA)	.06280	.06280
ENERGY-DISSIPATION THICKNESS	.11090	.11078
ENTHALPY THICKNESS	.00274	.00273
SHAPE FACTOR 12 (DELSTAR/THETA)	1.43730	1.44315
SHAPE FACTOR 32 (ENERGY/THETA)	1.76594	1.76410
MOMENTUM THICKNESS REYNOLDS NUMBER	3180.47	3180.34
DISPLACEMENT THICKNESS REYNOLDS NUMBER	4571.29	4589.72
SKIN FRICTION COEFFICIENT	.003195	
FRICTION VELOCITY	4.01412	
LAW OF THE WALL CONSTANT (K)	.41000	
LAW OF THE WALL CONSTANT (C)	5.00000	
WAKE STRENGTH		.49082
CLAUSEPS 'DELTA' INTEGRAL	-2.07555	-2.16672
CLAUSEPS 'G' INTEGRAL	14.68922	14.91446
DISPLACEMENT THICKNESS - CONSTANT DENSITY	.08589	.08792
MOMENTUM THICKNESS - CONSTANT DENSITY	.06337	.06336
SHAPE FACTOR 12 - CONSTANT DENSITY	1.35544	1.36758

LOCATION -X- 52.00000

Te = 0.2%

Table B2

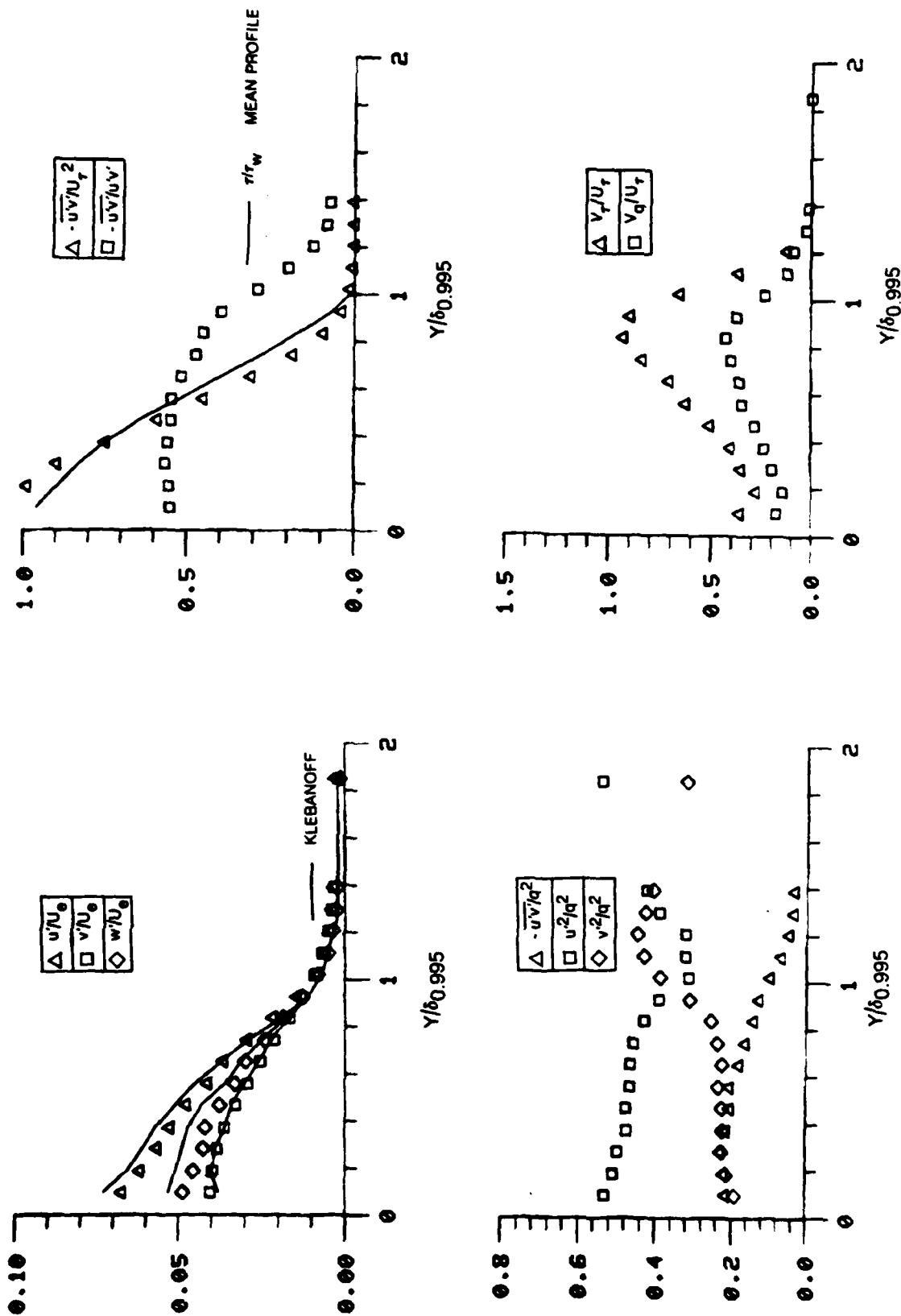


Figure B2A. Boundary Layer Turbulence Quantities $x = 52$ in, $T_e = 0.2\%$

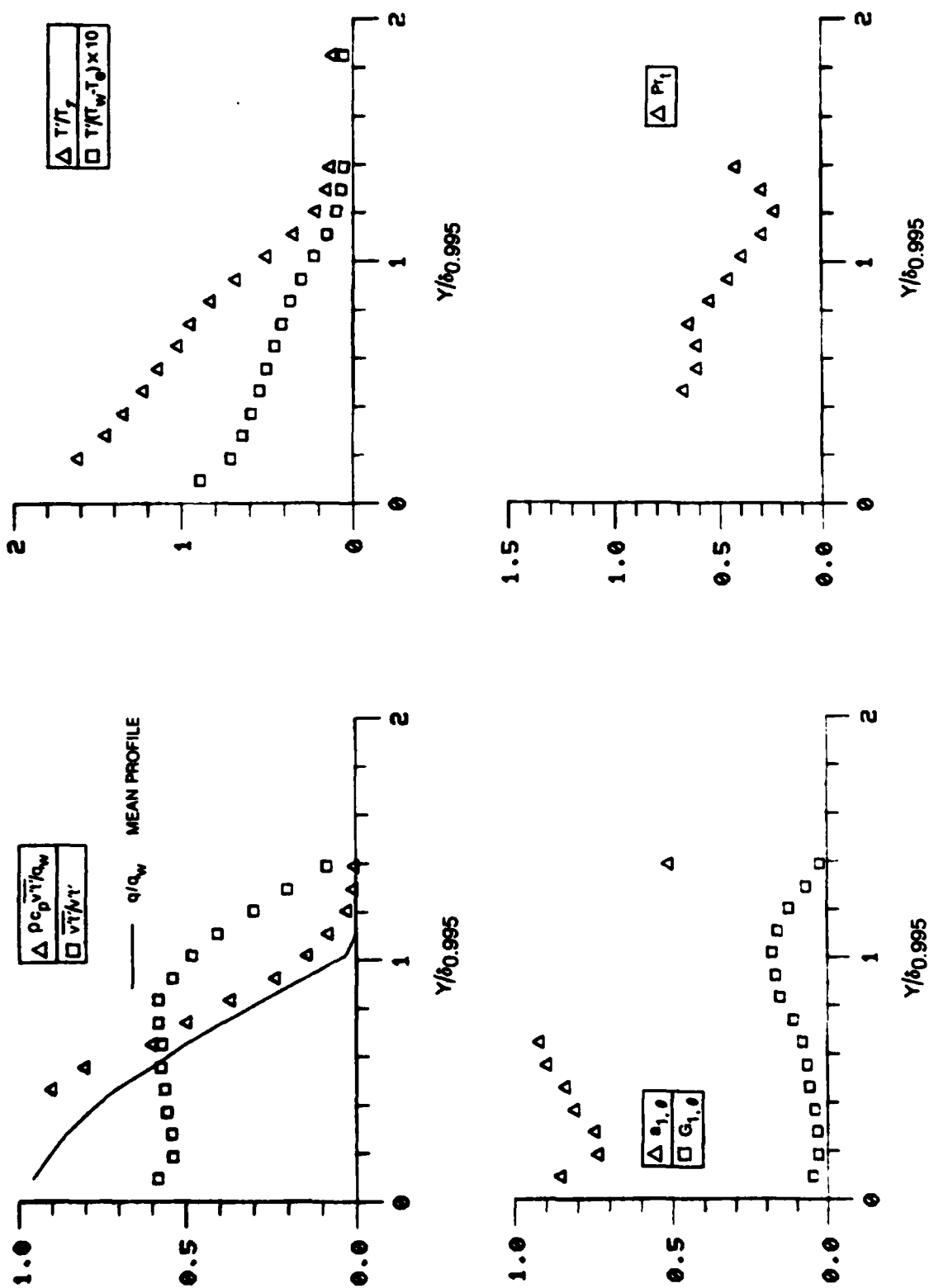


Figure B2B. Boundary Layer Turbulence Quantities, $x = 52$ in, $T_e = 0.2\%$

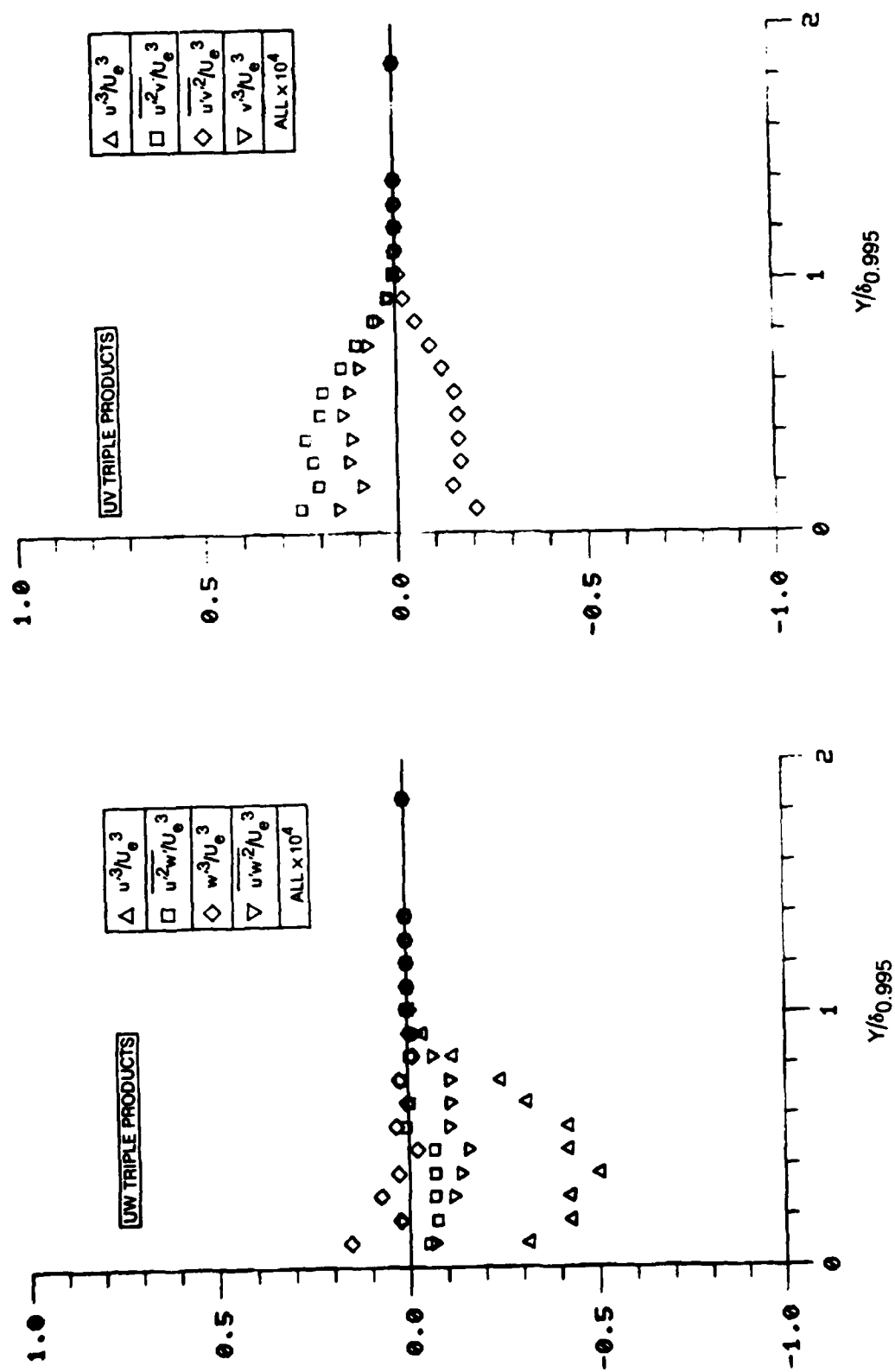


Figure B2C. Boundary Layer Triple Product Distributions $x = 52$ in, $T_e = 0.2\%$

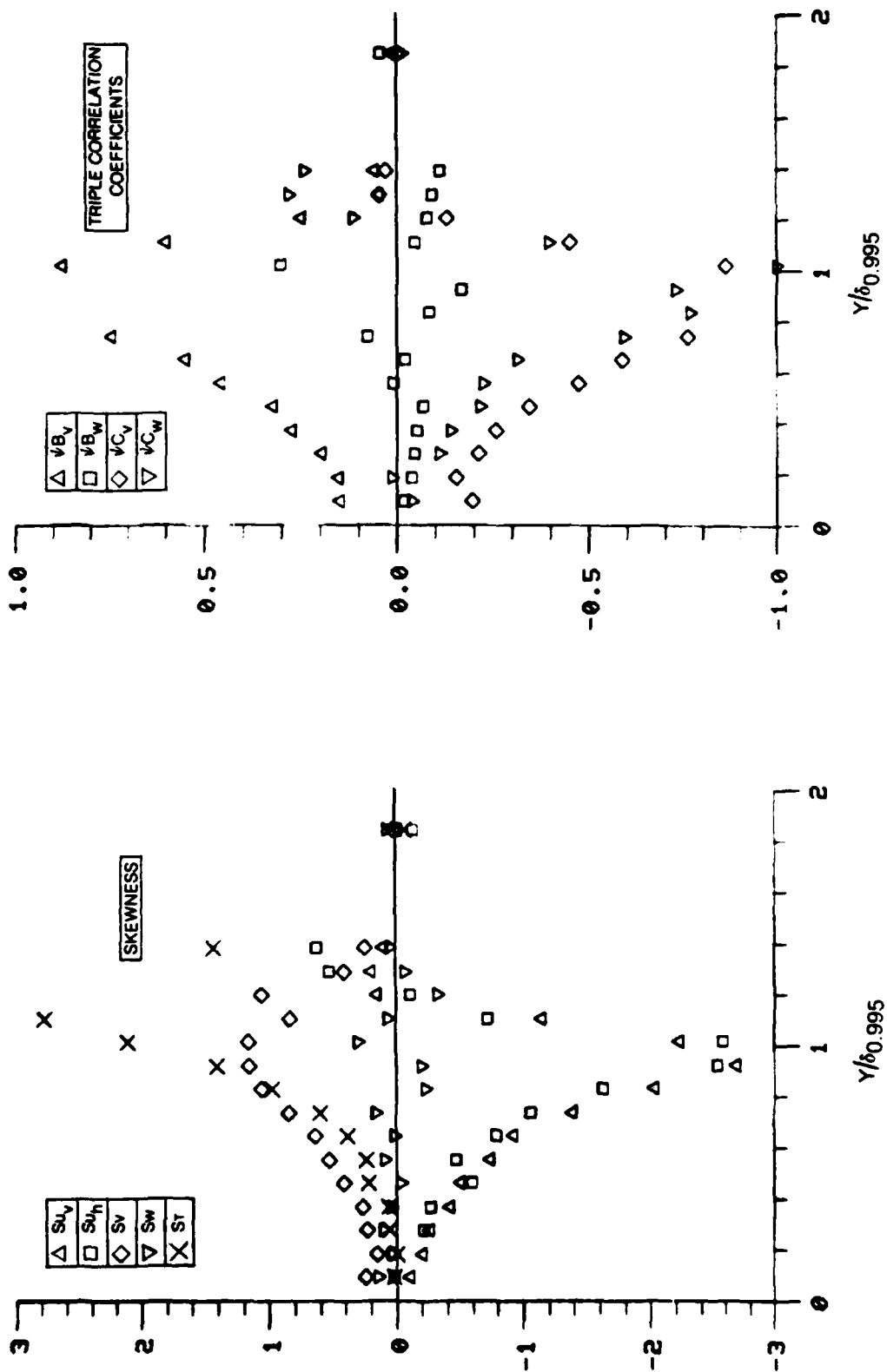


Figure B2D. Boundary Layer Skewness and Triple Product Correlation
 Coefficient Distributions $x = 52$ in, $T_e = 0.2\%$

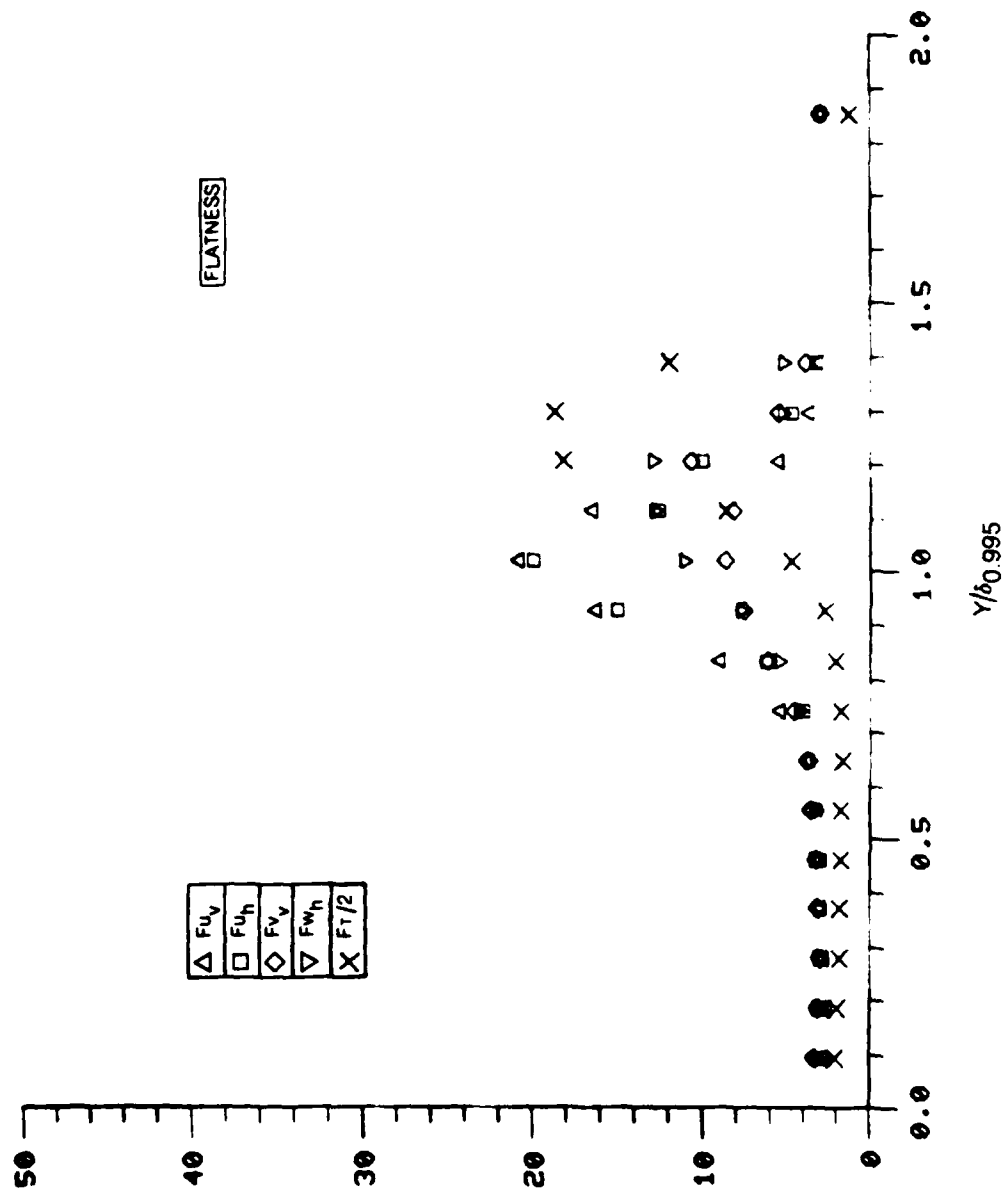


Figure B2E. Boundary Layer Flatness Distributions $x = 52$ in, $T_e = 0.2\%$

Fluctuating Profile Data

x = 52 in, Te = 0.2%

N	Y: INCHES	Y/ DELTA	U'/UE	V'/UE	W'/UE	$\sqrt{U'V'}/UE$	$\overline{U'V'}/U'V'$ UTAU2	$\overline{U'V'}/U'V'$	C/UE
1	3.000	5.556	.0011	.0016	.0000	.0002	-.0000	-.0101	.0019
2	.0500	.093	.0072	.0003	.0466	.0427	1.1054	.5476	.0022
3	.100	.185	.0017	.0098	.0456	.0404	.9912	.5565	.0015
4	.150	.276	.0067	.0362	.0423	.0385	.8960	.5656	.0008
5	.200	.370	.0023	.0357	.0419	.0381	.7479	.5592	.0008
6	.250	.463	.0076	.0312	.0377	.0312	.5861	.5496	.0008
7	.300	.556	.0409	.0259	.0329	.0272	.4465	.5451	.0008
8	.350	.648	.0360	.0251	.0295	.0225	.3068	.5171	.0008
9	.400	.741	.0291	.0210	.0239	.0174	.1837	.4712	.0008
10	.450	.833	.0214	.0165	.0184	.0124	.0931	.4525	.0008
11	.500	.926	.0141	.0126	.0123	.0089	.0391	.3967	.0008
12	.550	1.019	.0061	.0090	.0079	.0045	.0123	.2911	.0008
13	.600	1.111	.0035	.0064	.0048	.0026	.0040	.1954	.0008
14	.650	1.204	.0042	.0050	.0035	.0016	.0015	.1246	.0008
15	.700	1.296	.0037	.0038	.0025	.0011	.0007	.0827	.0008
16	.750	1.389	.0033	.0022	.0021	.0009	.0005	.0733	.0008
17	1.000	1.852	.0028	.0013	.0014	.0004	-.0001	-.0216	.0008
18	3.000	5.556	.0023	.0016	.0011	.0005	-.0001	-.0498	.0008

N	Y: INCHES	Y/ DELTA	$\overline{V'^2}/C2$	$U'^2/C2$	$V'^2/C2$	$W'^2/C2$	$\overline{V'U'}/U'U'$ UTAU	$\overline{V'U'}/U'U'$	$\overline{V'T'}/\overline{P'HO}/C2$ CALL
1	3.000	5.556	-.0144	.3261	.6739	.0000	.4930	.0021	.0019
2	.0500	.093	.2145	.5312	.1909	.2779	.3548	.1723	
3	.100	.185	.2189	.5059	.2121	.276	.2753	.1469	
4	.150	.276	.2266	.4971	.2261	.2766	.3522	.1941	
5	.200	.370	.2142	.4744	.2215	.3041	.4059	.2376	
6	.250	.463	.2043	.4762	.2253	.2985	.5053	.2845	.6996
7	.300	.556	.2058	.4662	.2328	.3009	.6197	.3420	.7966
8	.350	.648	.1808	.4637	.2250	.3113	.7033	.3589	.5900
9	.400	.741	.1629	.4558	.2369	.3074	.8336	.4027	.4911
10	.450	.833	.1435	.4498	.2539	.3163	.9265	.4266	.3600
11	.500	.926	.1266	.4414	.3123	.2962	.8932	.3730	.2336
12	.550	1.019	.0971	.3445	.3855	.2966	.6531	.2312	.1420
13	.600	1.111	.0693	.3225	.4307	.2468	.3620	.1171	.0700
14	.650	1.204	.0466	.3244	.4477	.2280	.3237	.0915	.0000
15	.700	1.296	.0355	.3002	.4273	.1825	.2559	.0229	.0000
16	.750	1.389	.0331	.2449	.4045	.1706	.0443	.0115	.0000
17	1.000	1.852	.0104	.5351	.3153	.1416	.0131	.0000	.0000
18	3.000	5.556	.0255	.5770	.2831	.1399	.0540	.0006	.0000

N	Y: INCHES	Y/ DELTA	$\overline{V'T'}/V'T'$	T'/TAU	T'/(TW-TE)	A10	G10	PRT
1	3.000	5.556	-.0385	.1470	.0065	-.8704	.0012	-1.5202
2	.0500	.093	.5613	2.0110	.0891	.8526	.0496	
3	.100	.185	.5389	1.6112	.0714	.7351	.0312	
4	.150	.276	.5404	1.4474	.0641	.7457	.0327	
5	.200	.370	.5535	1.3417	.0594	.8058	.0426	
6	.250	.463	.5604	1.2262	.0543	.8372	.0599	.6707
7	.300	.556	.5726	1.1399	.0505	.8978	.0654	.6062
8	.350	.648	.5697	1.0209	.0452	.9203	.0800	.6041
9	.400	.741	.5780	.9421	.0417	1.0504	.1096	.6456
10	.450	.833	.5789	.8252	.0367	1.2202	.1562	.5457
11	.500	.926	.5384	.6880	.0301	1.4007	.1718	.4556
12	.550	1.019	.4797	.5005	.0224	1.8409	.1800	.3898
13	.600	1.111	.4029	.3564	.0153	2.2637	.1822	.2886
14	.650	1.204	.2965	.2359	.0096	2.7649	.1672	.2274
15	.700	1.296	.1945	.1359	.0068	3.2742	.1216	.2076
16	.750	1.389	.0858	.1200	.0057	3.5113	.0268	.4156
17	1.000	1.852	.0108	.1123	.0053	2.405	.0017	.6186
18	3.000	5.556	.0079	.1123	.0050	.0799	.0000	-3.0404

Table B3A

Fluctuating Profile Data

x = 52 in., Te = 0.2%

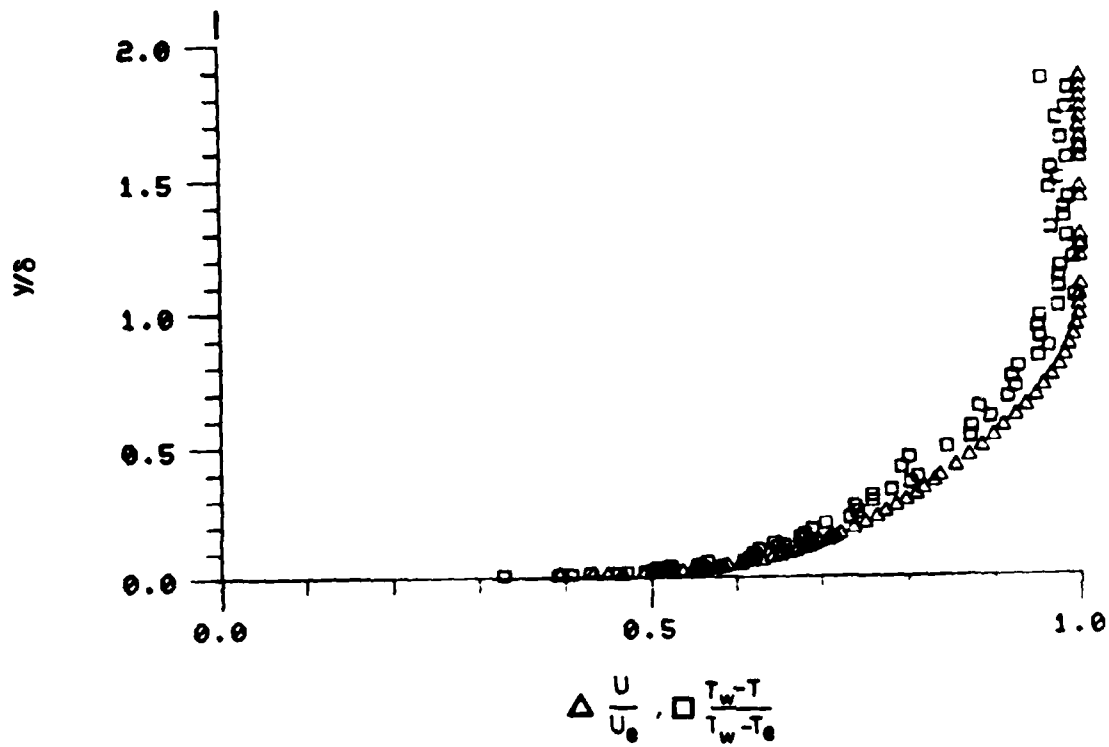
N	Y: INCHES	Y/ DELTA	U ³ /UE ³ x 10000	U ² W ² / UE ³ x 10000	U ³ /LE ³ x 10000	U ² W ² / UE ³ x 10000	U ² W ² / UE ³ x 10000	U ² W ² / UE ³ x 10000	V ³ /UE ³ x 10000
1	3.0000	5.5556	-.0000	.00000	.00000	-.0000	.00000	-.0000	.00000
2	.0500	.0933	-.3162	-.0050	.1535	-.0659	.2500	-.0049	.1535
3	.1000	.1855	-.4296	-.0077	.0236	-.0186	.2058	-.0145	.0933
4	.1500	.2788	-.4271	-.0067	.0130	-.1162	.2195	-.0167	.1260
5	.2000	.3700	-.5037	-.0064	.0291	-.1354	.2386	-.0162	.1160
6	.2500	.4633	-.4229	-.0058	.0218	-.1587	.1949	-.0160	.1433
7	.3000	.5566	-.4237	-.0058	.0337	-.1068	.1947	-.0152	.1260
8	.3500	.6466	-.3132	-.0047	.0040	-.1094	.1453	-.0120	.0933
9	.4000	.7411	-.2465	-.0198	.0222	-.1100	.1094	-.0157	.0556
10	.4500	.8333	-.1204	-.0067	.0138	-.0653	.0566	-.0150	.0278
11	.5000	.9226	-.0403	-.0060	.0038	-.0185	.0211	-.0208	.0000
12	.5500	1.0119	-.0077	-.0022	.0014	-.0057	.0039	-.0049	.0000
13	.6000	1.1111	-.0013	-.0000	.0001	-.0006	.0009	-.0009	.0000
14	.6500	1.2044	.0001	-.0001	-.0002	.0001	.0002	.0001	.0000
15	.7000	1.2966	.0001	-.0000	.0000	.0001	.0000	.0000	.0000
16	.7500	1.3899	.0000	-.0000	.0000	.0000	.0000	.0000	.0000
17	.8000	1.4832	.0000	-.0000	.0000	.0000	.0000	.0000	.0000
18	.8500	1.5556	.0000	-.0000	.0000	.0000	.0000	.0000	.0000

N	Y: INCHES	Y/ DELTA	SU V	SU H	SV	SW	ST	PSIBV	PSIEA
1	3.0000	5.5556	-.0089	.0000	.1593	.0000	-.3002	-.0024	.0000
2	.0500	.0933	-.1185	.0002	.2349	.1338	-.0078	-.1497	.0000
3	.1000	.1855	-.2137	.0034	.1462	.0263	-.0091	-.1506	.0000
4	.1500	.2788	-.2698	.0033	.2255	.0999	.0532	-.0561	.0000
5	.2000	.3700	-.4216	.0032	.2600	.0429	.0596	.2753	.0000
6	.2500	.4633	-.5138	.0033	.4093	-.0416	.2196	.2215	.0000
7	.3000	.5566	-.7500	.0036	.5202	.0915	.2332	.4568	.0000
8	.3500	.6466	-.9242	.0018	.6275	.0063	.3772	.5525	.0000
9	.4000	.7411	-.1.3927	-.1.0619	.6290	.1506	.5875	.7468	.0000
10	.4500	.8333	-.0.364	-.1.6232	.1.0497	-.2327	.9722	.0512	.0000
11	.5000	.9226	-.6.934	-.2.5142	.1.1390	-.2045	1.3936	.2750	.0000
12	.5500	1.0119	-.2.307	-.2.5805	.1.1372	.2927	2.0928	.8817	.0000
13	.6000	1.1111	-.1.1474	-.7.2855	.8.223	.0555	2.7547	.6047	.0000
14	.6500	1.2044	.1456	-.1.128	.1.0417	-.3304	3.7660	.2507	.0000
15	.7000	1.2966	.1866	.5162	.3.969	-.0802	3.1489	.0471	.0000
16	.7500	1.3899	.0864	.6099	.2.289	.0367	1.4124	.0622	.0000
17	.8000	1.4832	-.0262	.1436	.0079	.0576	-.0760	.0180	.0000
18	.8500	1.5556	-.1217	-.2463	.0061	.0468	-.0199	.0211	.0000

N	Y: INCHES	Y/ DELTA	PSICV	PSICW	FU V	FU H	FU V	FU H	FT
1	3.0000	5.5556	-.0500	-.0000	.3.0487	.0000	.3.1967	.0000	.2.9466
2	.0500	.0933	-.1956	-.0081	.2.7187	.6631	.3.3205	.1602	.2.1137
3	.1000	.1855	-.1564	-.0133	.2.7937	.6363	.3.1902	.1656	.3.0857
4	.1500	.2788	-.2113	-.1093	.2.8492	.8241	.3.0121	.1038	.3.6763
5	.2000	.3700	-.2579	-.1364	.2.9966	.9831	.3.1900	.0835	.3.5067
6	.2500	.4633	-.3446	-.2147	.3.1500	.0313	.3.2549	.0500	.3.4358
7	.3000	.5566	-.4743	-.2269	.3.5947	.2109	.3.5732	.2260	.3.4505
8	.3500	.6466	-.5865	-.3116	.3.8225	.7721	.3.8738	.2489	.3.2851
9	.4000	.7411	-.7598	-.3933	.4.4175	.0350	.4.6076	.2489	.3.4415
10	.4500	.8333	-.1.0323	-.7693	.4.0202	.6.2371	.6.1534	.5371	.3.2209
11	.5000	.9226	-.1.1411	-.7286	.16.2345	.9.9672	.7.6221	.7329	.5.5655
12	.5500	1.0119	-.8598	-.9994	.20.7781	.8.8666	.8.6562	.1158	.7.8444
13	.6000	1.1111	-.4516	-.3.682	.16.5380	.2.6018	.6.2341	.6563	.7.3305
14	.6500	1.2044	.1306	.1146	.5.5241	.0.9953	.10.6298	.2091	.3.1627
15	.7000	1.2966	.0495	.2824	.3.6986	.4.6467	.5.5041	.2091	.7.3227
16	.7500	1.3899	.0338	.2456	.3.1782	.2.8338	.3.9224	.2874	.2.8974
17	.8000	1.4832	.0022	-.0101	.3.0145	.0273	.3.0345	.7838	.2.8974
18	.8500	1.5556	.0672	-.0366	.3.1378	.8422	.3.0933	.7387	.2.6326

Table B3B

VELOCITY AND TEMPERATURE RATIOS



VELOCITY AND TEMPERATURE DISTRIBUTIONS IN UNIVERSAL COORDINATES

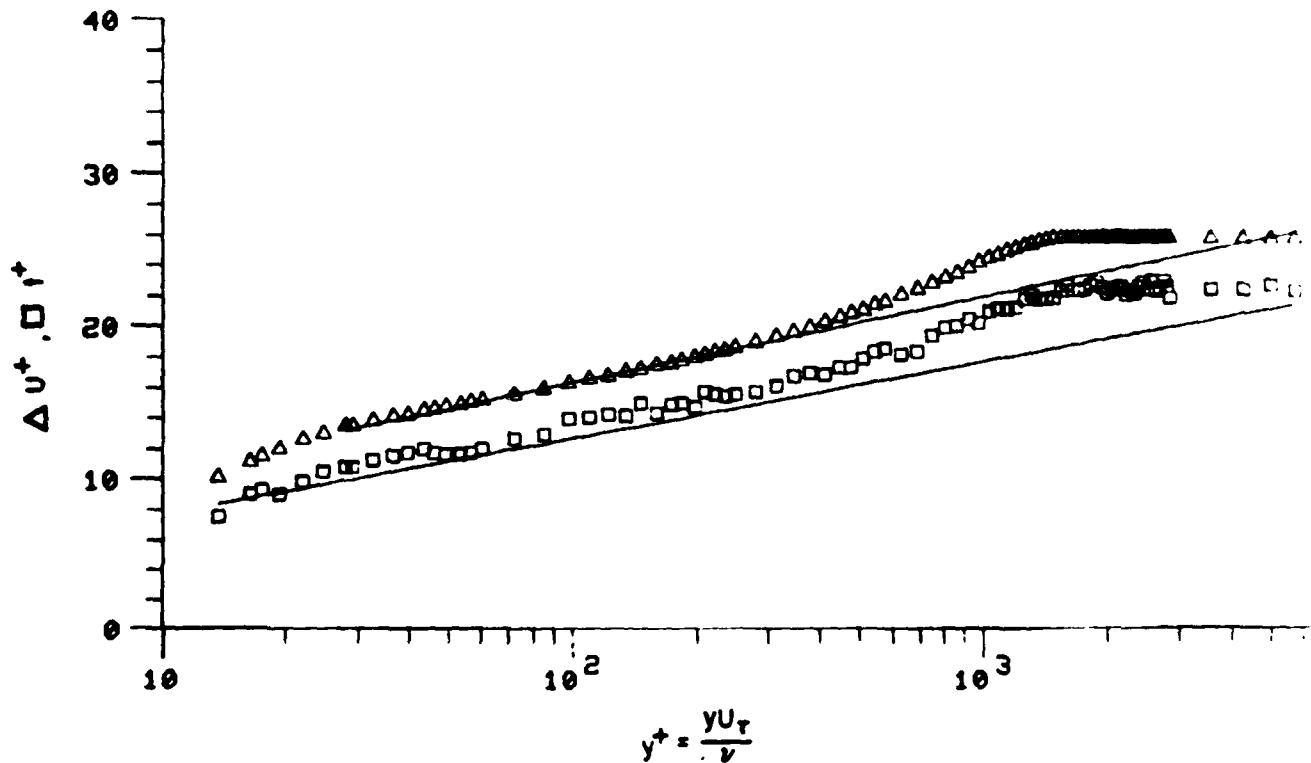


Figure B3. Mean Velocity and Temperature Profiles $x = 68$ in., $Te = 0.2\%$

Mean Profile Data

x = 68 in., Te = 0.2%

	Y	Y/	U	T	U/UE	THETA	U-UE	U+1	Y+1	Y+1
	INCHES	DELTA	FT/SEC	DEG.F			UTAU			
1	.004	.004	28.21	88.10	.284	.272	.18	7.470	5.460	8.065
2	.005	.005	30.00	88.10	.303	.266	.18	7.464	5.467	9.011
3	.007	.007	37.62	88.20	.379	.344	.16	9.963	7.556	13.199
4	.006	.006	44.50	88.20	.419	.385	.15	11.012	8.453	15.390
5	.009	.009	44.32	81.93	.402	.402	.14	11.736	9.813	17.396
6	.011	.011	47.17	61.34	.475	.437	.13	12.491	9.592	20.866
7	.013	.013	49.39	81.15	.498	.448	.13	13.078	9.789	24.116
8	.015	.015	50.89	81.01	.513	.456	.12	13.476	10.014	26.556
9	.017	.017	51.95	81.19	.523	.446	.12	13.757	9.789	31.656
10	.018	.018	52.49	80.61	.529	.481	.12	13.900	10.551	33.629
11	.020	.020	53.26	80.19	.537	.506	.12	14.110	11.097	37.560
12	.022	.022	55.13	80.23	.545	.479	.11	14.334	10.516	40.949
13	.024	.024	55.87	80.23	.553	.504	.11	14.551	11.051	44.783
14	.026	.026	55.35	76.99	.556	.518	.11	14.657	11.360	47.666
15	.028	.028	56.87	76.20	.573	.565	.11	14.866	12.401	52.394
16	.030	.030	60.79	76.63	.591	.539	.10	15.537	12.920	57.765
17	.032	.032	60.79	76.24	.604	.563	.10	16.874	13.522	64.444
18	.034	.034	62.13	78.89	.612	.589	.10	16.096	12.918	95.711
19	.036	.036	62.13	78.89	.626	.584	.09	16.454	12.814	106.650
20	.038	.038	63.75	78.25	.633	.587	.09	16.650	12.676	117.994
21	.040	.040	64.45	78.26	.642	.622	.09	16.681	13.645	132.044
22	.042	.042	65.27	78.30	.649	.621	.09	17.068	13.637	145.192
23	.044	.044	65.91	78.77	.658	.619	.09	17.284	13.581	156.156
24	.046	.046	66.51	77.93	.664	.637	.08	17.453	13.980	166.561
25	.048	.048	66.51	77.93	.670	.641	.08	17.612	14.071	181.503
26	.050	.050	67.26	77.75	.678	.652	.08	17.817	14.300	194.119
27	.052	.052	67.85	77.63	.684	.659	.08	17.979	14.466	205.621
28	.054	.054	68.54	77.72	.691	.654	.08	18.151	14.348	218.765
29	.056	.056	68.95	77.87	.695	.654	.08	18.258	14.154	231.150
30	.058	.058	70.09	77.02	.706	.695	.08	18.560	15.263	246.641
31	.060	.060	71.50	77.23	.720	.683	.07	18.933	14.984	264.115
32	.062	.062	71.50	77.19	.733	.686	.07	19.013	15.046	282.566
33	.064	.064	73.70	76.56	.744	.700	.06	19.729	15.557	303.991
34	.066	.066	74.82	76.35	.754	.735	.06	19.472	16.141	318.955
35	.068	.068	75.79	76.40	.763	.733	.06	20.217	16.064	334.666
36	.070	.070	76.66	76.28	.772	.740	.05	20.962	16.236	350.334
37	.072	.072	76.66	76.23	.782	.743	.05	21.723	16.300	366.466
38	.074	.074	78.55	75.73	.791	.773	.05	22.498	16.967	383.990
39	.076	.076	79.38	75.47	.800	.788	.05	23.266	17.296	402.222
40	.078	.078	80.75	75.45	.813	.796	.05	24.004	17.459	421.382
41	.080	.080	82.05	75.12	.827	.809	.04	24.559	17.727	441.765
42	.082	.082	83.61	74.99	.842	.818	.04	25.141	17.942	463.607
43	.084	.084	85.11	75.11	.854	.810	.04	25.851	17.775	486.976
44	.086	.086	86.99	75.00	.866	.817	.04	26.525	17.921	511.934
45	.088	.088	88.12	74.62	.878	.839	.03	27.217	18.423	538.555
46	.090	.090	89.20	74.16	.886	.866	.03	27.908	19.004	566.866
47	.092	.092	90.30	74.37	.900	.854	.03	28.633	19.747	595.999
48	.094	.094	91.40	74.54	.911	.844	.03	29.366	19.960	625.999
49	.096	.096	92.50	74.13	.920	.869	.03	30.109	19.069	656.866
50	.098	.098	93.60	73.49	.931	.907	.03	30.824	19.462	688.555
51	.100	.100	94.70	73.48	.939	.908	.03	31.603	19.916	721.172
52	.102	.102	95.80	73.76	.949	.900	.03	32.337	19.528	754.777
53	.104	.104	96.90	73.53	.957	.905	.03	33.124	19.855	789.334
54	.106	.106	98.00	73.22	.964	.923	.03	33.945	19.441	824.866
55	.108	.108	99.10	73.00	.971	.931	.03	34.763	19.232	861.444
56	.110	.110	99.20	72.24	.977	.922	.03	35.606	19.680	899.066
57	.112	.112	99.51	72.95	.982	.940	.03	36.464	19.624	937.777
58	.114	.114	99.79	72.19	.987	.973	.03	37.352	19.934	977.555
59	.116	.116	99.88	72.32	.993	.965	.03	38.264	20.022	1018.444
60	.118	.118	99.88	72.50	.996	.965	.03	39.176	20.100	1060.334
61	.120	.120	99.88	72.10	.997	.990	.03	40.071	20.179	1103.222
62	.122	.122	99.88	72.15	.998	.987	.03	40.953	20.664	1147.111
63	.124	.124	99.88	72.58	.999	.962	.03	41.820	21.105	1192.000
64	.126	.126	99.88	72.51	.999	.966	.03	42.687	21.191	1237.889
65	.128	.128	99.88	72.26	.999	.981	.03	43.554	21.524	1284.777
66	.130	.130	99.88	72.70	.999	.954	.03	44.421	21.944	1332.666
67	.132	.132	99.88	72.33	.999	.977	.03	45.288	22.364	1381.555
68	.134	.134	99.88	72.61	.999	.966	.03	46.155	22.784	1431.444
69	.136	.136	99.88	72.32	.999	.977	.03	47.022	23.204	1482.334
70	.138	.138	99.88	72.20	.999	.977	.03	47.889	23.624	1534.222
71	.140	.140	99.88	72.06	.999	.977	.03	48.756	24.044	1587.111
72	.142	.142	99.88	72.06	.999	.977	.03	49.623	24.464	1641.000
73	.144	.144	99.88	72.06	.999	.977	.03	50.490	24.884	1695.889
74	.146	.146	99.88	72.06	.999	.977	.03	51.357	25.304	1751.777
75	.148	.148	99.88	72.06	.999	.977	.03	52.224	25.724	1808.666
76	.150	.150	99.88	72.06	.999	.977	.03	53.091	26.144	1866.555
77	.152	.152	99.88	72.06	.999	.977	.03	53.958	26.564	1925.444
78	.154	.154	99.88	72.06	.999	.977	.03	54.825	26.984	1985.334
79	.156	.156	99.88	72.06	.999	.977	.03	55.692	27.404	2046.222
80	.158	.158	99.88	72.06	.999	.977	.03	56.559	27.824	2108.111
81	.160	.160	99.88	72.06	.999	.977	.03	57.426	28.244	2171.000
82	.162	.162	99.88	72.06	.999	.977	.03	58.293	28.664	2234.889
83	.164	.164	99.88	72.06	.999	.977	.03	59.160	29.084	2299.777
84	.166	.166	99.88	72.06	.999	.977	.03	60.027	29.504	2365.666
85	.168	.168	99.88	72.06	.999	.977	.03	60.894	29.924	2432.555
86	.170	.170	99.88	72.06	.999	.977	.03	61.761	30.344	2500.444
87	.172	.172	99.88	72.06	.999	.977	.03	62.628	30.764	2569.334
88	.174	.174	99.88	72.06	.999	.977	.03	63.495	31.184	2639.222
89	.176	.176	99.88	72.06	.999	.977	.03	64.362	31.604	2710.111
90	.178	.178	99.88	72.06	.999	.977	.03	65.229	32.024	2782.000
91	.180	.180	99.88	72.06	.999	.977	.03	66.096	32.444	2854.889
92	.182	.182	99.88	72.06	.999	.977	.03	66.963	32.864	2928.777
93	.184	.184	99.88	72.06	.999	.977	.03	67.830	33.284	3003.666
94	.186	.186	99.88	72.06	.999	.977	.03	68.697	33.704	3079.555
95	.188	.188	99.88	72.06	.999	.977	.03	69.564	34.124	3156.444
96	.190	.190	99.88	72.06	.999	.977	.03	70.431	34.544	3234.334
97	.192	.192	99.88	72.06	.999	.977	.03	71.298	34.964	3313.222
98	.194	.194	99.88	72.06	.999	.977	.03	72.165	35.384	3393.111
99	.196	.196	99.88	72.06	.999	.977	.03	73.032	35.804	3474.000
100	.198	.198	99.88	72.06	.999	.977	.03	73.899	36.224	3555.889

Table B4

RUN NO. 3. POINT 2.
 BOUNDARY LAYER PROPERTIES

	LINEAR INTERPOLATION TO WALL	STANDARD SUBLAYER FUNCTION FROM WALL TO $y^+ = 35$
FREE STREAM VELOCITY	99.171	99.171
FREE STREAM TEMPERATURE	73.270	
WALL TEMPERATURE	90.270	
WALL HEAT FLUX	.05020	
FREE STREAM DENSITY	.07493	
FREE STREAM KINEMATIC VISCOSITY	.0001639	
DENSITY OF FLUID AT WALL	.07262	
KINEMATIC VISCOSITY OF FLUID AT WALL	.0001733	
WALL/FREE STREAM DENSITY RATIO	.96909	
LOCATION REYNOLDS NUMBER (REX)	3428173.22	
INPUT VALUE OF VELOCITY DELTA	.90000	
INPUT VALUE OF TEMPERATURE DELTA	.97000	
CALCULATED DELTA		.61093
DELTA 99.5% INPUT	.00000	
DISPLACEMENT THICKNESS (DELSTAR)	.12319	.12306
MOMENTUM THICKNESS (THETA)	.08551	.08564
ENERGY-DISSIPATION THICKNESS	.15118	.15148
ENTHALPY THICKNESS	.00370	.00371
SHAPE FACTOR 12 (DELSTAR/THETA)	1.44071	1.43351
SHAPE FACTOR 32 (ENERGY/THETA)	1.76804	1.76469
MOMENTUM THICKNESS REYNOLDS NUMBER	4310.75	4327.68
DISPLACEMENT THICKNESS REYNOLDS NUMBER	6210.57	6203.78
SKIN FRICTION COEFFICIENT	.002940	
FRICTION VELOCITY	3.86252	
LAW OF THE WALL CONSTANT (K)	.41000	
LAW OF THE WALL CONSTANT (C)	5.00000	
WAKE STRENGTH		.57972
CLAUSERS 'DELTA' INTEGRAL	-2.88141	-3.06592
CLAUSERS 'G' INTEGRAL	21.95430	21.63072
DISPLACEMENT THICKNESS - CONSTANT DENSITY	.11589	.11941
MOMENTUM THICKNESS - CONSTANT DENSITY	.08625	.08660
SHAPE FACTOR 12 - CONSTANT DENSITY	1.34363	1.37890

LOCATION -X- 68.00000

Te = 0.2%

Table B5

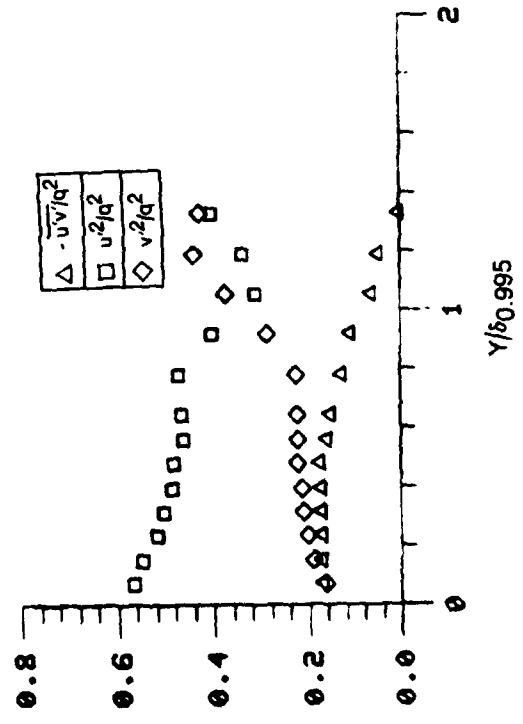
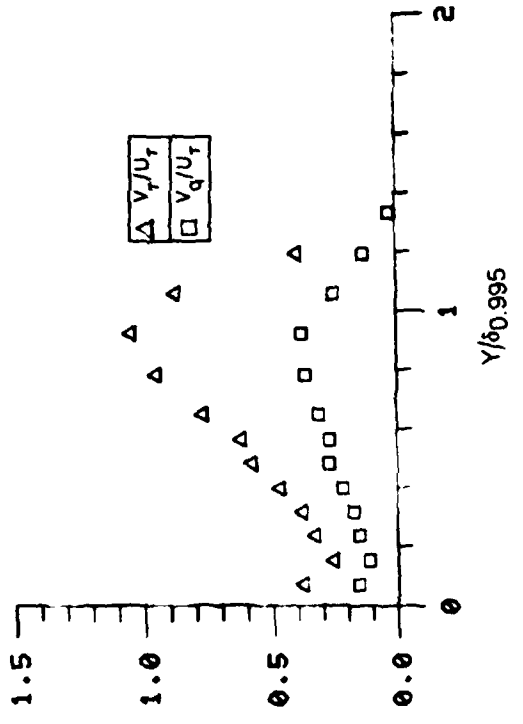
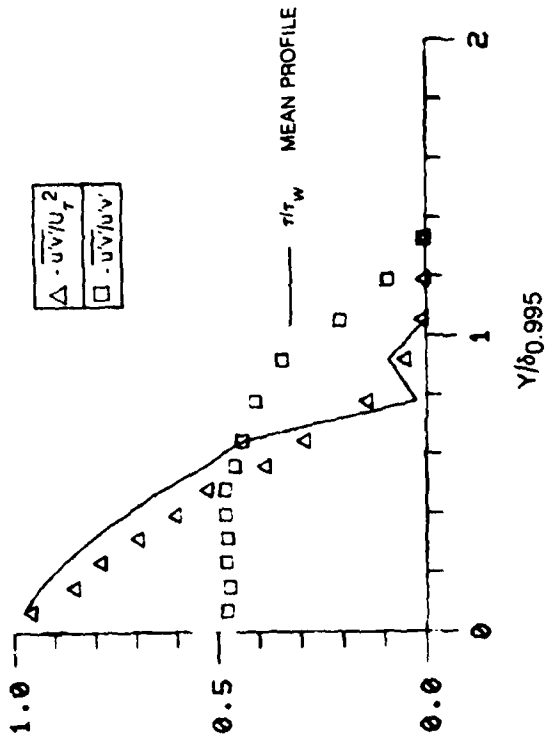


Figure B4A. Boundary Layer Turbulence Quantities $x = 68$ in, $T_e = 0.2\%$

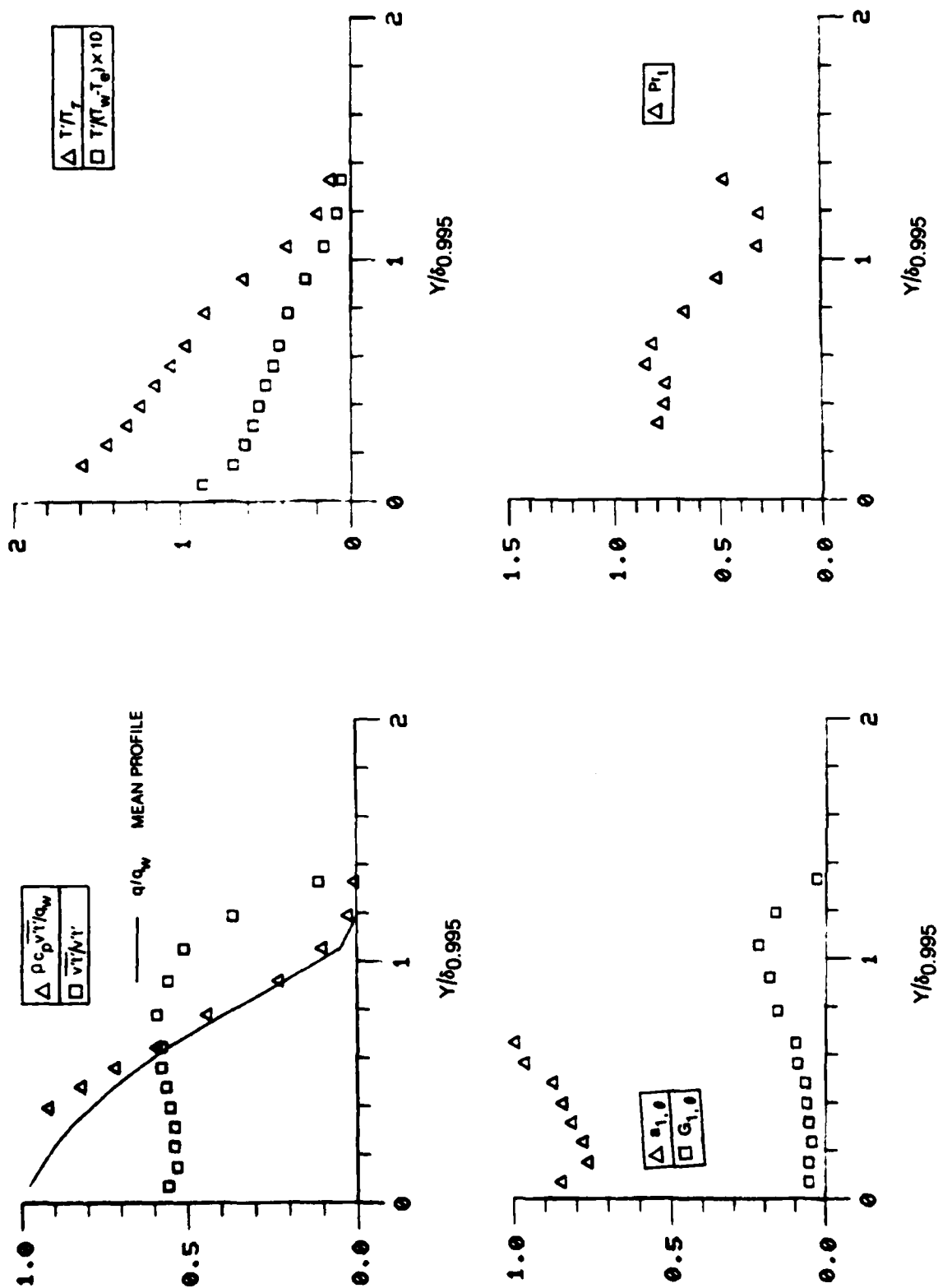


Figure B48. Boundary Layer Turbulence Quantities, $x = 68$ in, $T_e = 0.2\%$

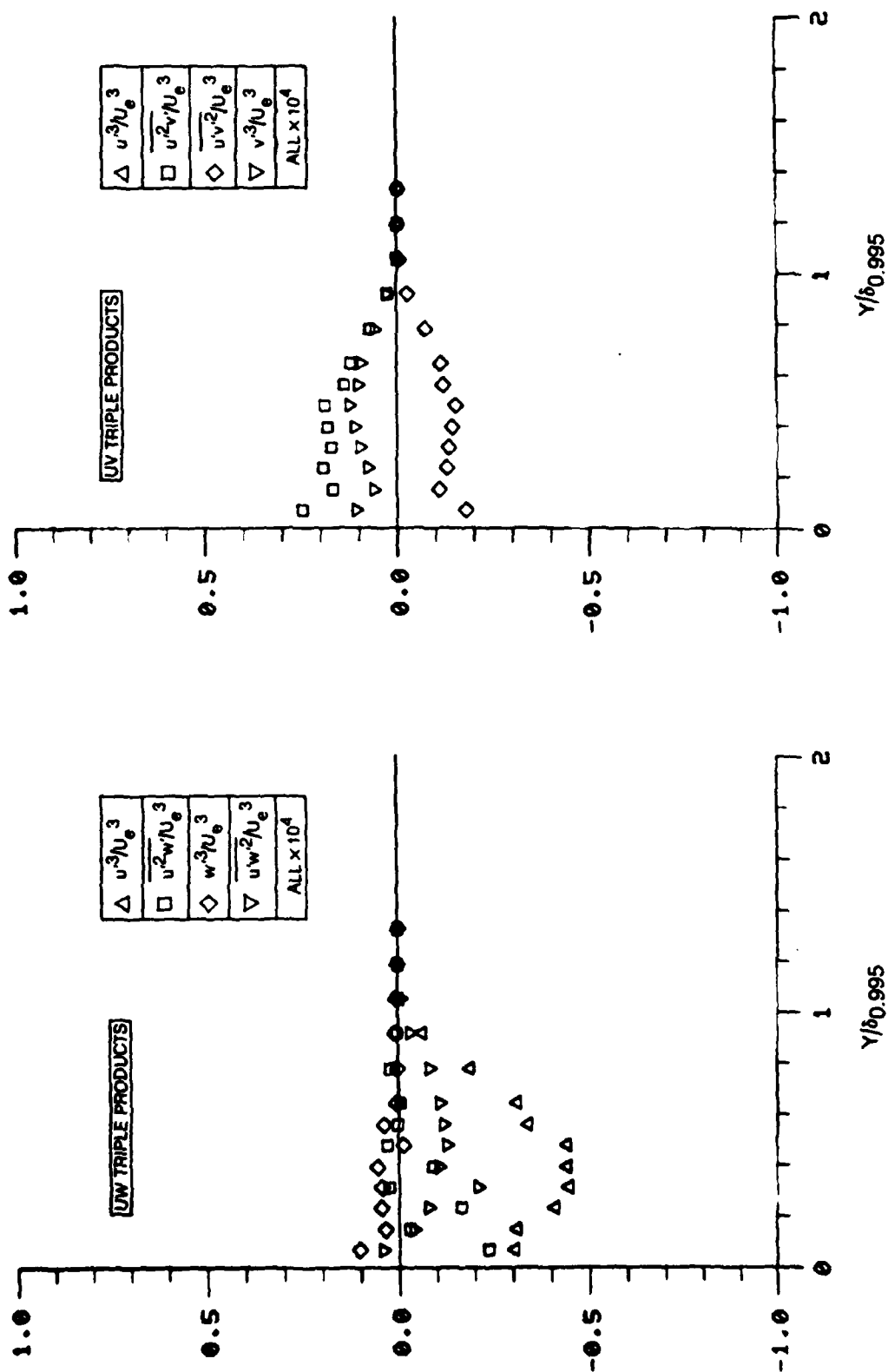


Figure B4C. Boundary Layer Triple Product Distributions $x = 68$ in, $T_e = 0.2\%$

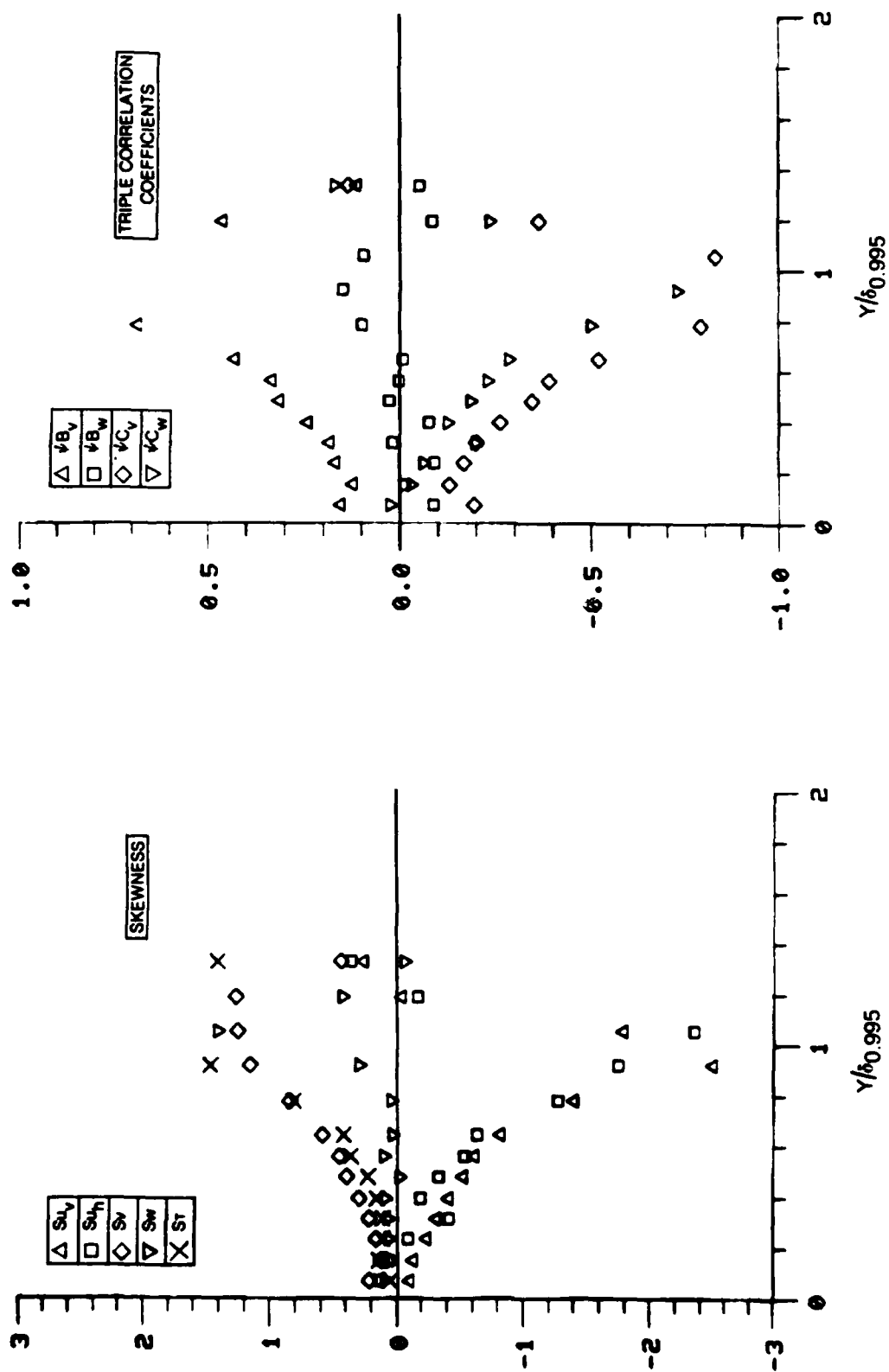


Figure B4D. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 68$ in, $T_e = 0.2\%$

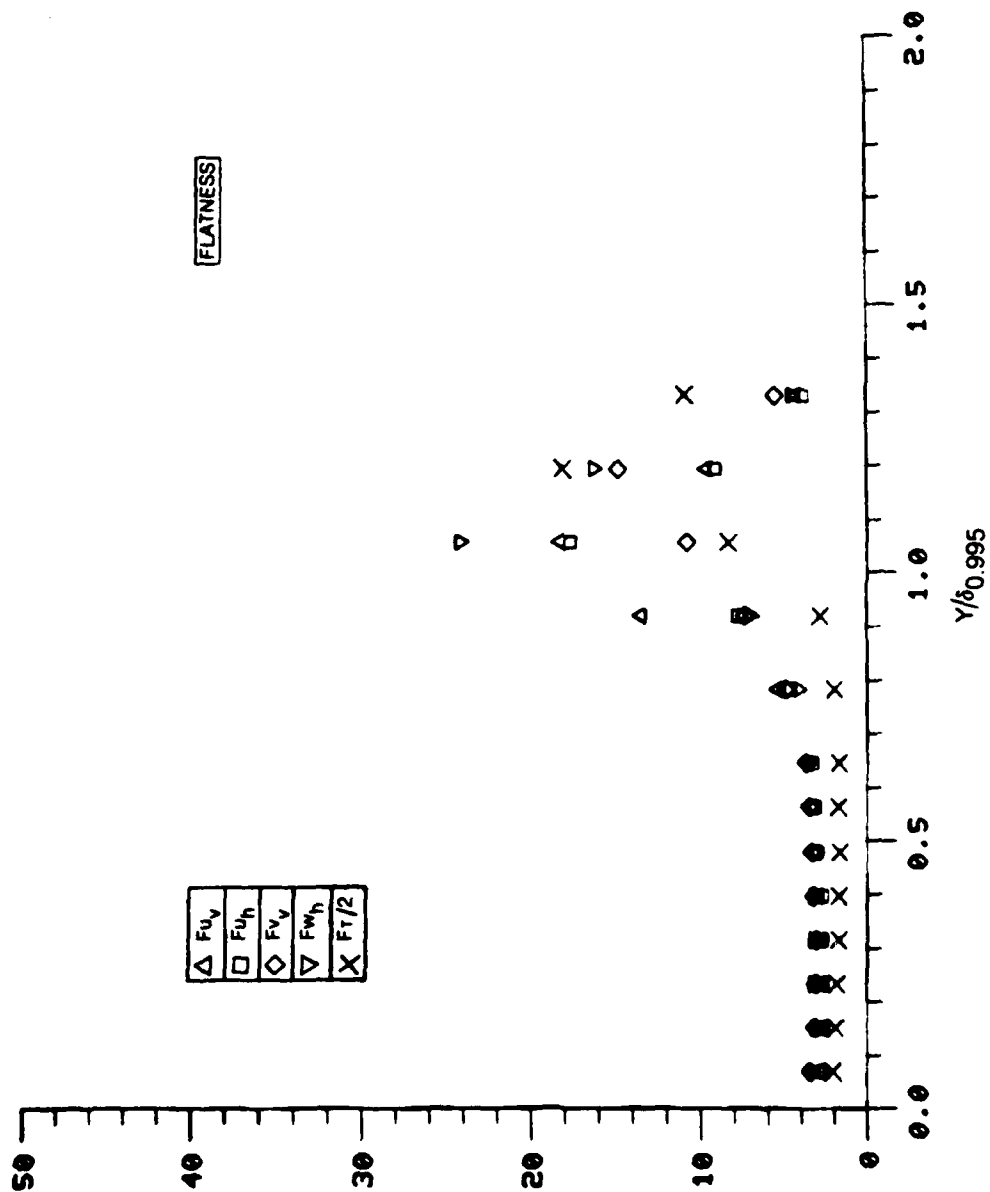


Figure B4E. Boundary Layer Flatness Distributions $x = 68$ in, $T_e = 0.2\%$

Fluctuating Profile Data

x = 68 in., Te = 0.2%

N	Y: INCHES	Y/ DELTA	U'/UE	V'/UE	W'/UE	$\sqrt{U'^2+V'^2}$ /UE	$\frac{U'V'}{U^2AU^2}$	$\frac{U'V'}{U^2V'}$	C/UE
1	3.000	4.110	.0026	.0019	.0011	.002	.0048	-.1956	.0000
2	.050	.068	.0000	.0014	.0005	.002	.0059	-.4797	.0000
3	.110	.151	.0043	.0027	.0044	.0036	.0051	.4719	.0000
4	.170	.232	.0099	.0073	.0044	.0046	.0057	.4607	.0000
5	.230	.315	.0056	.0036	.0020	.0032	.0046	.4766	.0000
6	.290	.397	.0011	.0039	.0040	.0030	.0051	.4813	.0000
7	.350	.479	.0070	.0018	.0068	.0028	.0038	.4835	.0000
8	.410	.562	.0110	.0028	.0039	.0022	.0041	.4582	.0000
9	.470	.644	.0070	.0055	.0030	.0021	.0054	.4419	.0000
10	.530	.761	.0000	.0194	.0023	.0146	.0001	.4101	.0000
11	.590	.916	.0163	.0138	.0042	.0085	.0069	.3461	.0000
12	.650	1.055	.0076	.0086	.0079	.0035	.0062	.2071	.0000
13	.710	1.192	.0047	.0054	.0038	.0016	.0021	.0093	.0000
14	.770	1.329	.0036	.0037	.0023	.0003	.0001	.0006	.0000
15	.830	1.466	.0031	.0019	.0014	.0009	.0001	.0006	.0000
16	.890	1.603	.0027	.0016	.0011	.0007	.0001	.0006	.0000
17	.950	1.740	.0000	.0000	.0000	.0000	.0000	.0000	.0000
18	1.000	1.877	.0000	.0000	.0000	.0000	.0000	.0000	.0000

N	Y: INCHES	Y/ DELTA	$\frac{V'U'}{U^2Q^2}$	$\frac{U'^2}{Q^2}$	$\frac{V'^2}{Q^2}$	$\frac{W'^2}{Q^2}$	$\frac{V'U'}{U^2AU^2}$	$\frac{V'U'}{U^2AU^2}$	$\frac{V'U'}{U^2AU^2}$
1	3.000	4.110	.6413	.5756	.3090	.1154	-.0071	-.0004	.0000
2	.050	.068	.1669	.5658	.1621	.2721	.0001	.1622	.0000
3	.110	.151	.1723	.5491	.1894	.2615	.0026	.1556	.0000
4	.170	.232	.1723	.5317	.2002	.2520	.0049	.1539	.0000
5	.230	.315	.1710	.5020	.2105	.2426	.0071	.1773	.0000
6	.290	.397	.1708	.4846	.2228	.2326	.0094	.1723	.0000
7	.350	.479	.1742	.4826	.2312	.2266	.0119	.1723	.0000
8	.410	.562	.1606	.4627	.2333	.2150	.0149	.1723	.0000
9	.470	.644	.1501	.4656	.2222	.2123	.0177	.1723	.0000
10	.530	.761	.1289	.4724	.2266	.2010	.0207	.1723	.0000
11	.590	.916	.1067	.4032	.2286	.2062	.0231	.1723	.0000
12	.650	1.055	.0634	.3112	.2339	.2149	.0255	.1723	.0000
13	.710	1.192	.0477	.3387	.2398	.2215	.0280	.1723	.0000
14	.770	1.329	.0335	.4024	.2472	.2170	.0305	.1723	.0000
15	.830	1.466	.0272	.6340	.2446	.2114	.0330	.1723	.0000
16	.890	1.603	.0207	.6742	.2442	.2016	.0355	.1723	.0000
17	.950	1.740	.0100	.0000	.2400	.2000	.0380	.1723	.0000
18	1.000	1.877	.0000	.0000	.2400	.2000	.0400	.1723	.0000

N	Y: INCHES	Y/ DELTA	$\frac{V'U'}{U^2V'}$	$\frac{T'}{TTAU}$	$\frac{T'}{(TH-TE)}$	A10	G10	PRT
1	3.000	4.110	-.0007	.0097	.0043	.0000	.0000	.0000
2	.050	.068	.0000	.0074	.0070	.0047	.0055	.0000
3	.110	.151	.0000	.0067	.0088	.0070	.0053	.0000
4	.170	.232	.0000	.0061	.0088	.0070	.0053	.0000
5	.230	.315	.0000	.0055	.0088	.0070	.0053	.0000
6	.290	.397	.0000	.0050	.0088	.0070	.0053	.0000
7	.350	.479	.0000	.0045	.0088	.0070	.0053	.0000
8	.410	.562	.0000	.0040	.0088	.0070	.0053	.0000
9	.470	.644	.0000	.0035	.0088	.0070	.0053	.0000
10	.530	.761	.0000	.0030	.0088	.0070	.0053	.0000
11	.590	.916	.0000	.0025	.0088	.0070	.0053	.0000
12	.650	1.055	.0000	.0020	.0088	.0070	.0053	.0000
13	.710	1.192	.0000	.0015	.0088	.0070	.0053	.0000
14	.770	1.329	.0000	.0010	.0088	.0070	.0053	.0000
15	.830	1.466	.0000	.0005	.0088	.0070	.0053	.0000
16	.890	1.603	.0000	.0000	.0088	.0070	.0053	.0000
17	.950	1.740	.0000	.0000	.0088	.0070	.0053	.0000
18	1.000	1.877	.0000	.0000	.0088	.0070	.0053	.0000

Table B6A

Fluctuating Profile Data

x = 68 in., Te = 0.2%

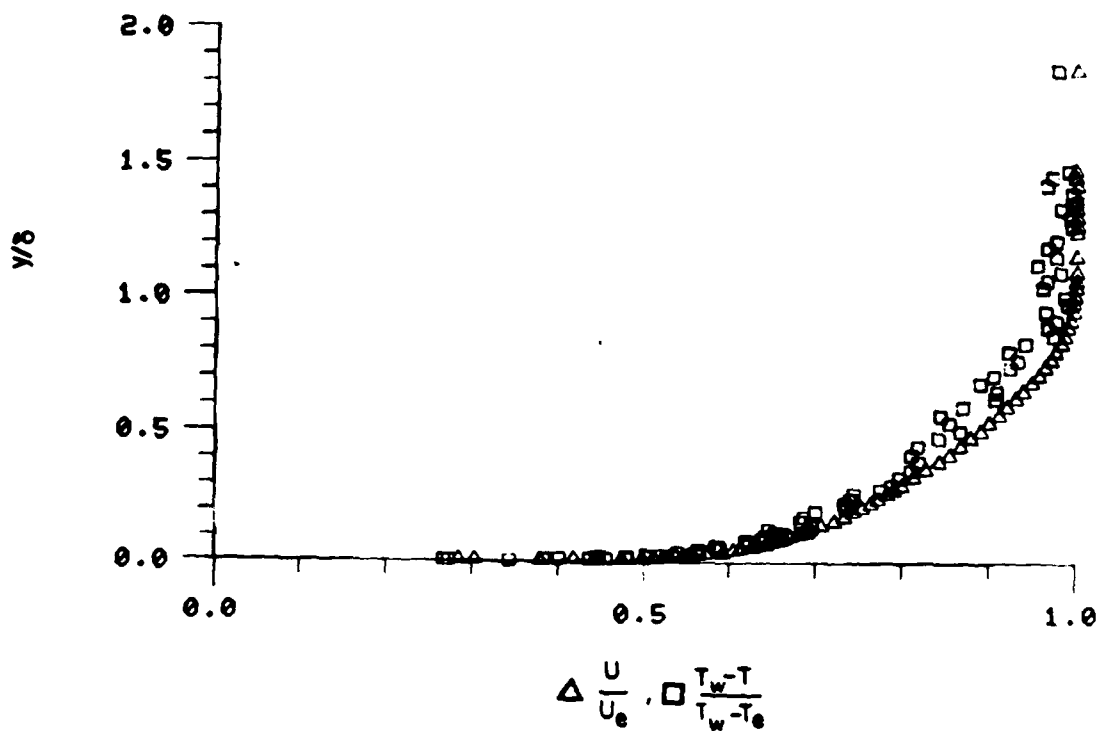
N	Y: INCHES	Y/ DELTA	U ³ /UE ³ x 10000	L ² U ³ / UE ³ x 10000	U ³ /UE ³ x 10000	U ⁴ U ² / UE ³ x 10000	U ² U ² / UE ³ x 10000	U ⁴ U ² / UE ³ x 10000	V ³ /UE ³ x 10000
1	3.000	4.110	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
2	.050	.068	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
3	.110	.151	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
4	.170	.233	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
5	.230	.315	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
6	.290	.397	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
7	.350	.479	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
8	.410	.562	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
9	.470	.644	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
10	.570	.781	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
11	.670	.918	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
12	.770	1.055	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
13	.870	1.192	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
14	.970	1.329	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
15	1.500	2.055	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
16	3.000	4.110	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
17	.000	.000	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000
18	.000	.000	-.0000	-.0000	-.0000	-.0000	.0000	-.0000	-.0000

N	Y: INCHES	Y/ DELTA	SU V	SU H	SV	SH	ST	PSIEV	PSIEH
1	3.000	4.110	-.1433	-.0034	-.0398	-.4208	.0273	.0090	-.1161
2	.050	.068	-.1036	-.1372	-.2109	-.0843	.0549	.1552	-.0085
3	.110	.151	-.1336	-.0548	-.1158	-.0345	.1433	.1211	-.0085
4	.170	.233	-.2361	-.0950	-.1523	-.0542	.1036	.1682	-.0085
5	.230	.315	-.3240	-.4190	-.2117	-.0649	.1094	.1828	-.0085
6	.290	.397	-.4141	-.1899	-.2855	-.0846	.1525	.2407	-.0085
7	.350	.479	-.5299	-.3355	-.3844	-.0251	.2221	.3149	-.0085
8	.410	.562	-.6199	-.5386	-.4446	-.0917	.3597	.3339	-.0085
9	.470	.644	-.6199	-.6376	-.5799	-.0328	.4162	.4319	-.0085
10	.570	.781	-.3980	-.2780	-.8360	.0376	.5076	.6876	-.0085
11	.670	.918	-.2501	-.1755	1.1376	.2880	.5502	1.0418	-.0085
12	.770	1.055	-.1793	-.2528	1.2399	1.3923	.0275	1.0351	-.0085
13	.870	1.192	-.0491	-.1697	1.2477	1.4168	.1170	.4642	-.0085
14	.970	1.329	.2644	-.3479	1.4267	-.0666	.3920	.1169	-.0085
15	1.500	2.055	.1154	-.2066	1.0225	-.1279	1.4523	.00128	-.0085
16	3.000	4.110	.2069	-.8690	-.0228	-.0671	-.2043	-.0000	-.0085
17	.000	.000	.0000	.0000	.0000	.0000	.0000	.0000	-.0085
18	.000	.000	.0000	.0000	.0000	.0000	.0000	.0000	-.0085

N	Y: INCHES	Y/ DELTA	PSICV	PSICH	FU V	FU H	FU V	FU H	FT
1	3.000	4.110	-.0267	-.2917	.0291	.2710	.0379	.7406	2.6777
2	.050	.068	-.1262	-.0260	.8096	.6306	.3938	.3530	4.1134
3	.110	.151	-.1275	-.0291	.7371	.6681	.1789	.1543	4.6061
4	.170	.233	-.1675	-.0617	.7174	.6968	.0549	.2251	3.7161
5	.230	.315	-.1965	-.1963	.8463	.7914	.1224	.2488	3.4657
6	.290	.397	-.2617	-.1210	.9808	.7615	.2415	.2765	3.5706
7	.350	.479	-.3345	-.1838	.1622	.2986	.3747	.0655	3.4289
8	.410	.562	-.3895	-.2304	.2922	.3174	.584	.3665	3.4289
9	.470	.644	-.5204	-.2833	.6550	.3340	.7791	.5881	3.4289
10	.570	.781	-.7887	-.5004	.4422	.4667	.9047	.1493	3.9211
11	.670	.918	-.1031	-.7246	.4379	7.7491	.7122	.0297	5.6711
12	.770	1.055	-.8222	-.0129	1.1795	17.5620	.7762	.9625	5.6711
13	.870	1.192	-.3642	-.2370	9.5933	9.5933	.7623	.1623	5.6711
14	.970	1.329	.1345	-.726	.2823	.0941	.9376	.5272	5.6711
15	1.500	2.055	.0845	-.5575	.1113	.9376	.9376	.9466	5.6711
16	3.000	4.110	.0000	-.0000	.0000	.0000	.0000	.0000	5.6711
17	.000	.000	.0000	.0000	.0000	.0000	.0000	.0000	5.6711
18	.000	.000	.0000	.0000	.0000	.0000	.0000	.0000	5.6711

Table B6B

VELOCITY AND TEMPERATURE RATIOS



VELOCITY AND TEMPERATURE DISTRIBUTIONS IN UNIVERSAL COORDINATES

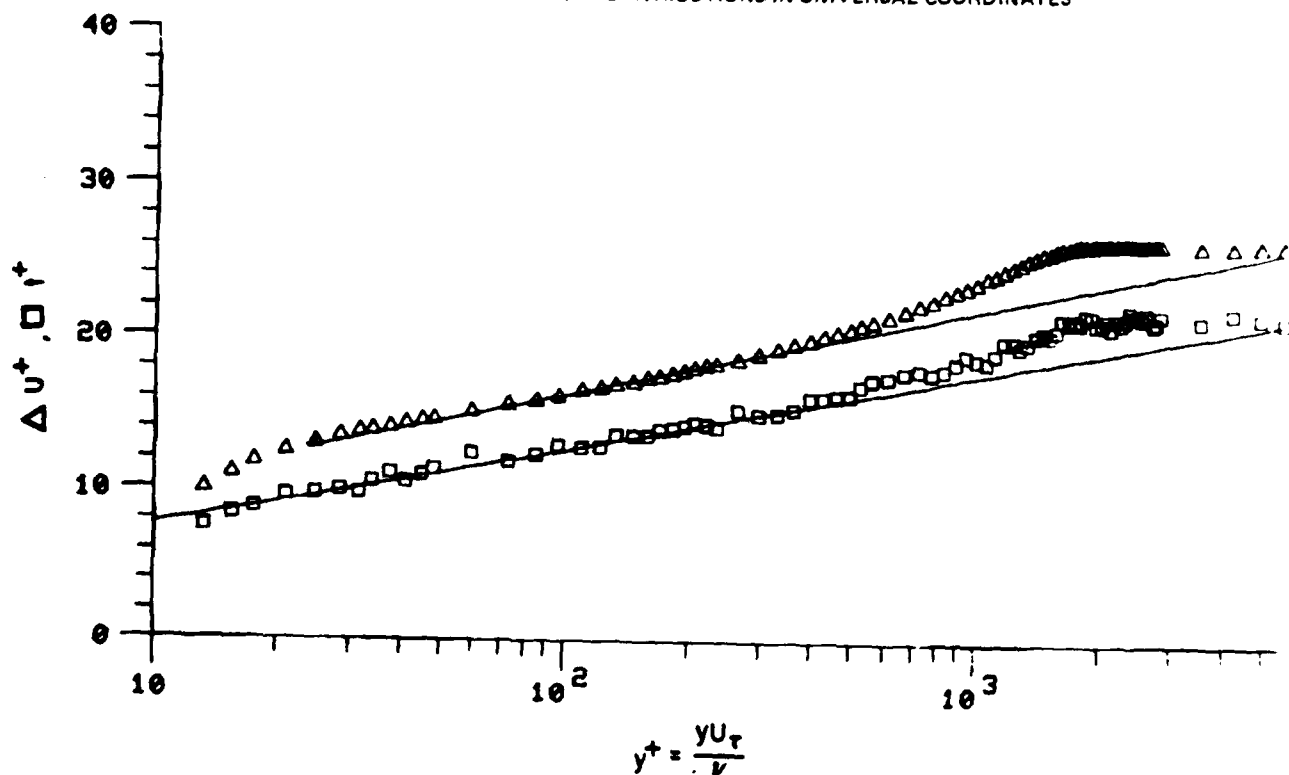


Figure B5. Mean Velocity and Temperature Profiles $x = 84$ in., $Te = 0.2\%$

Mean Profile Data

x = 84 in., Te = 0.2%

N	Y INCHES	Y/ DELTA	L FT/SEC	T DEG.F	U/C	THETA	U-UE CTAU	U(%)	T(%)	Y(%)
1	.0073	.009	32.89	84.66	.392	.329	-15.606	10.66	7.45	13.45
2	.0066	.011	42.91	83.56	.423	.394	-14.566	11.109	6.977	16.402
3	.0064	.012	44.47	83.36	.446	.407	-14.163	11.512	6.272	17.215
4	.0103	.013	46.27	82.59	.467	.393	-13.695	11.982	6.966	19.666
5	.0116	.015	48.69	82.98	.491	.429	-13.066	12.607	9.777	21.744
6	.0132	.016	50.10	82.44	.509	.460	-12.704	12.971	10.449	24.756
7	.0150	.019	51.77	82.26	.522	.471	-12.272	13.403	11.736	27.166
8	.0156	.019	51.99	82.20	.524	.471	-12.218	13.460	10.743	29.322
9	.0174	.021	53.13	81.90	.536	.493	-11.921	13.754	11.227	32.744
10	.0196	.024	54.35	81.73	.546	.502	-11.603	14.072	11.444	35.222
11	.0223	.026	54.80	81.50	.553	.511	-11.467	14.166	11.551	37.666
12	.0233	.029	55.64	81.30	.561	.524	-11.270	14.405	11.699	40.000
13	.0244	.032	56.07	81.55	.565	.513	-11.158	14.511	11.699	42.333
14	.0266	.033	57.37	81.65	.578	.506	-10.969	14.700	11.551	44.666
15	.0280	.037	57.73	81.65	.578	.507	-10.823	14.853	11.551	46.999
16	.0310	.040	58.34	81.39	.586	.513	-10.702	14.973	11.699	49.333
17	.0336	.044	59.80	80.65	.603	.523	-10.570	15.105	11.699	51.666
18	.0455	.056	61.23	80.67	.617	.554	-9.193	15.463	12.633	54.000
19	.0525	.065	62.44	79.93	.630	.565	-9.824	15.851	12.633	56.333
20	.0556	.072	63.56	79.81	.641	.608	-9.509	16.167	13.866	58.666
21	.0566	.072	63.56	79.81	.641	.615	-9.213	16.462	14.020	60.999
22	.0554	.071	64.42	79.73	.650	.620	-8.996	16.679	14.139	63.333
23	.0723	.089	65.44	79.74	.660	.619	-8.733	16.942	14.114	65.666
24	.0763	.097	66.24	79.16	.666	.653	-8.525	17.151	14.863	67.999
25	.0857	.106	67.15	79.64	.677	.625	-8.290	17.366	14.249	70.333
26	.0923	.114	67.75	79.25	.683	.648	-8.134	17.541	14.773	72.666
27	.0963	.121	66.36	79.13	.684	.655	-7.978	17.696	14.933	74.999
28	.1056	.130	69.05	79.35	.696	.642	-7.798	17.677	14.621	77.333
29	.1125	.139	69.79	78.62	.704	.685	-7.606	18.070	15.627	79.666
30	.1167	.146	70.31	78.74	.709	.678	-7.471	18.204	15.466	81.999
31	.1257	.155	70.61	78.63	.714	.673	-7.342	18.333	15.333	84.333
32	.1327	.164	71.19	78.75	.720	.678	-7.191	18.484	15.455	86.666
33	.1446	.185	72.97	78.58	.735	.688	-6.794	18.682	15.688	88.999
34	.1672	.206	74.24	78.33	.749	.702	-6.454	19.221	16.000	91.333
35	.1844	.227	75.50	77.63	.761	.732	-6.128	19.547	16.679	93.666
36	.2024	.250	76.49	77.69	.771	.740	-5.871	19.804	16.666	95.999
37	.2193	.270	77.79	77.75	.764	.737	-5.535	20.140	16.794	98.333
38	.2374	.293	78.89	77.41	.795	.757	-5.251	20.425	17.247	100.666
39	.2547	.314	80.04	77.40	.807	.757	-4.953	20.723	17.256	102.999
40	.2697	.336	82.07	77.04	.816	.779	-4.737	20.936	17.747	105.333
41	.2897	.357	82.07	76.65	.828	.801	-4.423	21.252	16.261	107.666
42	.3075	.379	82.07	76.50	.836	.810	-4.220	21.455	16.466	109.999
43	.3371	.416	84.65	76.80	.854	.791	-3.759	21.937	16.821	112.333
44	.3677	.453	86.24	76.67	.870	.800	-3.324	22.326	16.821	114.666
45	.3975	.490	87.62	75.93	.884	.844	-2.989	22.696	19.233	116.999
46	.4276	.527	88.97	75.46	.897	.844	-2.640	23.035	19.634	119.333
47	.4576	.565	90.22	75.44	.910	.872	-2.317	23.358	19.881	121.666
48	.4876	.602	91.56	75.06	.923	.895	-1.965	23.710	19.400	123.999
49	.5175	.636	92.82	75.28	.936	.882	-1.645	24.031	20.095	126.333
50	.5477	.675	93.90	74.71	.947	.915	-1.364	24.311	20.000	128.666
51	.5777	.712	94.82	74.57	.956	.923	-1.126	24.549	21.055	130.999
52	.6077	.749	95.62	74.62	.966	.921	-0.867	24.809	21.986	133.333
53	.6377	.786	96.50	74.50	.974	.928	-0.676	24.996	21.145	135.666
54	.6675	.823	97.26	74.10	.981	.951	-0.490	25.185	21.685	137.999
55	.6974	.860	97.80	73.89	.986	.963	-0.354	25.321	21.906	140.333
56	.7275	.897	98.26	74.06	.991	.952	-0.230	25.444	21.706	142.666
57	.7577	.934	98.67	74.11	.995	.951	-0.130	25.544	21.677	144.999
58	.7874	.971	98.94	74.07	.998	.953	-0.059	25.616	21.720	147.333
59	.8177	1.006	98.99	73.70	.998	.975	-0.046	25.633	22.220	149.666
60	.8477	1.045	99.07	73.39	.999	.993	-0.026	25.644	22.633	151.999
61	.8775	1.082	99.14	73.71	1.000	.974	-0.007	25.668	22.600	154.333
62	.9075	1.119	99.20	73.71	1.000	.974	-0.007	25.682	22.200	156.666
63	.9376	1.156	99.18	73.66	1.000	.977	-0.003	25.679	22.269	158.999
64	.9677	1.193	99.13	73.41	1.000	.992	-0.010	25.665	22.613	161.333
65	.9974	1.230	99.14	73.27	1.000	.992	-0.008	25.667	22.792	163.666
66	.0276	1.267	99.12	73.54	.999	.984	-0.013	25.662	22.435	165.999
67	.0575	1.304	99.19	73.85	1.000	.966	-0.086	25.681	22.025	168.333
68	.0877	1.341	99.16	73.60	1.000	.981	-0.001	25.677	22.355	170.666
69	.1176	1.378	99.19	73.58	1.000	.982	-0.006	25.681	22.483	172.999
70	.1476	1.415	99.15	73.51	1.000	.986	-0.004	25.671	22.488	175.333
71	.1776	1.452	99.16	73.88	1.000	.964	-0.002	25.673	22.080	177.666
72	.2073	1.489	99.24	73.71	1.001	.974	-0.018	25.633	22.200	179.999
73	.2375	1.526	99.22	73.84	1.000	.966	-0.012	25.684	22.032	182.333
74	.2675	1.563	99.10	73.52	.999	.985	-0.020	25.656	22.000	184.666
75	.2976	1.600	99.14	73.28	1.000	.977	-0.001	25.666	22.000	186.999
76	.3277	1.637	99.17	73.65	1.000	.977	-0.001	25.674	22.000	189.333
77	.3576	1.674	99.06	73.22	.999	.973	-0.028	25.647	22.000	191.666
78	.3875	1.711	99.10	73.73	.999	.973	-0.020	25.656	22.000	193.999
79	.4177	1.748	99.11	73.55	.999	.983	-0.017	25.658	22.000	196.333
80	.4477	1.785	99.12	73.25	.999	1.001	-0.014	25.662	22.000	198.666
81	.4775	1.822	99.12	73.51	.999	.986	-0.014	25.661	22.000	200.999
82	.5074	1.859	99.12	74.03	1.000	.955	-0.013	25.663	22.178	203.333
83	.5376	1.896	99.08	73.63	.999	.979	-0.024	25.652	22.331	205.666
84	.5676	1.933	99.05	73.63	.999	.979	-0.030	25.645	22.331	207.999
85	.5975	1.970	99.16	73.41	1.000	.992	-0.001	25.676	22.613	210.333
86	.6277	2.007	99.05	73.70	.999	.975	-0.031	25.644	22.216	212.666

Table B7

RUN NO. 3. POINT 1.

BOUNDARY LAYER PROPERTIES

	LINEAR INTERPOLATION TO WALL	STANDARD SUBLAYER FUNCTION FROM WALL TO $Y^+ = 35$
FREE STREAM VELOCITY	99.264	99.264
FREE STREAM TEMPERATURE	71.940	
WALL TEMPERATURE	88.630	
WALL HEAT FLUX	.05020	
FREE STREAM DENSITY	.07512	
FREE STREAM KINEMATIC VISCOSITY	.0001632	
DENSITY OF FLUID AT WALL	.07283	
KINEMATIC VISCOSITY OF FLUID AT WALL	.0001724	
WALL/FREE STREAM DENSITY RATIO	.96956	
LOCATION REYNOLDS NUMBER (REX)	4257589.31	
INPUT VALUE OF VELOCITY DELTA	1.13000	
INPUT VALUE OF TEMPERATURE DELTA	1.25000	
CALCULATED DELTA		1.01545
DELTA 99.5% INPUT	.00000	
DISPLACEMENT THICKNESS (DELSTAR)	.15211	.15221
MOMENTUM THICKNESS (THETA)	.10696	.10706
ENERGY-DISSIPATION THICKNESS	.18910	.18914
ENTHALPY THICKNESS	.00448	.00448
SHAPE FACTOR 12 (DELSTAR/THETA)	1.42212	1.42180
SHAPE FACTOR 12 (ENERGY/THETA)	1.76801	1.76676
MOMENTUM THICKNESS REYNOLDS NUMBER	5421.16	5426.27
DISPLACEMENT THICKNESS REYNOLDS NUMBER	7709.54	7715.06
SKIN FRICTION COEFFICIENT	.002806	
FRICTION VELOCITY	3.77632	
LAW OF THE WALL CONSTANT (K)	.41000	
LAW OF THE WALL CONSTANT (C)	5.00000	
WAKE STRENGTH		.60112
CLAUSERS 'DELTA' INTEGRAL	-3.76703	-3.88635
CLAUSERS 'G' INTEGRAL	27.56274	27.56606
DISPLACEMENT THICKNESS - CONSTANT DENSITY	.14552	.14785
MOMENTUM THICKNESS - CONSTANT DENSITY	.10785	.10795
SHAPE FACTOR 12 - CONSTANT DENSITY	1.34934	1.36957

LOCATION -X- 84.00000

Te = 0.2%

Table B8

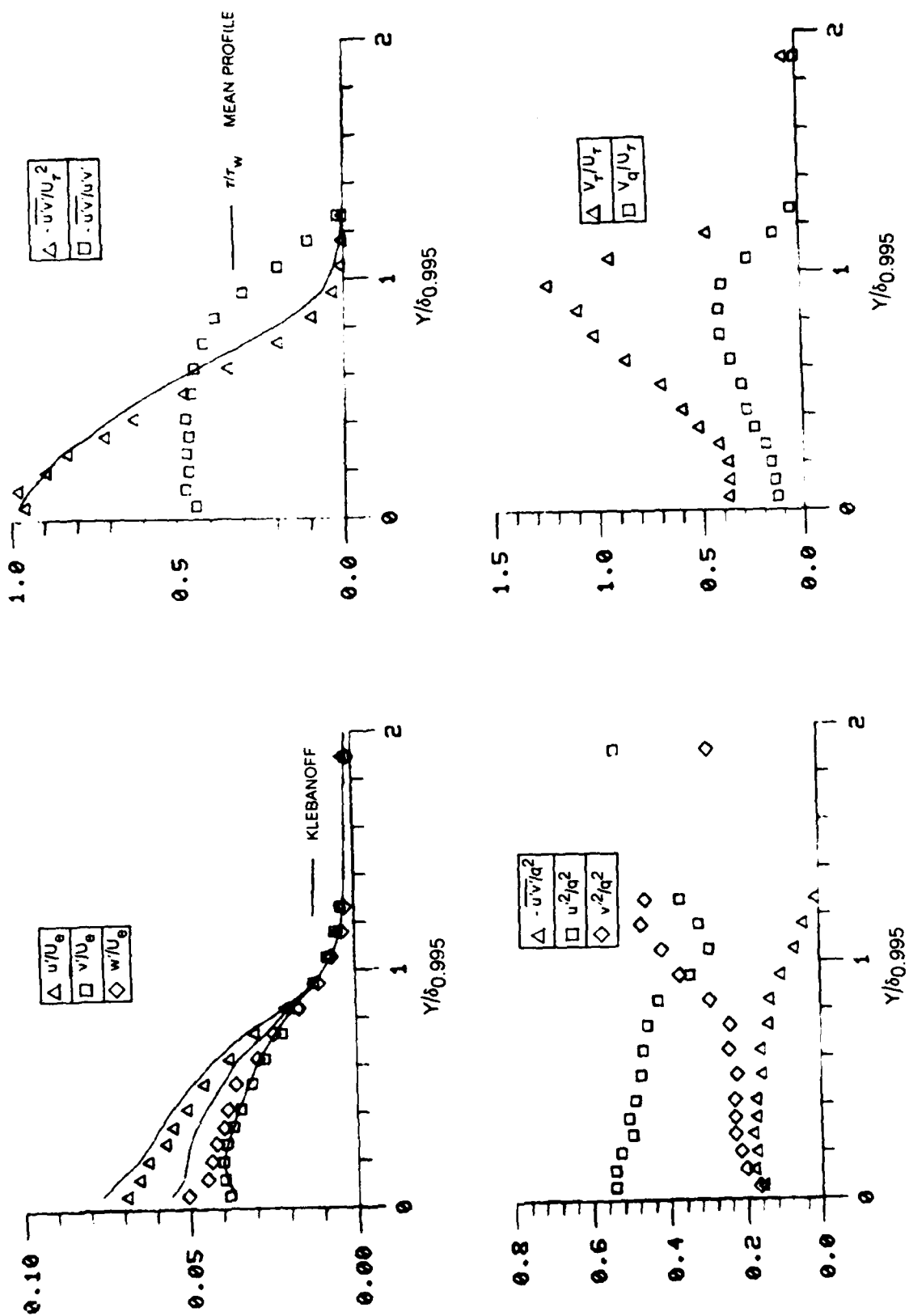


Figure B6A. Boundary Layer Turbulence Quantities $x = 84$ in, $T_e = 0.2\%$

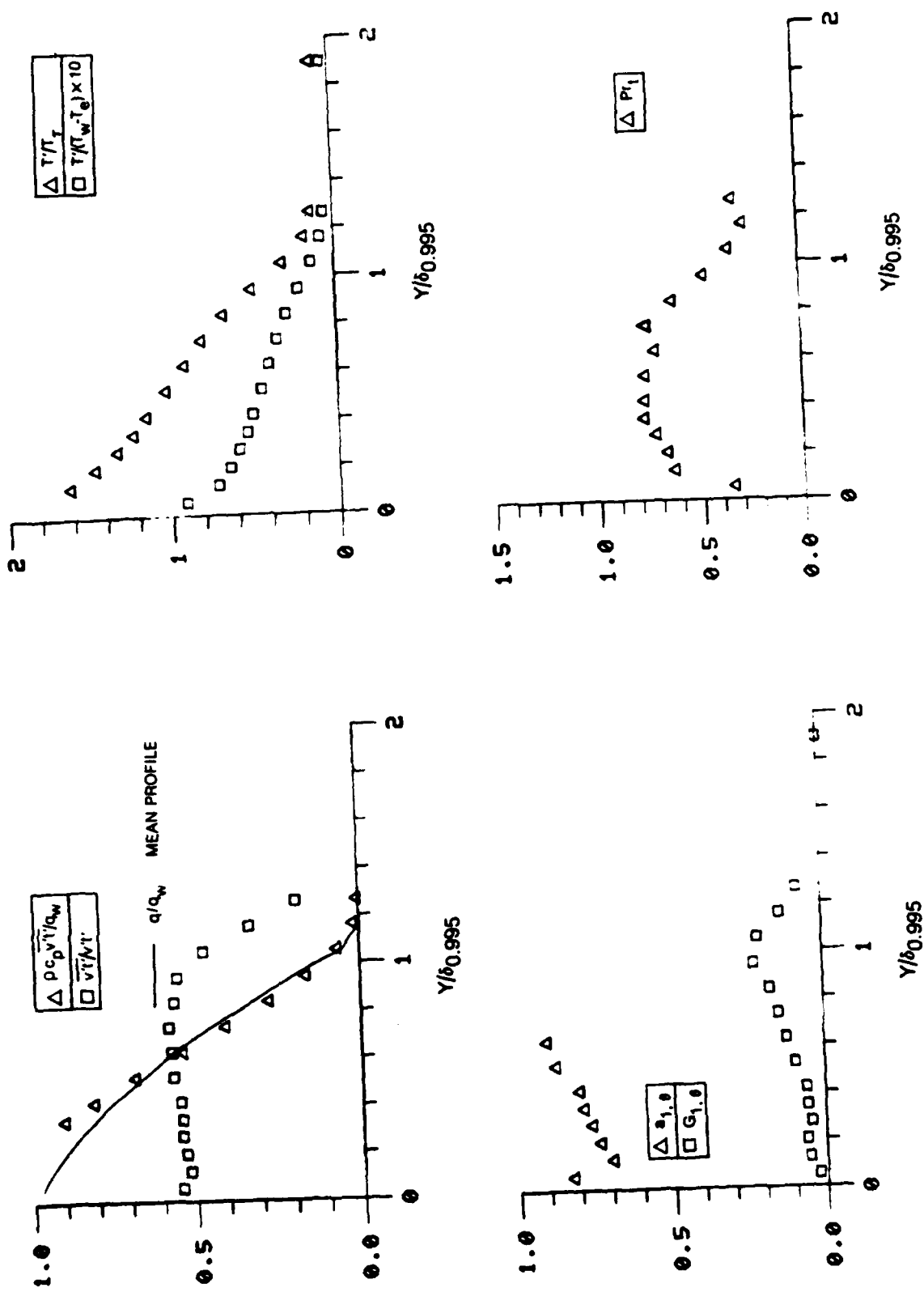


Figure B68. Boundary Layer Turbulence Quantities, $x = 84$ in, $T_e = 0.2\%$

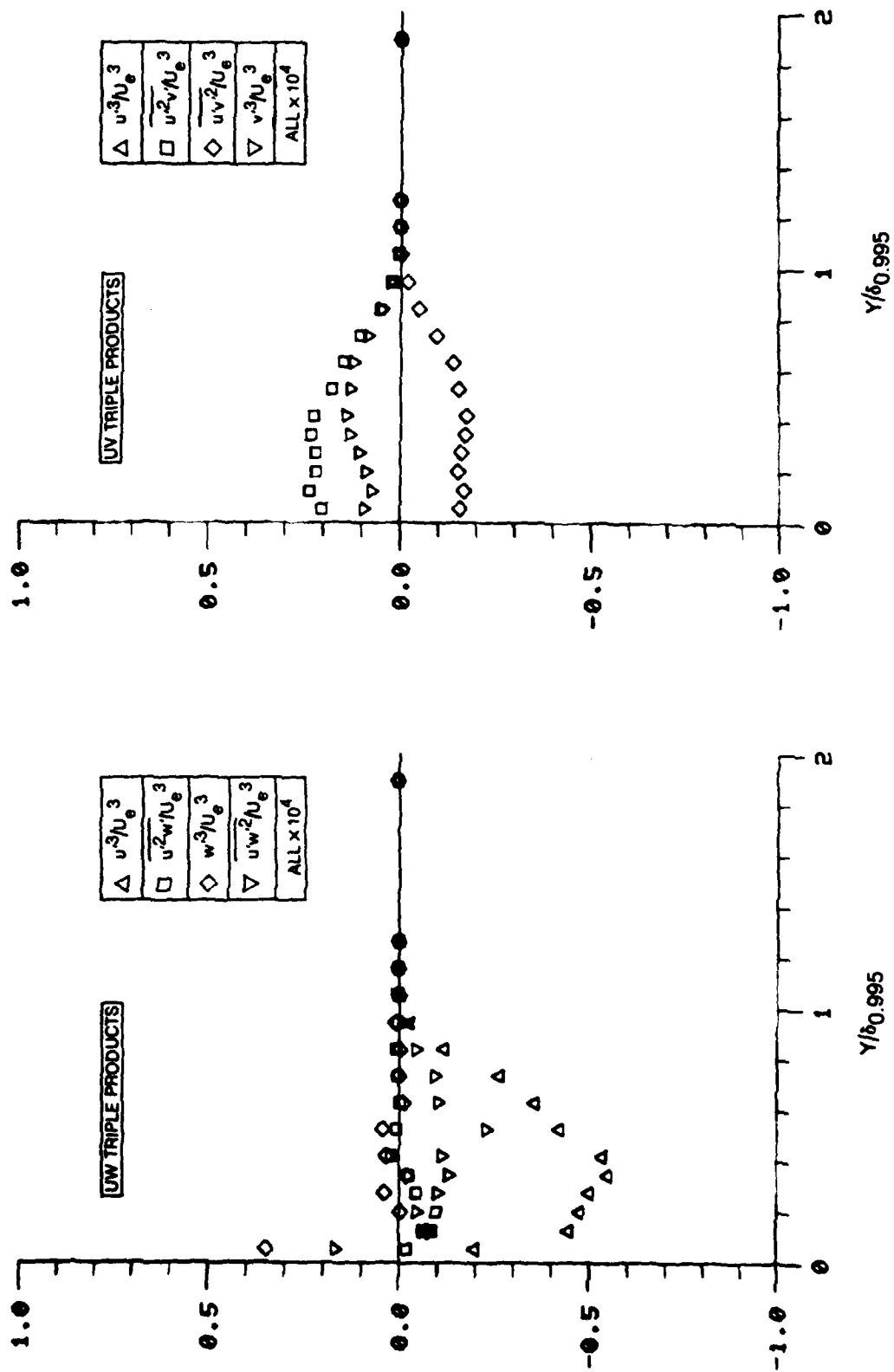


Figure B6C. Boundary Layer Triple Product Distributions $x = 84$ in, $Te = 0.2\%$

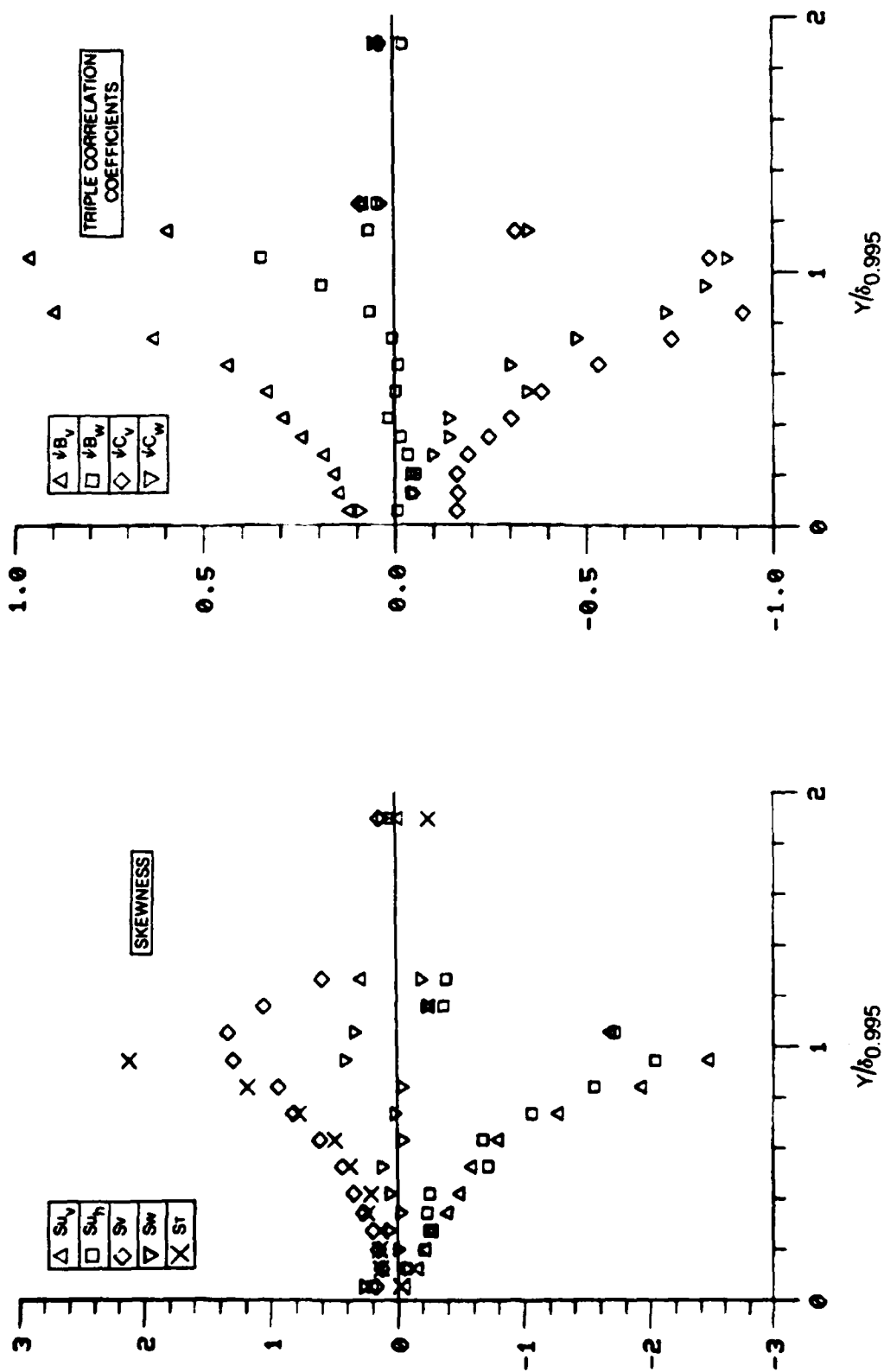


Figure B6D. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 84$ in, $T_e = 0.2\%$

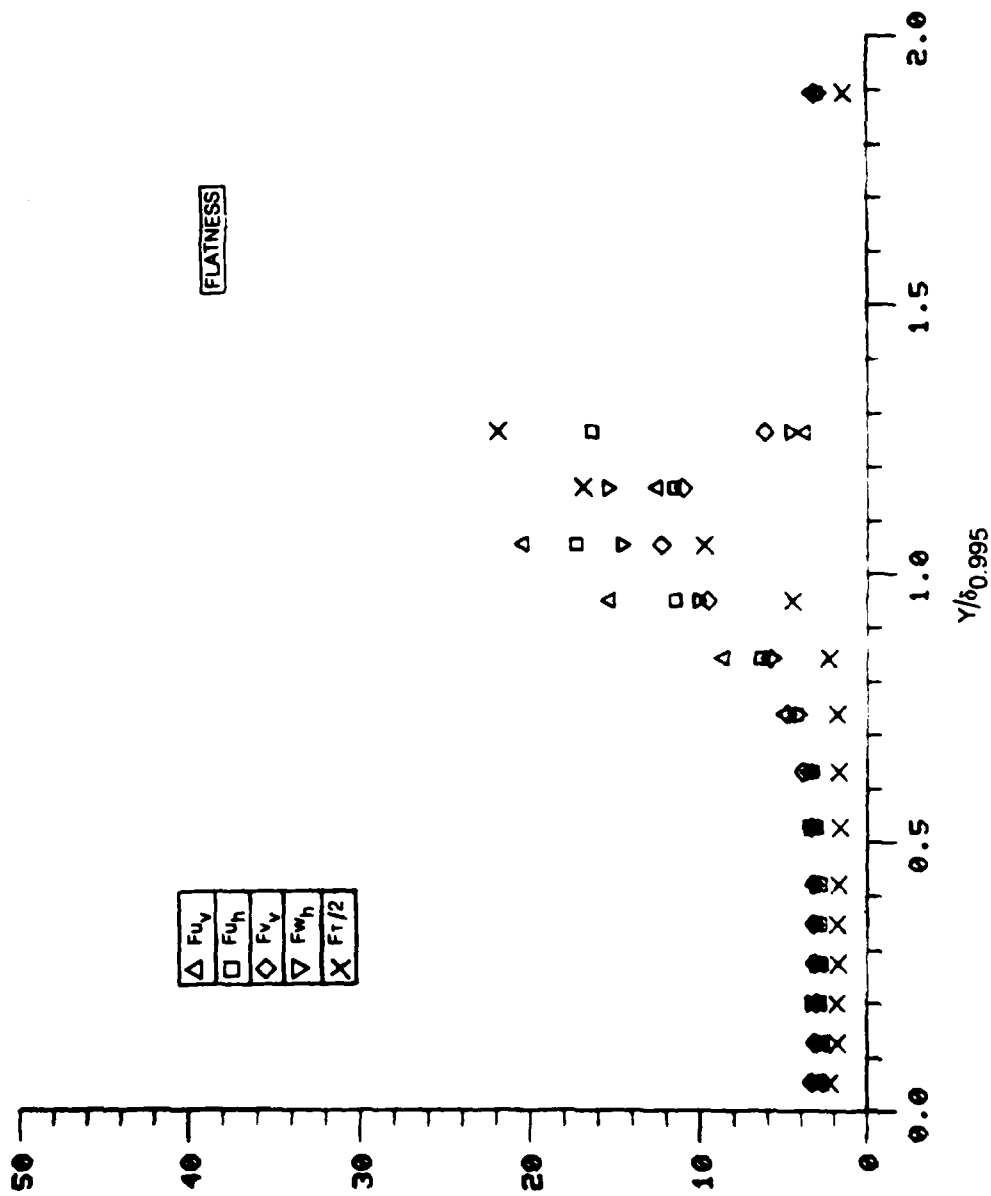


Figure B6E. Boundary Layer Flatness Distributions $x = 84$ in, $T_e = 0.2\%$

Fluctuating Profile Data

x = 84 in., Te = 0.2%

N	Y: INCHES	Y/ DELTA	U*/UE	V*/UE	W*/UE	$\sqrt{U^*V^*}/UE$	$\overline{U^*V^*}/U^*V^*$	C/UE
1	3.0000	3.1556	.0022	.0017	.0011	.0005	-.0002	.0000
2	.0500	.0556	.0690	.0081	.0507	.0370	.9582	.0000
3	.1000	.1111	.0651	.0197	.0450	.0373	.9784	.0000
4	.1500	.1667	.0623	.0399	.0436	.0357	.8916	.0000
5	.2000	.2222	.0571	.0389	.0421	.0344	.8262	.0000
6	.2500	.2778	.0548	.0370	.0396	.0319	.7138	.0000
7	.3000	.3333	.0505	.0346	.0381	.0299	.6279	.0000
8	.3500	.3889	.0452	.0312	.0359	.0260	.4746	.0000
9	.4000	.4444	.0377	.0272	.0294	.0220	.3408	.0000
10	.4500	.5000	.0301	.0219	.0245	.0167	.1947	.0000
11	.5000	.5556	.0208	.0172	.0168	.0116	.0037	.0000
12	.5500	.6111	.0120	.0125	.0110	.0066	.0037	.0000
13	.6000	.6667	.0071	.0084	.0071	.0034	.0074	.0000
14	.6500	.7222	.0048	.0058	.0039	.0017	.0027	.0000
15	.7000	.7778	.0038	.0042	.0029	.0006	.0002	.0000
16	.7500	.8333	.0026	.0031	.0015	.0006	.0000	.0000
17	.8000	.8889	.0022	.0016	.0018	.0005	.0000	.0000
18	.8500	.9444	.0000	.0000	.0000	.0000	.0000	.0000

N	Y: INCHES	Y/ DELTA	$\sqrt{U^*}/C2$	U*/C2	V*/C2	W*/C2	VTAU/ UTAU	VC/ UTAU	$\sqrt{V^*T^*}/C2$
1	3.0000	3.1556	-.0265	.5462	.3245	.1263	-.0311	.0020	.0016
2	.0500	.0556	.1555	.5416	.1654	.2930	.3702	.1326	.0000
3	.1000	.1111	.1780	.5417	.2013	.2580	.3686	.1460	.0000
4	.1500	.1667	.1724	.5271	.2156	.2573	.3712	.1617	.0000
5	.2000	.2222	.1807	.4963	.2210	.2707	.4157	.1864	.0000
6	.2500	.2778	.1713	.5054	.2300	.2646	.5150	.2431	.0000
7	.3000	.3333	.1721	.4901	.2306	.2743	.5926	.2820	.0000
8	.3500	.3889	.1571	.4749	.2257	.2994	.6944	.3030	.0000
9	.4000	.4444	.1607	.4653	.2448	.2859	.8629	.3578	.0000
10	.4500	.5000	.1395	.4559	.2416	.3024	1.0112	.4046	.0000
11	.5000	.5556	.1321	.4280	.2923	.2797	1.0841	.4139	.0000
12	.5500	.6111	.1033	.3427	.3717	.2856	1.2316	.3923	.0000
13	.6000	.6667	.0661	.2935	.4153	.2909	.9351	.2661	.0000
14	.6500	.7222	.0403	.3189	.4686	.2125	.4590	.1336	.0000
15	.7000	.7778	.0079	.3665	.4566	.1766	.7956	.0414	.0000
16	.7500	.8333	.0026	.4507	.2992	.1801	.6564	.0026	.0000
17	.8000	.8889	.0000	.4500	.2485	.3016	.6117	.0000	.0000
18	.8500	.9444	.0000	.0000	.0000	.0000	.0000	.0000	.0000

N	Y: INCHES	Y/ DELTA	$\sqrt{V^*T^*}/V^*T^*$	T*/TTAU	T*/(TW-TE)	A16	G16	PRT
1	3.0000	3.1556	.0833	.1024	.0045	.6516	-.0023	.6734
2	.0500	.0556	.5444	.0621	.0915	.8264	.0244	.0000
3	.1000	.1111	.5201	.1627	.0722	.7012	.0545	.0000
4	.1500	.1667	.5298	.1465	.0650	.7377	.0632	.0000
5	.2000	.2222	.5405	.1306	.0590	.7617	.0484	.0000
6	.2500	.2778	.5415	.1232	.0547	.7871	.0585	.0000
7	.3000	.3333	.5452	.1154	.0512	.8035	.0639	.0000
8	.3500	.3889	.5670	.1026	.0455	.8787	.0968	.0000
9	.4000	.4444	.5704	.0913	.0405	.9054	.1267	.0000
10	.4500	.5000	.5756	.0805	.0358	1.0112	.1536	.0000
11	.5000	.5556	.5592	.0678	.0298	1.1645	.1795	.0000
12	.5500	.6111	.5472	.0494	.0219	1.5421	.2305	.0000
13	.6000	.6667	.4668	.0307	.0137	1.8759	.2157	.0000
14	.6500	.7222	.3262	.0189	.0081	1.7551	.1420	.0000
15	.7000	.7778	.1854	.0051	.0057	2.0844	.0823	.0000
16	.7500	.8333	.0471	.0000	.0048	.2512	.0000	.0000
17	.8000	.8889	.0380	.0000	.0045	.0000	.0000	.0000
18	.8500	.9444	.0000	.0000	.0000	.0000	.0000	.0000

Table B9A

Flucutating Profile Data

x = 84 in., Te = 0.2%

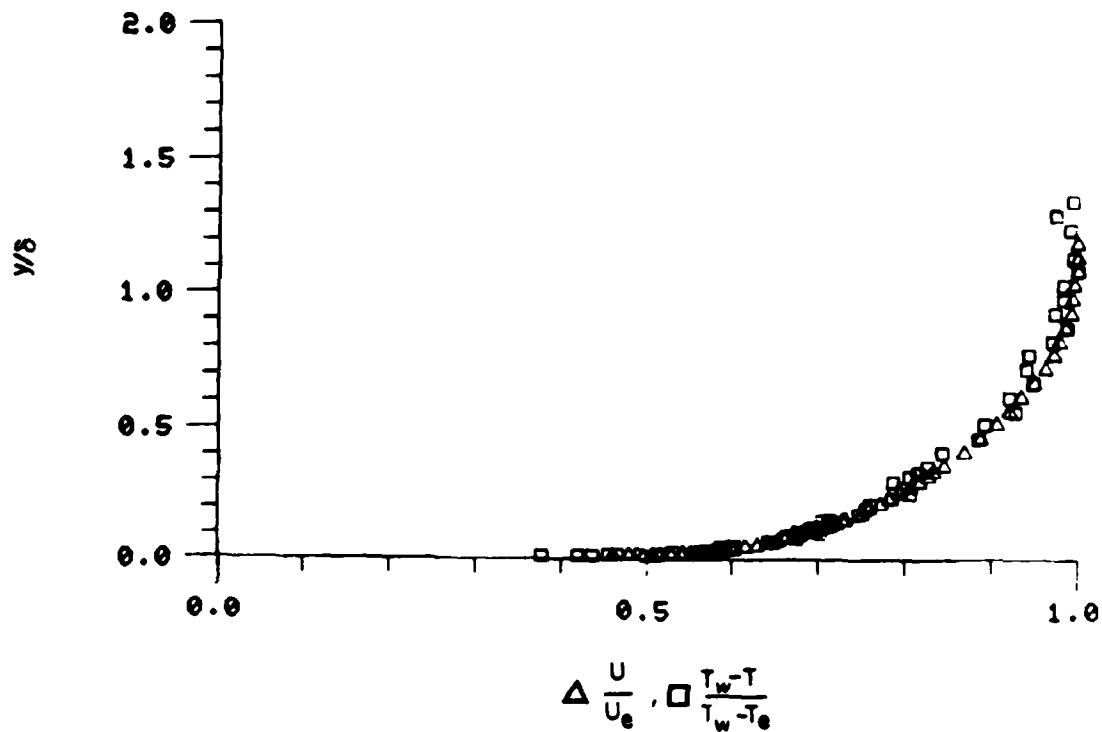
N	Y: INCHES	Y/ DELTA	U ³ /U ² x 10000	U ² /U ¹ x 10000	U ³ /U ² x 10000	U ⁴ /U ³ x 10000	U ⁵ /U ⁴ x 10000	U ⁶ /U ⁵ x 10000	U ⁷ /U ⁶ x 10000
1	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
2	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
3	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
4	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
5	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
6	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
7	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
8	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
9	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
10	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
11	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
12	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
13	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
14	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
15	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
16	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
17	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000
18	3.0000	3.1558	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000	-.0000

N	Y: INCHES	Y/ DELTA	SU V	SU H	SV	Sh	ST	PSIBV	PSIBH
1	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
2	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
3	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
4	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
5	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
6	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
7	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
8	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
9	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
10	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
11	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
12	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
13	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
14	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
15	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
16	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
17	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000
18	3.0000	3.1558	-.0762	-.1192	.0254	-.1439	-.0000	.0541	-.0000

N	Y: INCHES	Y/ DELTA	PSICV	PSICW	FU V	FU H	FU V	FU H	FT
1	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
2	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
3	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
4	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
5	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
6	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
7	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
8	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
9	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
10	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
11	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
12	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
13	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
14	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
15	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
16	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
17	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612
18	3.0000	3.1558	-.0350	-.0248	.0612	.2235	.0612	.2235	.0612

Table B9B

VELOCITY AND TEMPERATURE RATIOS



VELOCITY AND TEMPERATURE DISTRIBUTIONS IN UNIVERSAL COORDINATES

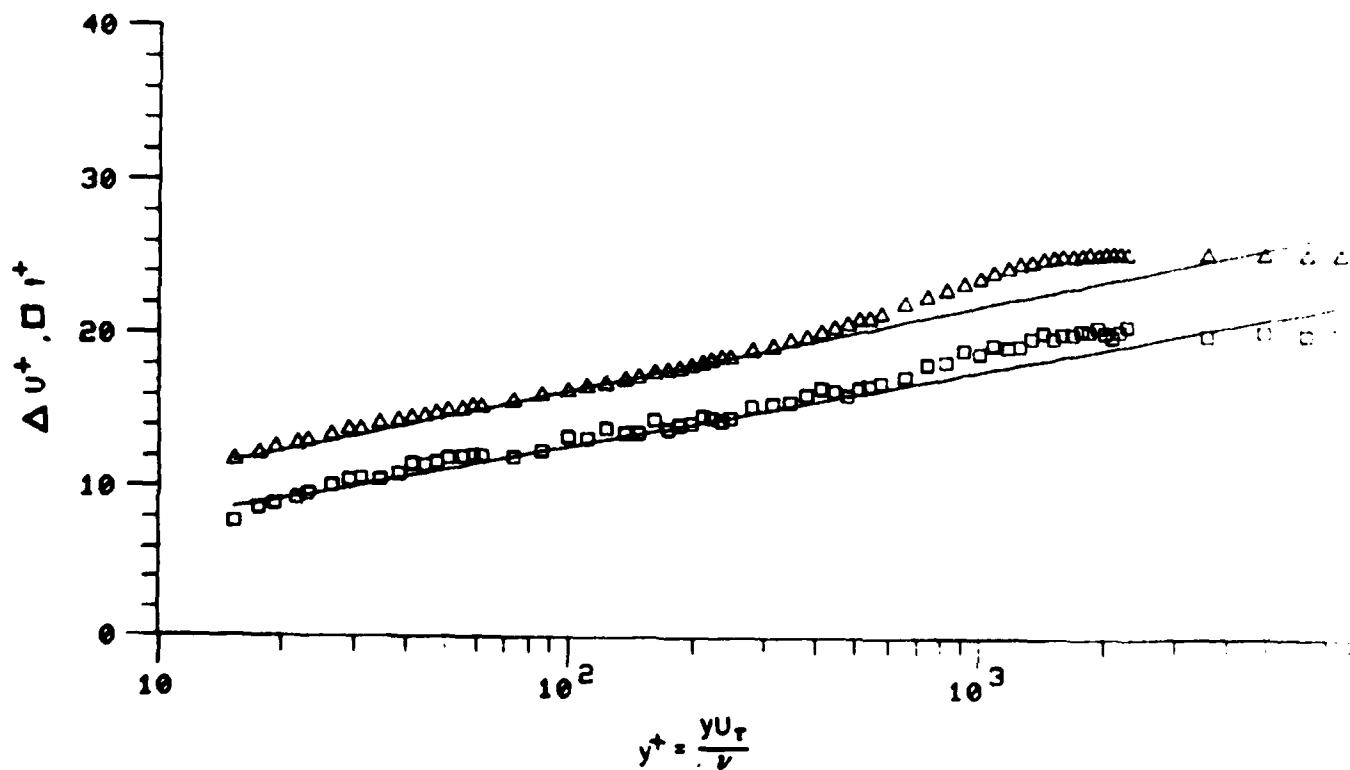


Figure B7. Mean Profile and Temperature Profiles $x = 52$ in., $Te = 1.8\%$

$x = 52 \text{ in.}, T_e = 1.8\%$ [illegible]

Table B10

RUN NO. 3. POINT 3.

BOUNDARY LAYER PROPERTIES

	LINEAR INTERPOLATION TO WALL	STANDARD SUBLAYER FUNCTION FROM WALL TO $Y^+ = 35$
FREE STREAM VELOCITY	98.101	98.101
FREE STREAM TEMPERATURE	70.960	
WALL TEMPERATURE	94.980	
WALL HEAT FLUX	.07908	
FREE STREAM DENSITY	.07541	
FREE STREAM KINEMATIC VISCOSITY	.0001623	
DENSITY OF FLUID AT WALL	.07214	
KINEMATIC VISCOSITY OF FLUID AT WALL	.0001756	
WALL/FREE STREAM DENSITY RATIO	.95669	
LOCATION REYNOLDS NUMBER (REX)	2618495.47	
INPUT VALUE OF VELOCITY DELTA	1.00000	
INPUT VALUE OF TEMPERATURE DELTA	1.00000	
CALCULATED DELTA		.86723
DELTA 99.5% INPUT	.00000	
DISPLACEMENT THICKNESS (DELSTAR)	.12408	.12411
MOMENTUM THICKNESS (THETA)	.08716	.08756
ENERGY-DISSIPATION THICKNESS	.15548	.15581
ENTHALPY THICKNESS	.00436	.00437
SHAPE FACTOR 12 (DELSTAR/THETA)	1.42349	1.41709
SHAPE FACTOR 32 (ENERGY/THETA)	1.78378	1.77907
MOMENTUM THICKNESS REYNOLDS NUMBER	4389.16	4410.12
DISPLACEMENT THICKNESS REYNOLDS NUMBER	6247.94	6249.55
SKIN FRICTION COEFFICIENT	.002998	
FRICTION VELOCITY	3.86308	
LAW OF THE WALL CONSTANT (K)	.41000	
LAW OF THE WALL CONSTANT (C)	5.00000	
WAKE STRENGTH		.46566
CLAUSERS 'DELTA' INTEGRAL	-2.81396	-3.02501
CLAUSERS 'G' INTEGRAL	20.20020	19.93822
DISPLACEMENT THICKNESS - CONSTANT DENSITY	.11555	.11974
MOMENTUM THICKNESS - CONSTANT DENSITY	.08806	.08850
SHAPE FACTOR 12 - CONSTANT DENSITY	1.31209	1.35299

LOCATION -X- 52.00000

Te = 1.8%

Table B11

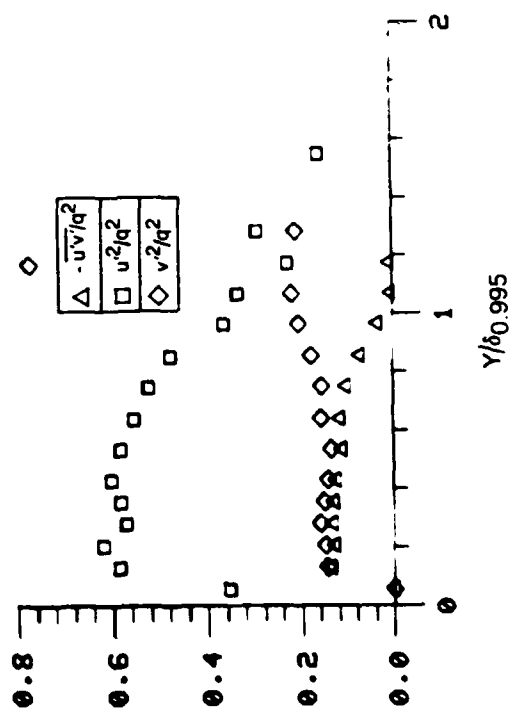
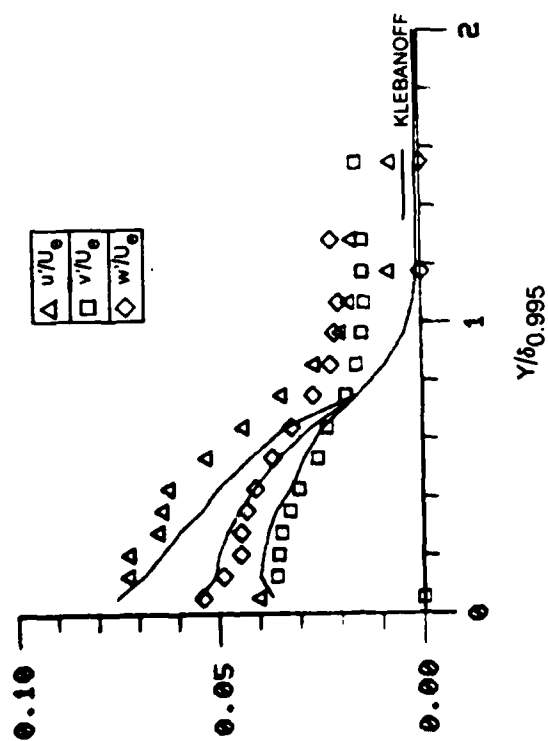
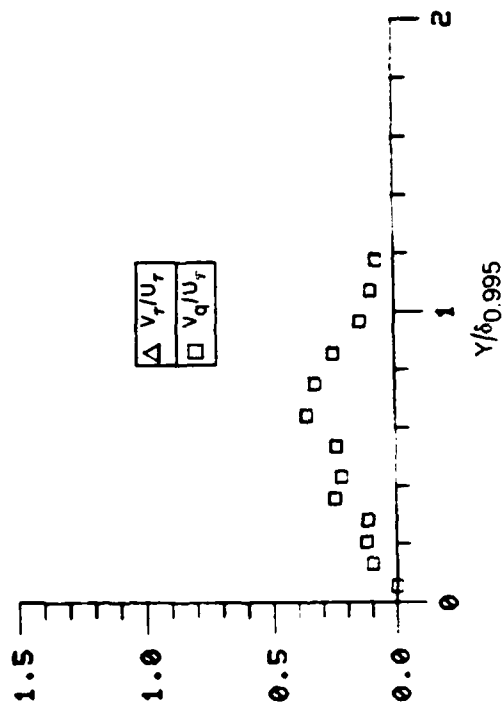
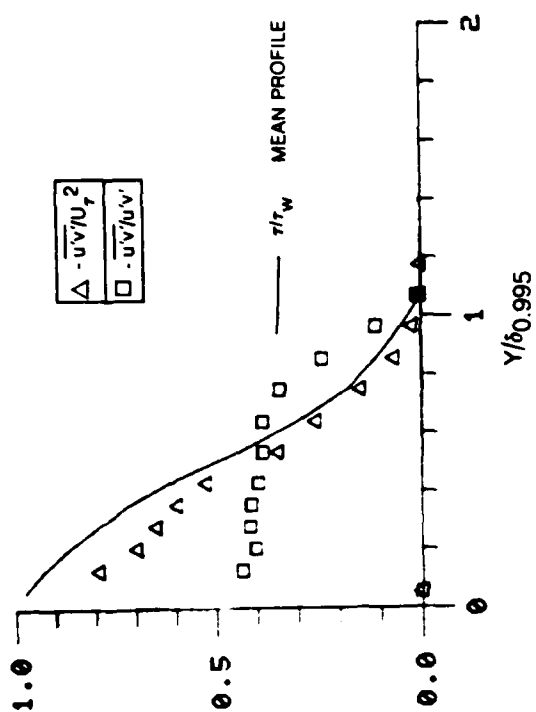


Figure B8A. Boundary Layer Turbulence Quantities $x = 52$ in, $T_e = 1.8\%$

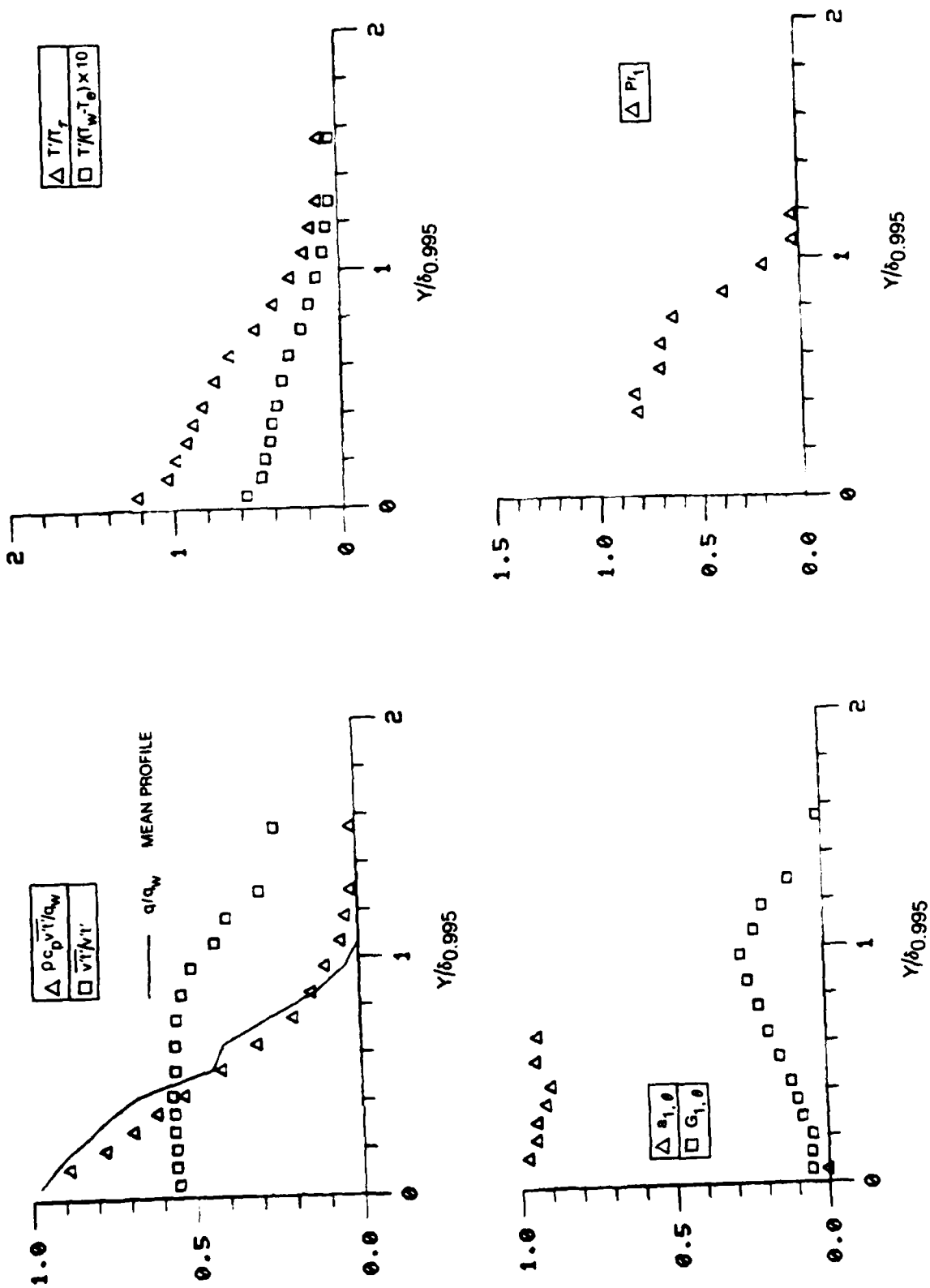


Figure B8B. Boundary Layer Turbulence Quantities $x = 52$ in, $T_e = 1.8\%$

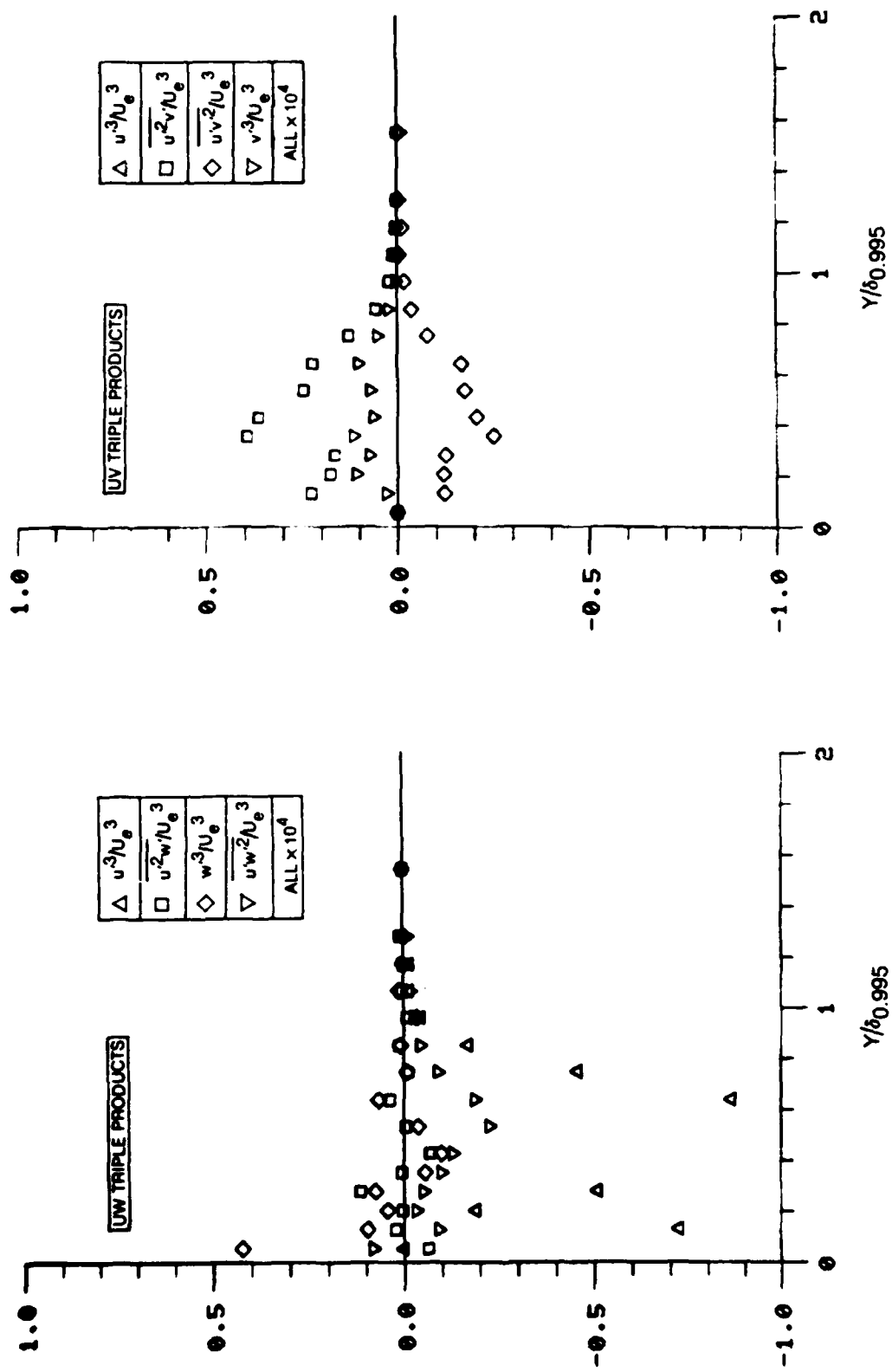


Figure B8C. Boundary Layer Triple Product Distributions $x = 52$ in, $T_e = 1.8\%$

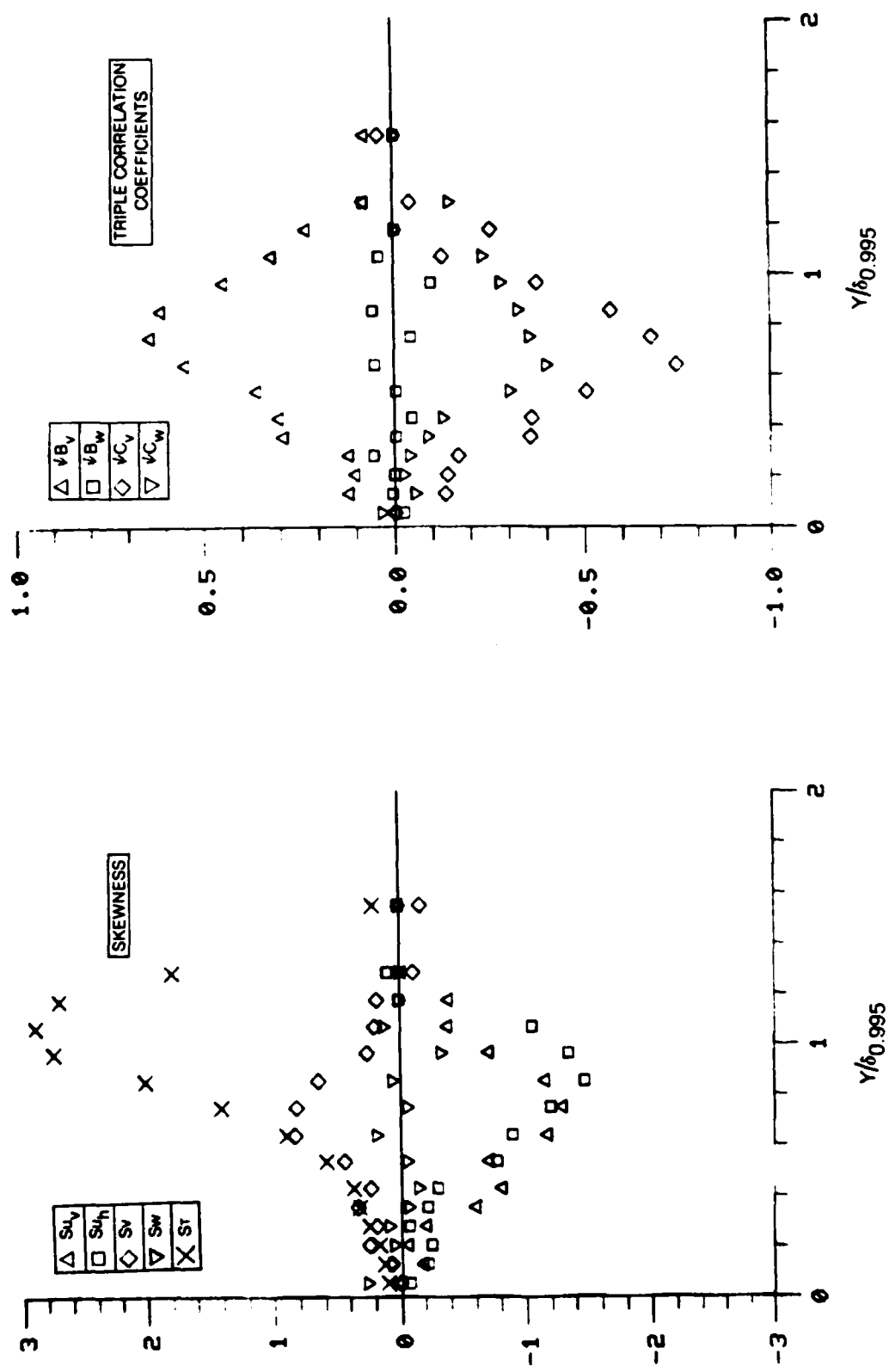


Figure B8D. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 52$ in, $T_e = 1.8^\circ$

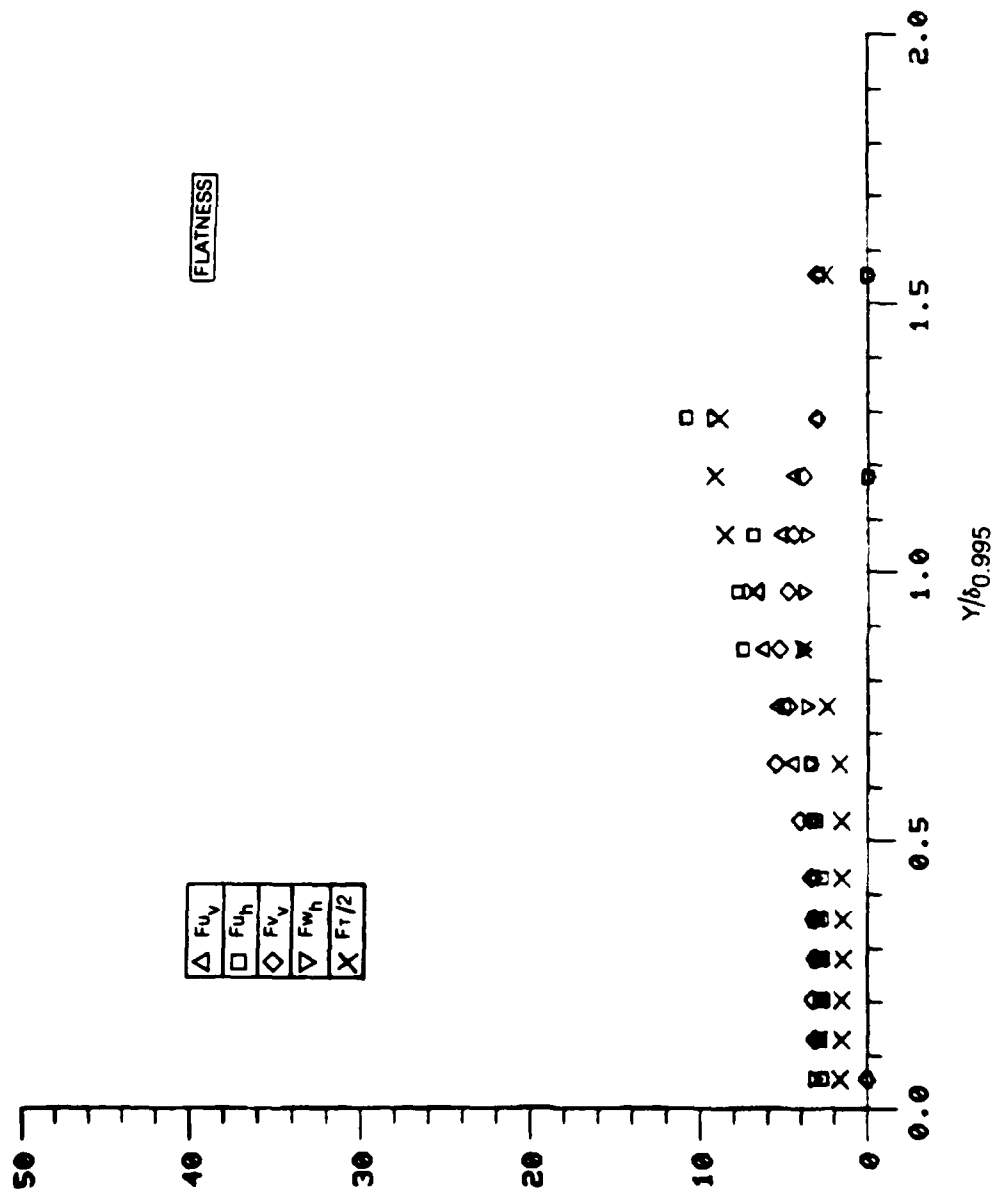


Figure B8E. Boundary Layer Flatness Distributions $x = 52$ in, $T_e = 1.8\%$

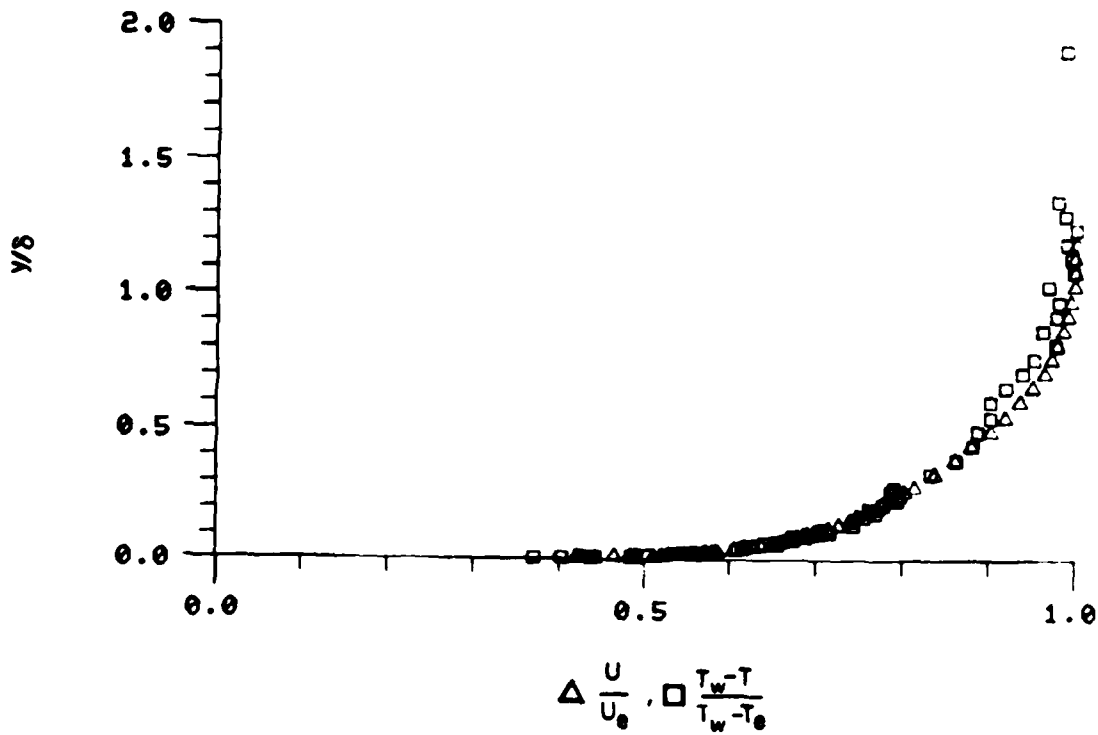
$x = 52 \text{ in.}, T_e = 1.8\%$

Table B12A

$$x = 52 \text{ in.}, T_e = 1.8\%$$
[illegible]

Table B12B.

VELOCITY AND TEMPERATURE RATIOS



VELOCITY AND TEMPERATURE DISTRIBUTIONS IN UNIVERSAL COORDINATES

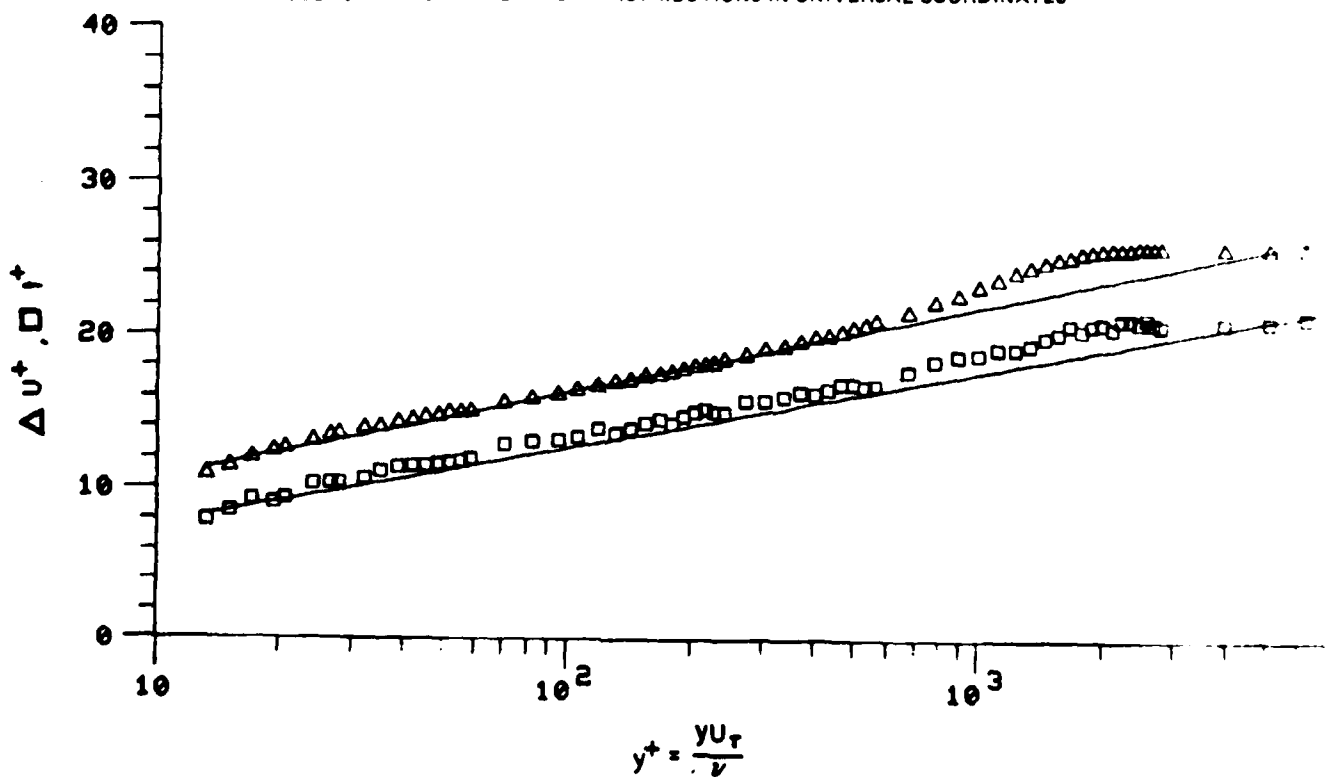


Figure B9. Mean Velocity and Temperature Profiles $x = 68$ in., $Te = 1.6\%$

Mean Profile Data

x = 68 in., Te = 1.6%

	Y	Y/	U	T	U/UE	THETA	U(1)	Y(1)	Y(1)
	INCH	DELTA	FT/SEC	DEG F	U/UE	THETA	U(1)	Y(1)	Y(1)
1	.0007	.0007	41.36	86.26	.421	.371	1.0	7.672	1.255
2	.0008	.0008	43.36	85.44	.442	.371	1.0	7.672	1.255
3	.0009	.0009	45.36	84.62	.464	.371	1.0	7.672	1.255
4	.0010	.0010	47.36	83.80	.486	.371	1.0	7.672	1.255
5	.0011	.0011	49.36	82.98	.508	.371	1.0	7.672	1.255
6	.0012	.0012	51.36	82.16	.530	.371	1.0	7.672	1.255
7	.0013	.0013	53.36	81.34	.552	.371	1.0	7.672	1.255
8	.0014	.0014	55.36	80.52	.574	.371	1.0	7.672	1.255
9	.0015	.0015	57.36	79.70	.596	.371	1.0	7.672	1.255
10	.0016	.0016	59.36	78.88	.618	.371	1.0	7.672	1.255
11	.0017	.0017	61.36	78.06	.640	.371	1.0	7.672	1.255
12	.0018	.0018	63.36	77.24	.662	.371	1.0	7.672	1.255
13	.0019	.0019	65.36	76.42	.684	.371	1.0	7.672	1.255
14	.0020	.0020	67.36	75.60	.706	.371	1.0	7.672	1.255
15	.0021	.0021	69.36	74.78	.728	.371	1.0	7.672	1.255
16	.0022	.0022	71.36	73.96	.750	.371	1.0	7.672	1.255
17	.0023	.0023	73.36	73.14	.772	.371	1.0	7.672	1.255
18	.0024	.0024	75.36	72.32	.794	.371	1.0	7.672	1.255
19	.0025	.0025	77.36	71.50	.816	.371	1.0	7.672	1.255
20	.0026	.0026	79.36	70.68	.838	.371	1.0	7.672	1.255
21	.0027	.0027	81.36	69.86	.860	.371	1.0	7.672	1.255
22	.0028	.0028	83.36	69.04	.882	.371	1.0	7.672	1.255
23	.0029	.0029	85.36	68.22	.904	.371	1.0	7.672	1.255
24	.0030	.0030	87.36	67.40	.926	.371	1.0	7.672	1.255
25	.0031	.0031	89.36	66.58	.948	.371	1.0	7.672	1.255
26	.0032	.0032	91.36	65.76	.970	.371	1.0	7.672	1.255
27	.0033	.0033	93.36	64.94	.992	.371	1.0	7.672	1.255
28	.0034	.0034	95.36	64.12	.101	.371	1.0	7.672	1.255
29	.0035	.0035	97.36	63.30	.110	.371	1.0	7.672	1.255
30	.0036	.0036	99.36	62.48	.119	.371	1.0	7.672	1.255
31	.0037	.0037	101.36	61.66	.128	.371	1.0	7.672	1.255
32	.0038	.0038	103.36	60.84	.137	.371	1.0	7.672	1.255
33	.0039	.0039	105.36	60.02	.146	.371	1.0	7.672	1.255
34	.0040	.0040	107.36	59.20	.155	.371	1.0	7.672	1.255
35	.0041	.0041	109.36	58.38	.164	.371	1.0	7.672	1.255
36	.0042	.0042	111.36	57.56	.173	.371	1.0	7.672	1.255
37	.0043	.0043	113.36	56.74	.182	.371	1.0	7.672	1.255
38	.0044	.0044	115.36	55.92	.191	.371	1.0	7.672	1.255
39	.0045	.0045	117.36	55.10	.200	.371	1.0	7.672	1.255
40	.0046	.0046	119.36	54.28	.209	.371	1.0	7.672	1.255
41	.0047	.0047	121.36	53.46	.218	.371	1.0	7.672	1.255
42	.0048	.0048	123.36	52.64	.227	.371	1.0	7.672	1.255
43	.0049	.0049	125.36	51.82	.236	.371	1.0	7.672	1.255
44	.0050	.0050	127.36	51.00	.245	.371	1.0	7.672	1.255
45	.0051	.0051	129.36	50.18	.254	.371	1.0	7.672	1.255
46	.0052	.0052	131.36	49.36	.263	.371	1.0	7.672	1.255
47	.0053	.0053	133.36	48.54	.272	.371	1.0	7.672	1.255
48	.0054	.0054	135.36	47.72	.281	.371	1.0	7.672	1.255
49	.0055	.0055	137.36	46.90	.290	.371	1.0	7.672	1.255
50	.0056	.0056	139.36	46.08	.299	.371	1.0	7.672	1.255
51	.0057	.0057	141.36	45.26	.308	.371	1.0	7.672	1.255
52	.0058	.0058	143.36	44.44	.317	.371	1.0	7.672	1.255
53	.0059	.0059	145.36	43.62	.326	.371	1.0	7.672	1.255
54	.0060	.0060	147.36	42.80	.335	.371	1.0	7.672	1.255
55	.0061	.0061	149.36	41.98	.344	.371	1.0	7.672	1.255
56	.0062	.0062	151.36	41.16	.353	.371	1.0	7.672	1.255
57	.0063	.0063	153.36	40.34	.362	.371	1.0	7.672	1.255
58	.0064	.0064	155.36	39.52	.371	.371	1.0	7.672	1.255
59	.0065	.0065	157.36	38.70	.380	.371	1.0	7.672	1.255
60	.0066	.0066	159.36	37.88	.389	.371	1.0	7.672	1.255
61	.0067	.0067	161.36	37.06	.398	.371	1.0	7.672	1.255
62	.0068	.0068	163.36	36.24	.407	.371	1.0	7.672	1.255
63	.0069	.0069	165.36	35.42	.416	.371	1.0	7.672	1.255
64	.0070	.0070	167.36	34.60	.425	.371	1.0	7.672	1.255
65	.0071	.0071	169.36	33.78	.434	.371	1.0	7.672	1.255
66	.0072	.0072	171.36	32.96	.443	.371	1.0	7.672	1.255

Table B13

BOUNDARY LAYER PROPERTIES	LINEAR INTERPOLATION TO WALL	STANDARD SUBLAYER FUNCTION FROM WALL TO $y^+ = 30$
FREE STREAM VELOCITY ==	98.170	98.170
FREE STREAM TEMPERATURE ==	70.180	
WALL TEMPERATURE ==	95.750	
WALL HEAT FLUX ==	.07954	
FREE STREAM DENSITY ==	.07552	
FREE STREAM KINEMATIC VISCOSITY ==	.0001619	
DENSITY OF FLUID AT WALL ==	.07204	
KINEMATIC VISCOSITY OF FLUID AT WALL ==	.0001760	
WALL/FREE STREAM DENSITY RATIO ==	.95396	
LOCATION REYNOLDS NUMBER (REX) ==	3435559.84	
INPUT VALUE OF VELOCITY DELTA ==	1.30000	
INPUT VALUE OF TEMPERATURE DELTA ==	1.30000	
CALCULATED DELTA ==		1.12046
DELTA 99.5% INPUT ==	.00000	
DISPLACEMENT THICKNESS (DELSTAR) ==	.15429	.15443
MOMENTUM THICKNESS (THETA) ==	.10938	.10967
ENERGY-DISSIPATION THICKNESS ==	.19539	.19556
ENTHALPY THICKNESS ==	.00597	.00598
SHAPE FACTOR 12 (DELSTAR/THETA) ==	1.41057	1.40819
SHAPE FACTOR 32 (ENERGY/THETA) ==	1.78634	1.78327
MOMENTUM THICKNESS REYNOLDS NUMBER ==	5526.16	5540.66
DISPLACEMENT THICKNESS REYNOLDS NUMBER ==	7795.01	7602.27
SKIN FRICTION COEFFICIENT ==	.002865	
FRICTION VELOCITY ==	3.81748	
LAW OF THE WALL CONSTANT (K) ==	.41000	
LAW OF THE WALL CONSTANT (C) ==	5.00000	
WAKE STRENGTH ==		.44004
CLAUSERS 'DELTA' INTEGRAL ==	-3.62559	-3.81767
CLAUSERS 'G' INTEGRAL ==	24.97566	24.86843
DISPLACEMENT THICKNESS - CONSTANT DENSITY ==	.14465	.14845
MOMENTUM THICKNESS - CONSTANT DENSITY ==	.11055	.11085
SHAPE FACTOR 12 - CONSTANT DENSITY ==	1.30848	1.33924
LOCATION -X-	68.00000	
Te = 1.6%		

Table B14

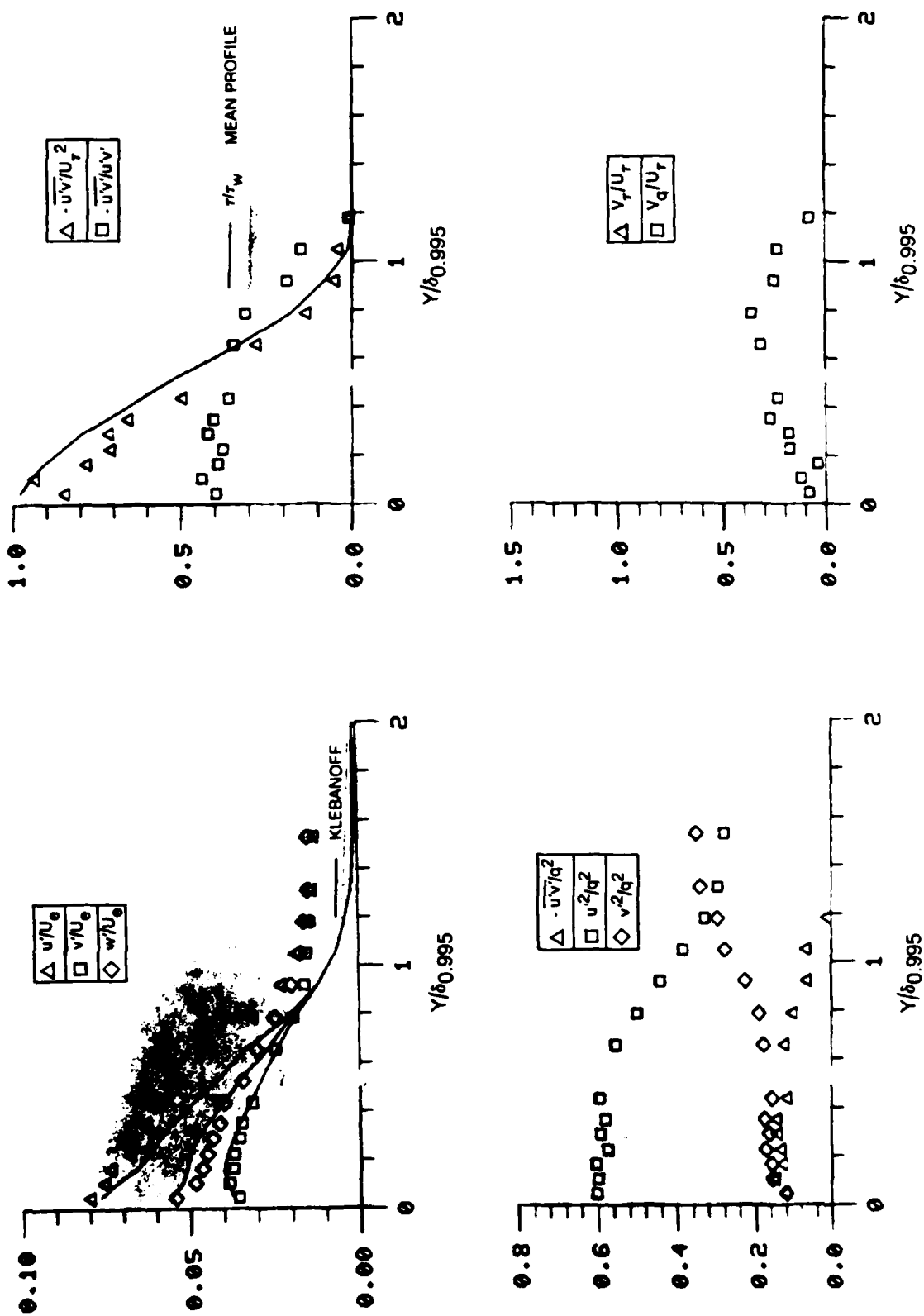


Figure B10A. Boundary Layer Turbulence Quantities $x = 68$ in, $T_e = 1.6\%$

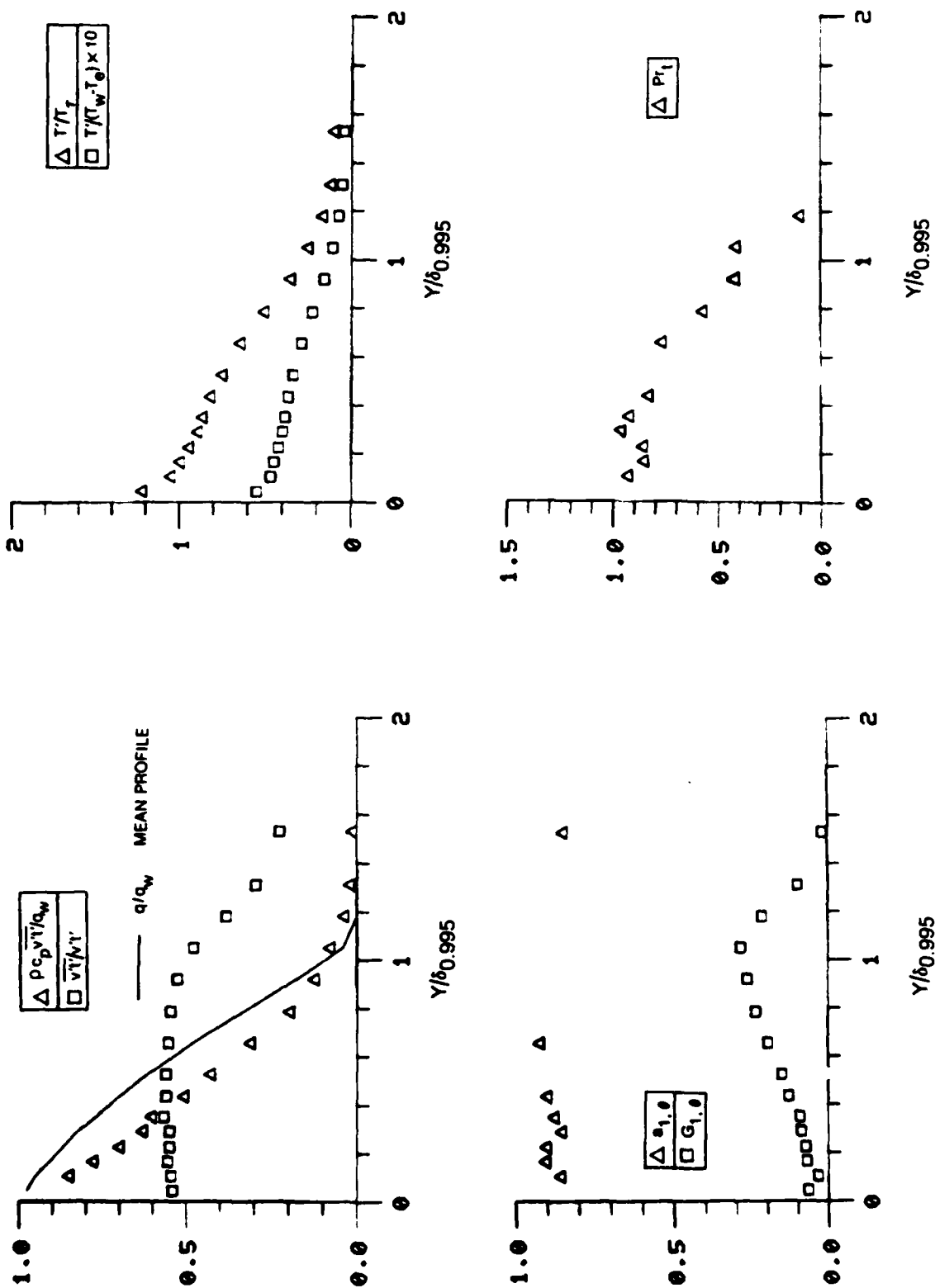


Figure B10B. Boundary Layer Turbulence Quantities $x = 68$ in, $T_e = 1.6\%$

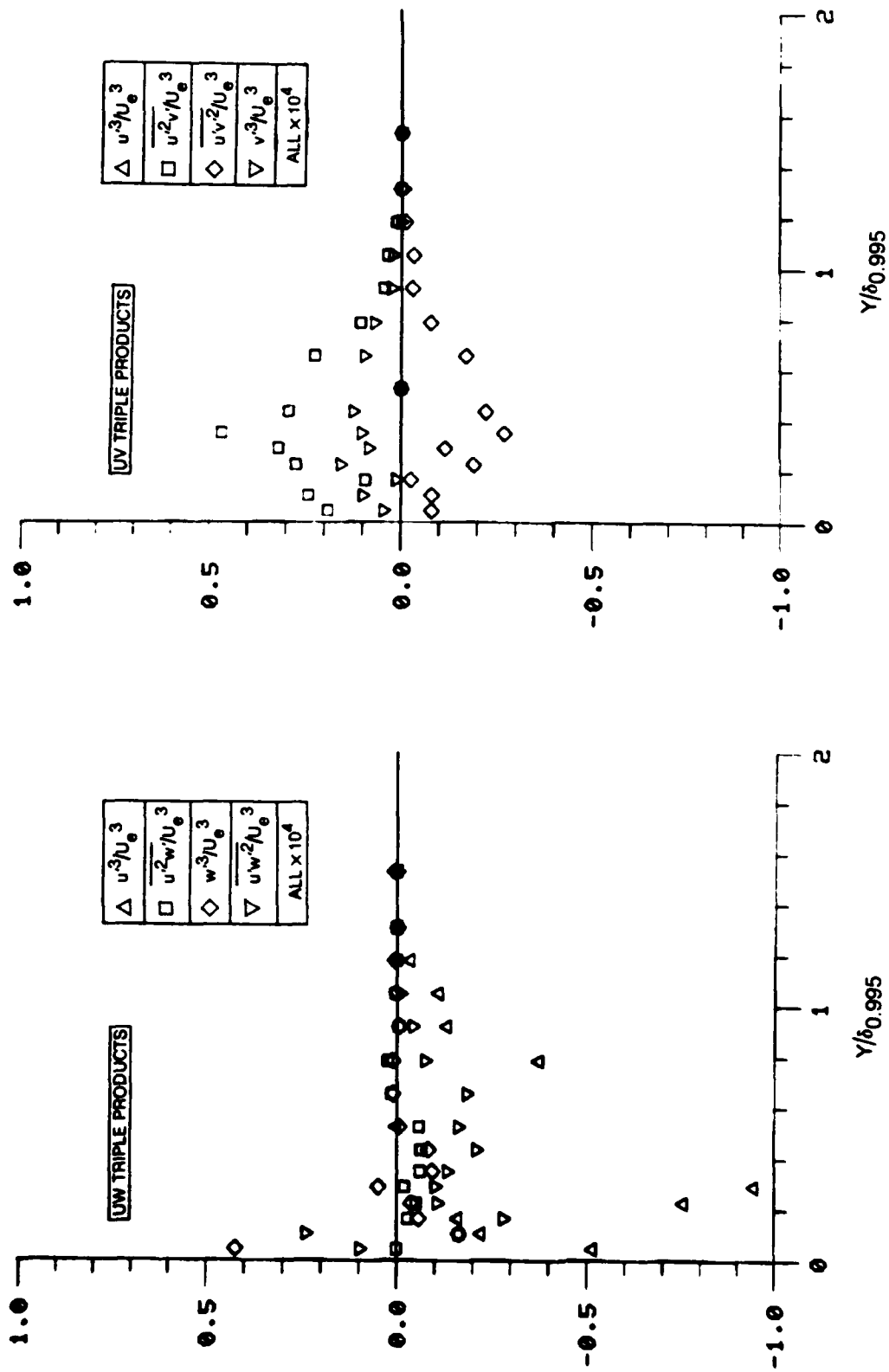


Figure B10C. Boundary Layer Triple Product Distributions $x = 68$ in, $T_e = 1.6\%$

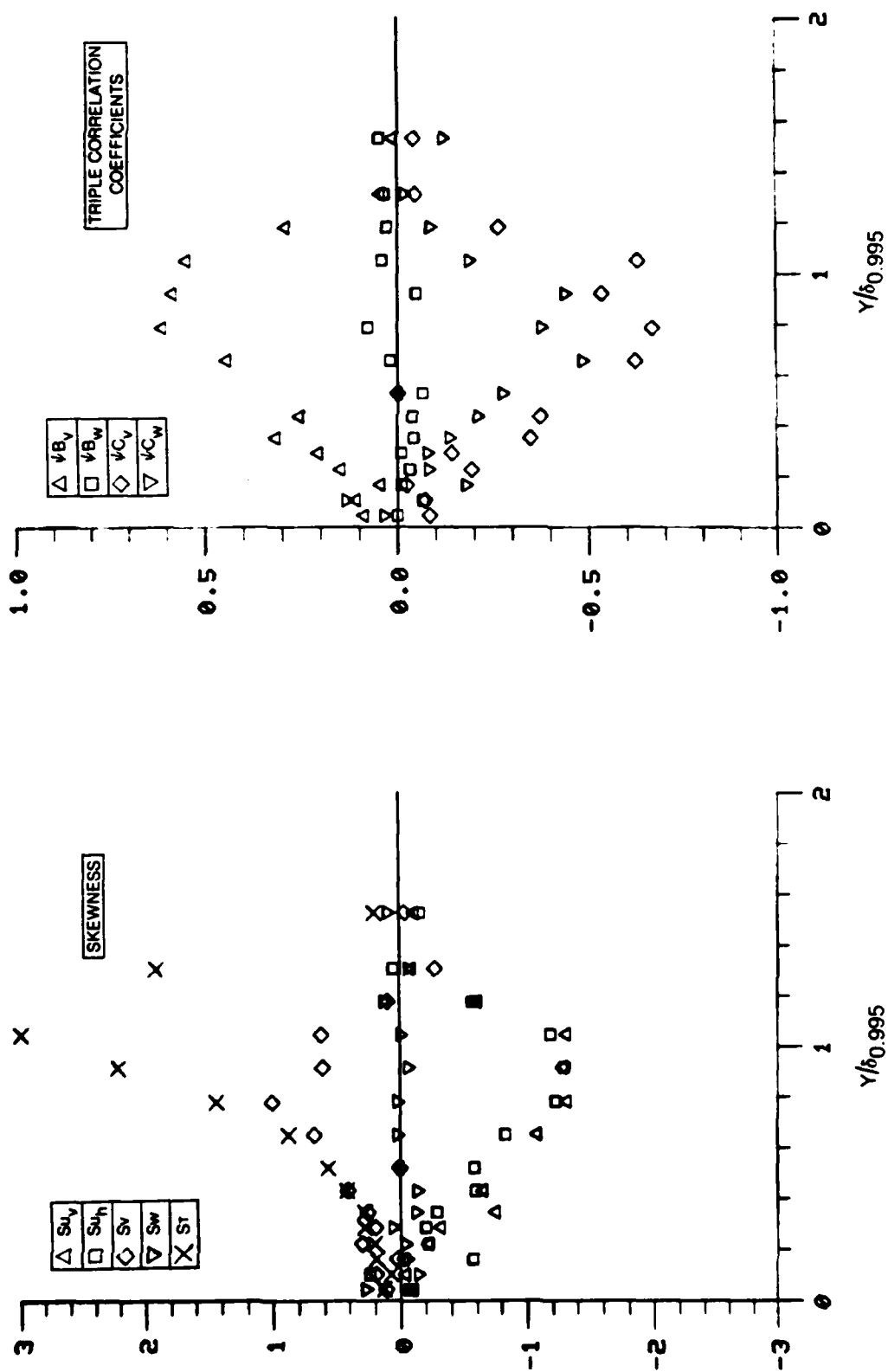


Figure B10D. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 68$ in, $T_e = 1.6\%$

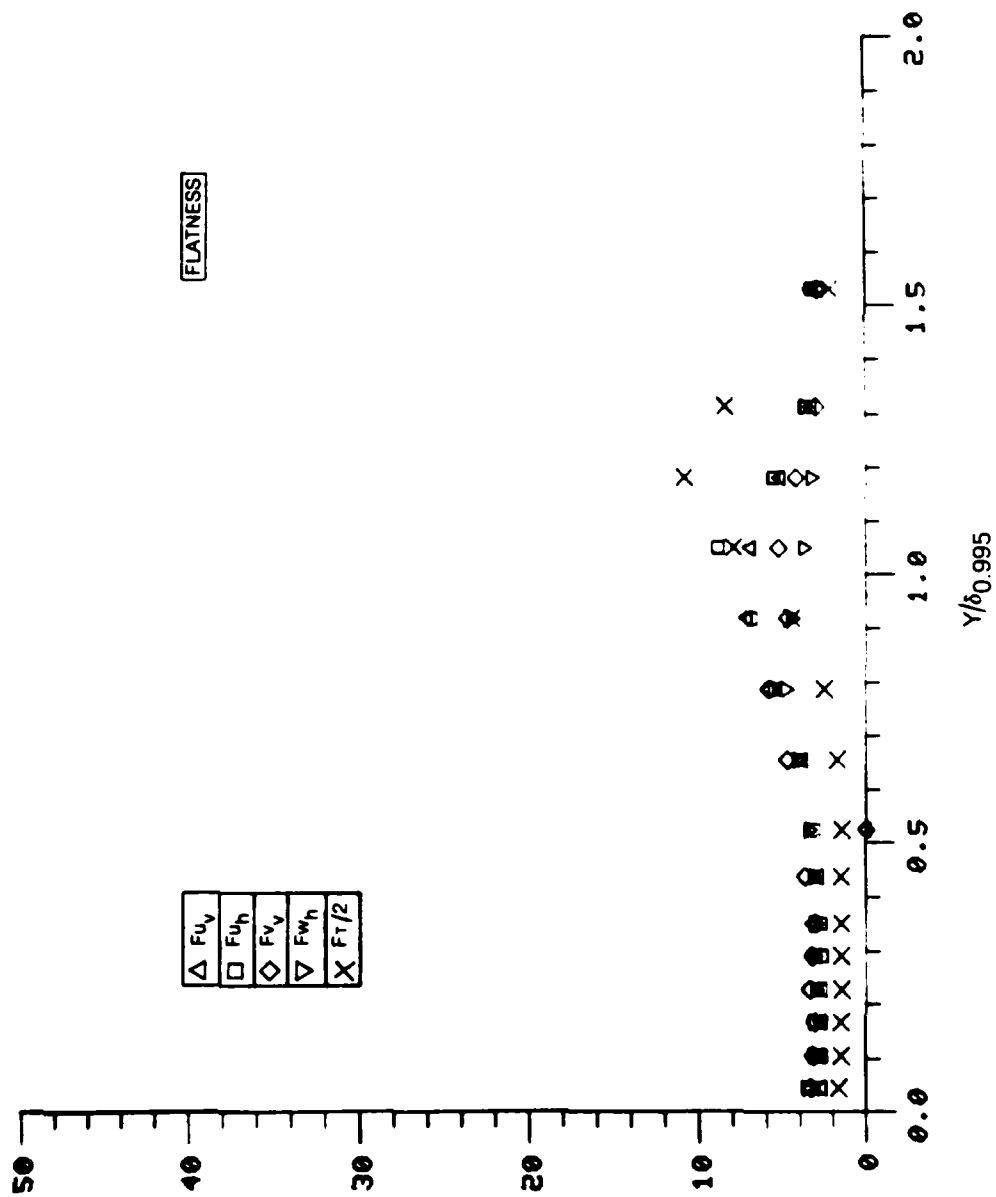


Figure B10E. Boundary Layer Flatness Distributions $x = 68$ in, $T_e = 1.6\%$

Fluctuating Profile Data

x = 68 in., Te = 1.6%

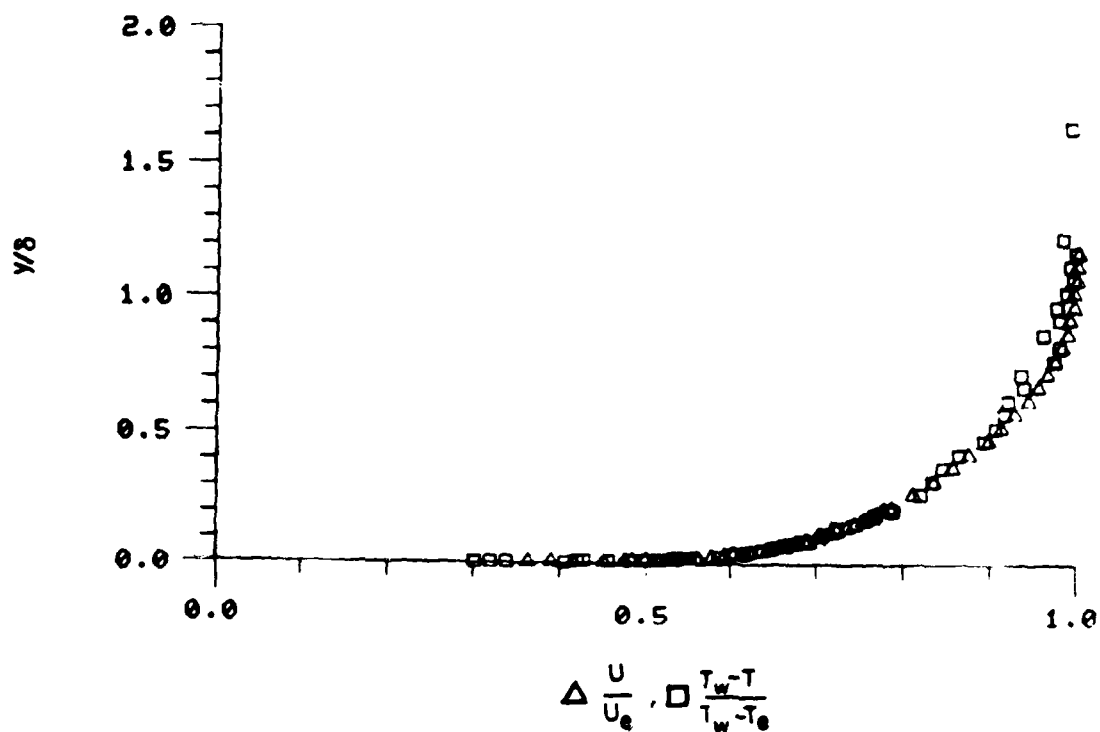
Y: INCHES	Y/ DELTA	U*/UE	V*/UE	W*/UE	√U*V*/UE	U*V*/ TABLE	U*V*/L*V*	L*/L*
1	1	0.0137	0.0179	0.0153	0.0000	0.01	0.00	0.00
2	2	0.0156	0.0200	0.0179	0.0000	0.02	0.00	0.00
3	3	0.0179	0.0229	0.0200	0.0000	0.03	0.00	0.00
4	4	0.0200	0.0258	0.0229	0.0000	0.04	0.00	0.00
5	5	0.0229	0.0287	0.0258	0.0000	0.05	0.00	0.00
6	6	0.0258	0.0316	0.0287	0.0000	0.06	0.00	0.00
7	7	0.0287	0.0345	0.0316	0.0000	0.07	0.00	0.00
8	8	0.0316	0.0374	0.0345	0.0000	0.08	0.00	0.00
9	9	0.0345	0.0403	0.0374	0.0000	0.09	0.00	0.00
10	10	0.0374	0.0432	0.0403	0.0000	0.10	0.00	0.00
11	11	0.0403	0.0461	0.0432	0.0000	0.11	0.00	0.00
12	12	0.0432	0.0490	0.0461	0.0000	0.12	0.00	0.00
13	13	0.0461	0.0519	0.0490	0.0000	0.13	0.00	0.00
14	14	0.0490	0.0548	0.0519	0.0000	0.14	0.00	0.00
15	15	0.0519	0.0577	0.0548	0.0000	0.15	0.00	0.00
16	16	0.0548	0.0606	0.0577	0.0000	0.16	0.00	0.00
17	17	0.0577	0.0635	0.0606	0.0000	0.17	0.00	0.00
18	18	0.0606	0.0664	0.0635	0.0000	0.18	0.00	0.00
19	19	0.0635	0.0693	0.0664	0.0000	0.19	0.00	0.00
20	20	0.0664	0.0722	0.0693	0.0000	0.20	0.00	0.00
21	21	0.0693	0.0751	0.0722	0.0000	0.21	0.00	0.00
22	22	0.0722	0.0780	0.0751	0.0000	0.22	0.00	0.00
23	23	0.0751	0.0809	0.0780	0.0000	0.23	0.00	0.00
24	24	0.0780	0.0838	0.0809	0.0000	0.24	0.00	0.00
25	25	0.0809	0.0867	0.0838	0.0000	0.25	0.00	0.00
26	26	0.0838	0.0896	0.0867	0.0000	0.26	0.00	0.00
27	27	0.0867	0.0925	0.0896	0.0000	0.27	0.00	0.00
28	28	0.0896	0.0954	0.0925	0.0000	0.28	0.00	0.00
29	29	0.0925	0.0983	0.0954	0.0000	0.29	0.00	0.00
30	30	0.0954	0.1012	0.0983	0.0000	0.30	0.00	0.00
31	31	0.0983	0.1041	0.1012	0.0000	0.31	0.00	0.00
32	32	0.1012	0.1070	0.1041	0.0000	0.32	0.00	0.00
33	33	0.1041	0.1099	0.1070	0.0000	0.33	0.00	0.00
34	34	0.1070	0.1128	0.1099	0.0000	0.34	0.00	0.00
35	35	0.1099	0.1157	0.1128	0.0000	0.35	0.00	0.00
36	36	0.1128	0.1186	0.1157	0.0000	0.36	0.00	0.00
37	37	0.1157	0.1215	0.1186	0.0000	0.37	0.00	0.00
38	38	0.1186	0.1244	0.1215	0.0000	0.38	0.00	0.00
39	39	0.1215	0.1273	0.1244	0.0000	0.39	0.00	0.00
40	40	0.1244	0.1302	0.1273	0.0000	0.40	0.00	0.00
41	41	0.1273	0.1331	0.1302	0.0000	0.41	0.00	0.00
42	42	0.1302	0.1360	0.1331	0.0000	0.42	0.00	0.00
43	43	0.1331	0.1389	0.1360	0.0000	0.43	0.00	0.00
44	44	0.1360	0.1418	0.1389	0.0000	0.44	0.00	0.00
45	45	0.1389	0.1447	0.1418	0.0000	0.45	0.00	0.00
46	46	0.1418	0.1476	0.1447	0.0000	0.46	0.00	0.00
47	47	0.1447	0.1505	0.1476	0.0000	0.47	0.00	0.00
48	48	0.1476	0.1534	0.1505	0.0000	0.48	0.00	0.00
49	49	0.1505	0.1563	0.1534	0.0000	0.49	0.00	0.00
50	50	0.1534	0.1592	0.1563	0.0000	0.50	0.00	0.00
51	51	0.1563	0.1621	0.1592	0.0000	0.51	0.00	0.00
52	52	0.1592	0.1650	0.1621	0.0000	0.52	0.00	0.00
53	53	0.1621	0.1679	0.1650	0.0000	0.53	0.00	0.00
54	54	0.1650	0.1708	0.1679	0.0000	0.54	0.00	0.00
55	55	0.1679	0.1737	0.1708	0.0000	0.55	0.00	0.00
56	56	0.1708	0.1766	0.1737	0.0000	0.56	0.00	0.00
57	57	0.1737	0.1795	0.1766	0.0000	0.57	0.00	0.00
58	58	0.1766	0.1824	0.1795	0.0000	0.58	0.00	0.00
59	59	0.1795	0.1853	0.1824	0.0000	0.59	0.00	0.00
60	60	0.1824	0.1882	0.1853	0.0000	0.60	0.00	0.00
61	61	0.1853	0.1911	0.1882	0.0000	0.61	0.00	0.00
62	62	0.1882	0.1940	0.1911	0.0000	0.62	0.00	0.00
63	63	0.1911	0.1969	0.1940	0.0000	0.63	0.00	0.00
64	64	0.1940	0.1998	0.1969	0.0000	0.64	0.00	0.00
65	65	0.1969	0.2027	0.1998	0.0000	0.65	0.00	0.00
66	66	0.1998	0.2056	0.2027	0.0000	0.66	0.00	0.00
67	67	0.2027	0.2085	0.2056	0.0000	0.67	0.00	0.00
68	68	0.2056	0.2114	0.2085	0.0000	0.68	0.00	0.00
69	69	0.2085	0.2143	0.2114	0.0000	0.69	0.00	0.00
70	70	0.2114	0.2172	0.2143	0.0000	0.70	0.00	0.00
71	71	0.2143	0.2201	0.2172	0.0000	0.71	0.00	0.00
72	72	0.2172	0.2230	0.2201	0.0000	0.72	0.00	0.00
73	73	0.2201	0.2259	0.2230	0.0000	0.73	0.00	0.00
74	74	0.2230	0.2288	0.2259	0.0000	0.74	0.00	0.00
75	75	0.2259	0.2317	0.2288	0.0000	0.75	0.00	0.00
76	76	0.2288	0.2346	0.2317	0.0000	0.76	0.00	0.00
77	77	0.2317	0.2375	0.2346	0.0000	0.77	0.00	0.00
78	78	0.2346	0.2404	0.2375	0.0000	0.78	0.00	0.00
79	79	0.2375	0.2433	0.2404	0.0000	0.79	0.00	0.00
80	80	0.2404	0.2462	0.2433	0.0000	0.80	0.00	0.00
81	81	0.2433	0.2491	0.2462	0.0000	0.81	0.00	0.00
82	82	0.2462	0.2520	0.2491	0.0000	0.82	0.00	0.00
83	83	0.2491	0.2549	0.2520	0.0000	0.83	0.00	0.00
84	84	0.2520	0.2578	0.2549	0.0000	0.84	0.00	0.00
85	85	0.2549	0.2607	0.2578	0.0000	0.85	0.00	0.00
86	86	0.2578	0.2636	0.2607	0.0000	0.86	0.00	0.00
87	87	0.2607	0.2665	0.2636	0.0000	0.87	0.00	0.00
88	88	0.2636	0.2694	0.2665	0.0000	0.88	0.00	0.00
89	89	0.2665	0.2723	0.2694	0.0000	0.89	0.00	0.00
90	90	0.2694	0.2752	0.2723	0.0000	0.90	0.00	0.00
91	91	0.2723	0.2781	0.2752	0.0000	0.91	0.00	0.00
92	92	0.2752	0.2810	0.2781	0.0000	0.92	0.00	0.00
93	93	0.2781	0.2839	0.2810	0.0000	0.93	0.00	0.00
94	94	0.2810	0.2868	0.2839	0.0000	0.94	0.00	0.00
95	95	0.2839	0.2897	0.2868	0.0000	0.95	0.00	0.00
96	96	0.2868	0.2926	0.2897	0.0000	0.96	0.00	0.00
97	97	0.2897	0.2955	0.2926	0.0000	0.97	0.00	0.00
98	98	0.2926	0.2984	0.2955	0.0000	0.98	0.00	0.00
99	99	0.2955	0.3013	0.2984	0.0000	0.99	0.00	0.00
100	100	0.2984	0.3042	0.3013	0.0000	1.00	0.00	0.00

Table B15A

$$x = 68 \text{ in.}, T_e = 1.6\%$$

Table B15B

VELOCITY AND TEMPERATURE RATIOS



VELOCITY AND TEMPERATURE DISTRIBUTIONS IN UNIVERSAL COORDINATES

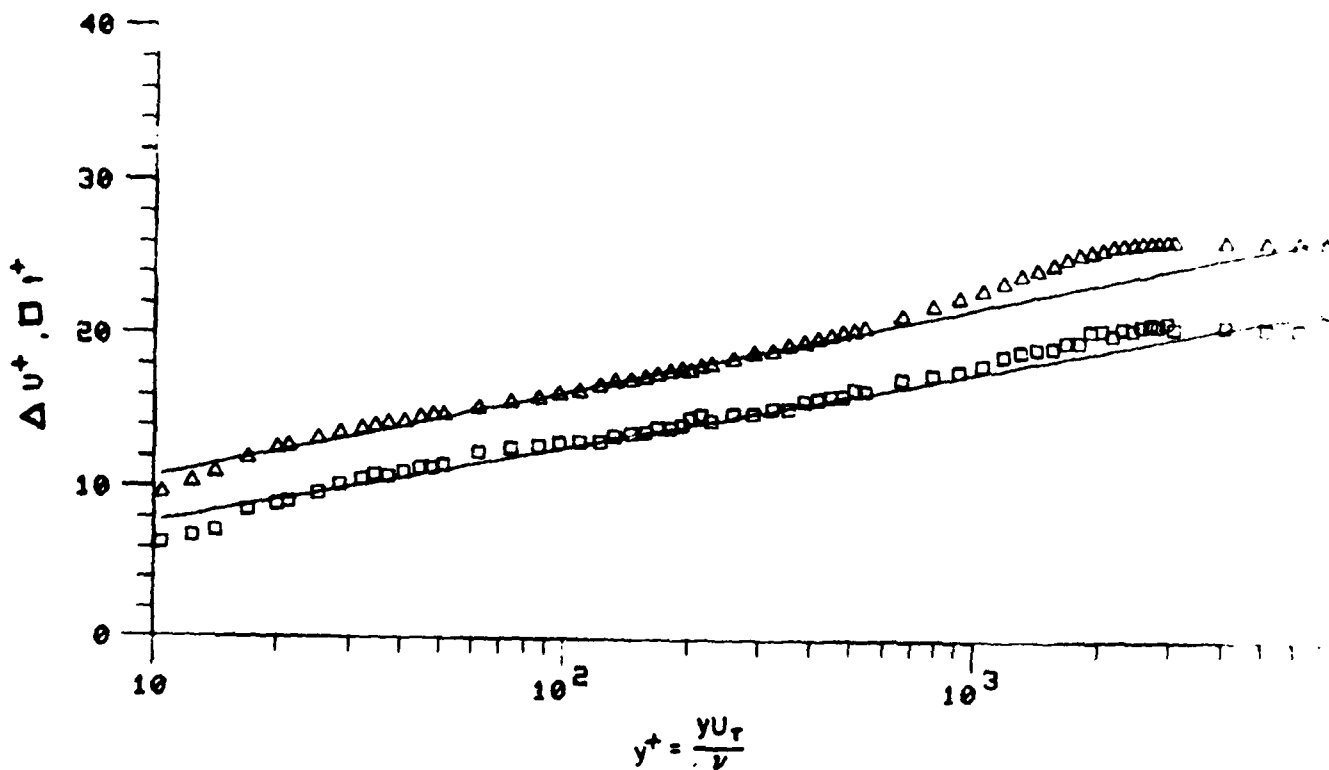


Figure B11. Mean Velocity and Temperature Profiles $x = 84$ in., $Te = 1.4\%$

$$x = 84 \text{ in.}, T_e = 1.4\%$$
Table B16

RUN NO. 3. POINT 1.
 BOLNDARY LAYER PROPERTIES

	LINEAR INTERPOLATION TO WALL	STANDARD SUBLAYER FUNCTION FROM WALL TO $Y^+ = 35$
FREE STREAM VELOCITY ==	97.379	97.379
FREE STREAM TEMPERATURE ==	69.380	
WALL TEMPERATURE ==	95.280	
WALL HEAT FLUX ==	.07879	
FREE STREAM DENSITY ==	.07563	
FREE STREAM KINEMATIC VISCOSITY ==	.0001615	
DENSITY OF FLUID AT WALL ==	.07210	
KINEMATIC VISCOSITY OF FLUID AT WALL ==	.0001757	
WALL/FREE STREAM DENSITY RATIO ==	.95333	
LOCATION REYNOLDS NUMBER (REX) ==	4220991.87	
INPUT VALUE OF VELOCITY DELTA ==	1.50000	
INPUT VALUE OF TEMPERATURE DELTA ==	1.80000	
CALCULATED DELTA ==		1.39524
DELTA 99.5% INPUT ==	.00000	
DISPLACEMENT THICKNESS (DELSTAR) ==	.19014	.19039
MOMENTUM THICKNESS (THETA) ==	.13559	.13572
ENERGY-DISSIPATION THICKNESS ==	.24207	.24207
ENTHALPY THICKNESS ==	.00739	.00739
SHAPE FACTOR 12 (DELSTAR/THETA) ==	1.40237	1.40265
SHAPE FACTOR 32 (ENERGY/THETA) ==	1.78534	1.78363
MOMENTUM THICKNESS REYNOLDS NUMBER ==	6813.21	6819.91
DISPLACEMENT THICKNESS REYNOLDS NUMBER ==	9554.62	9567.30
SKIN FRICTION COEFFICIENT ==	.002762	
FRICTION VELOCITY ==	3.70600	
LAW OF THE WALL CONSTANT (K) ==	.41000	
LAW OF THE WALL CONSTANT (C) ==	5.00000	
WAKE STRENGTH ==		.45923
CLAUSEPS 'DELTA' INTEGRAL ==	-4.64864	-4.81114
CLAUSEPS 'G' INTEGRAL ==	31.61966	31.69734
DISPLACEMENT THICKNESS - CONSTANT DENSITY ==	.17988	.18310
MOMENTUM THICKNESS - CONSTANT DENSITY ==	.13705	.13719
SHAPE FACTOR 12 - CONSTANT DENSITY ==	1.31253	1.33464
LOCATION -X- ==	64.00000	
Te = 1.4%		

Table B17

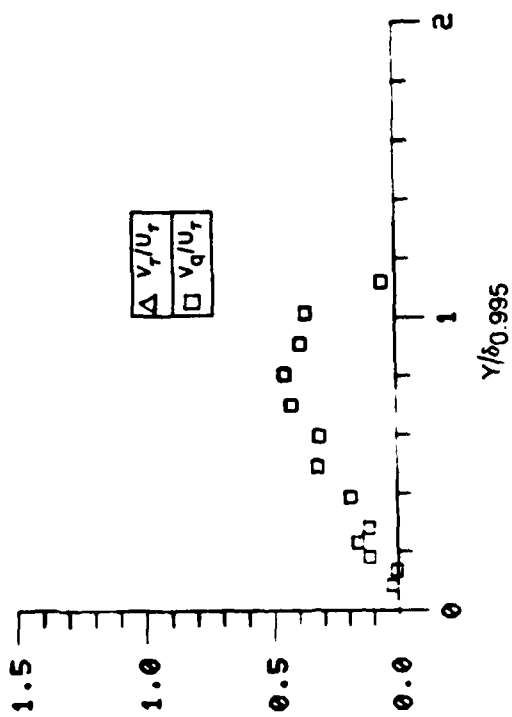
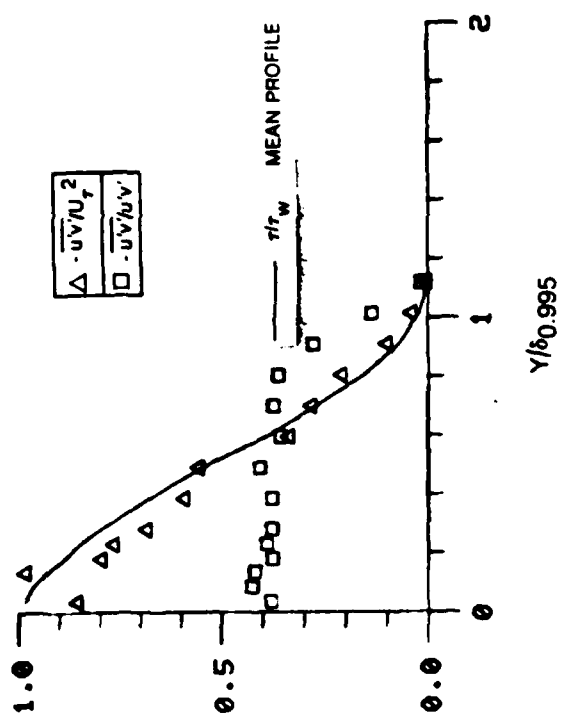
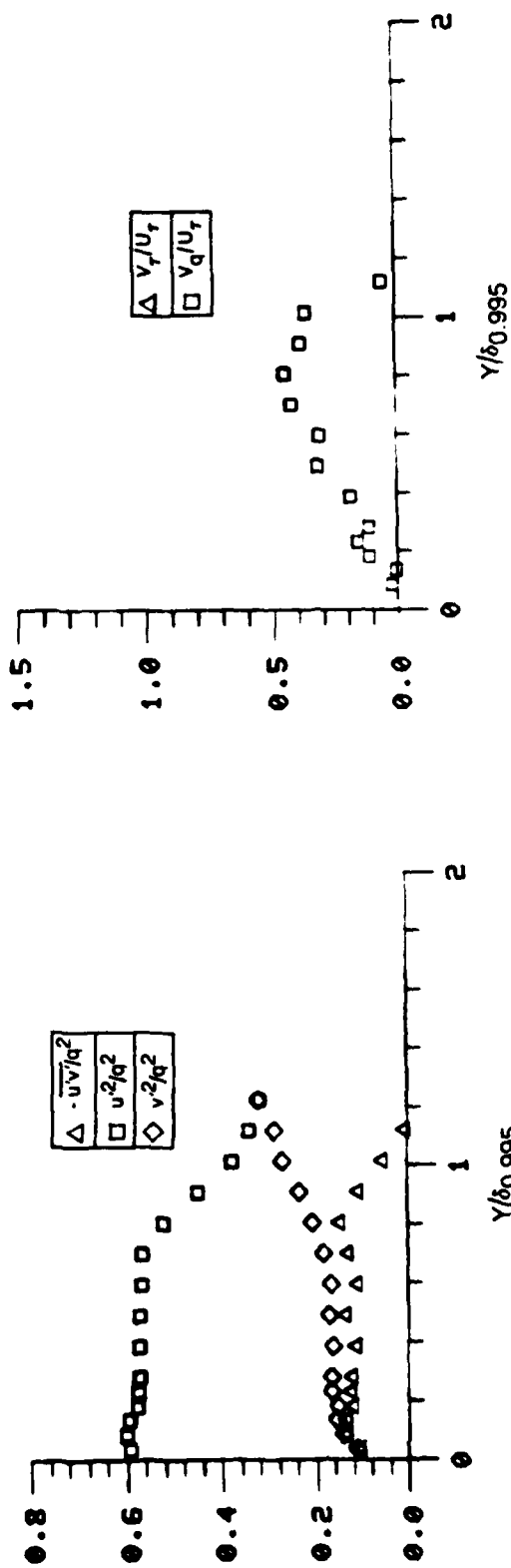
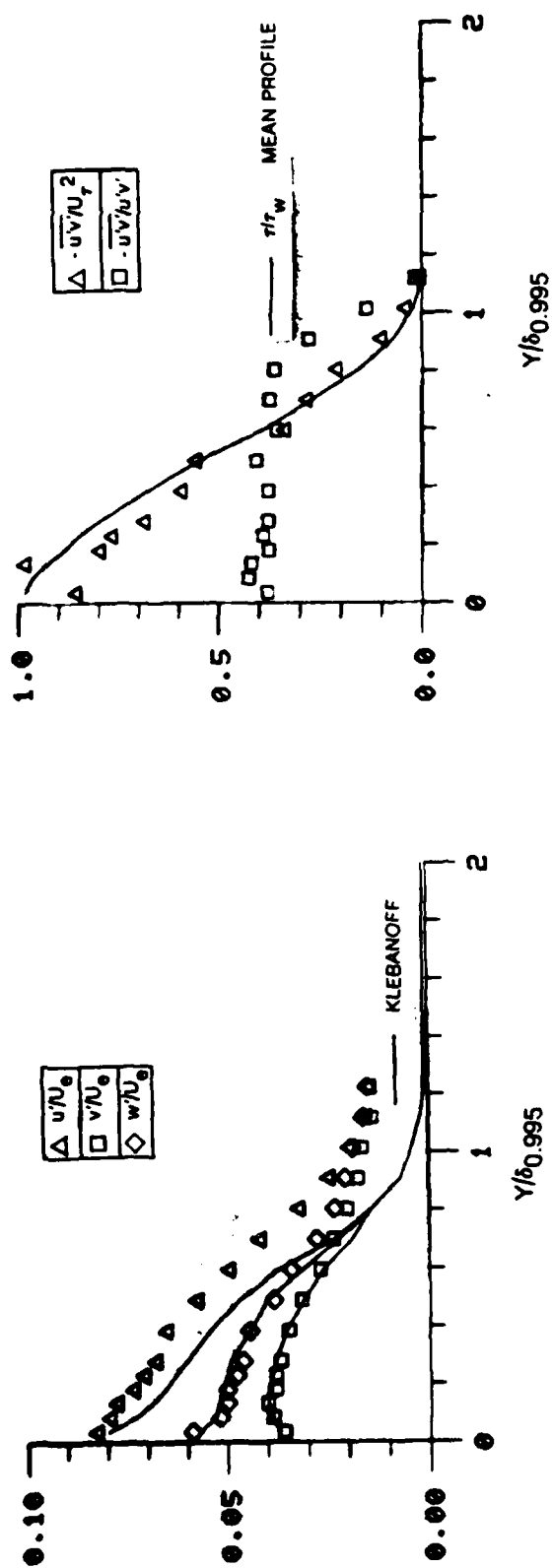


Figure B12A. Boundary Layer Turbulence Quantities $x = 84$ in, $T_e = 1.4\%$.

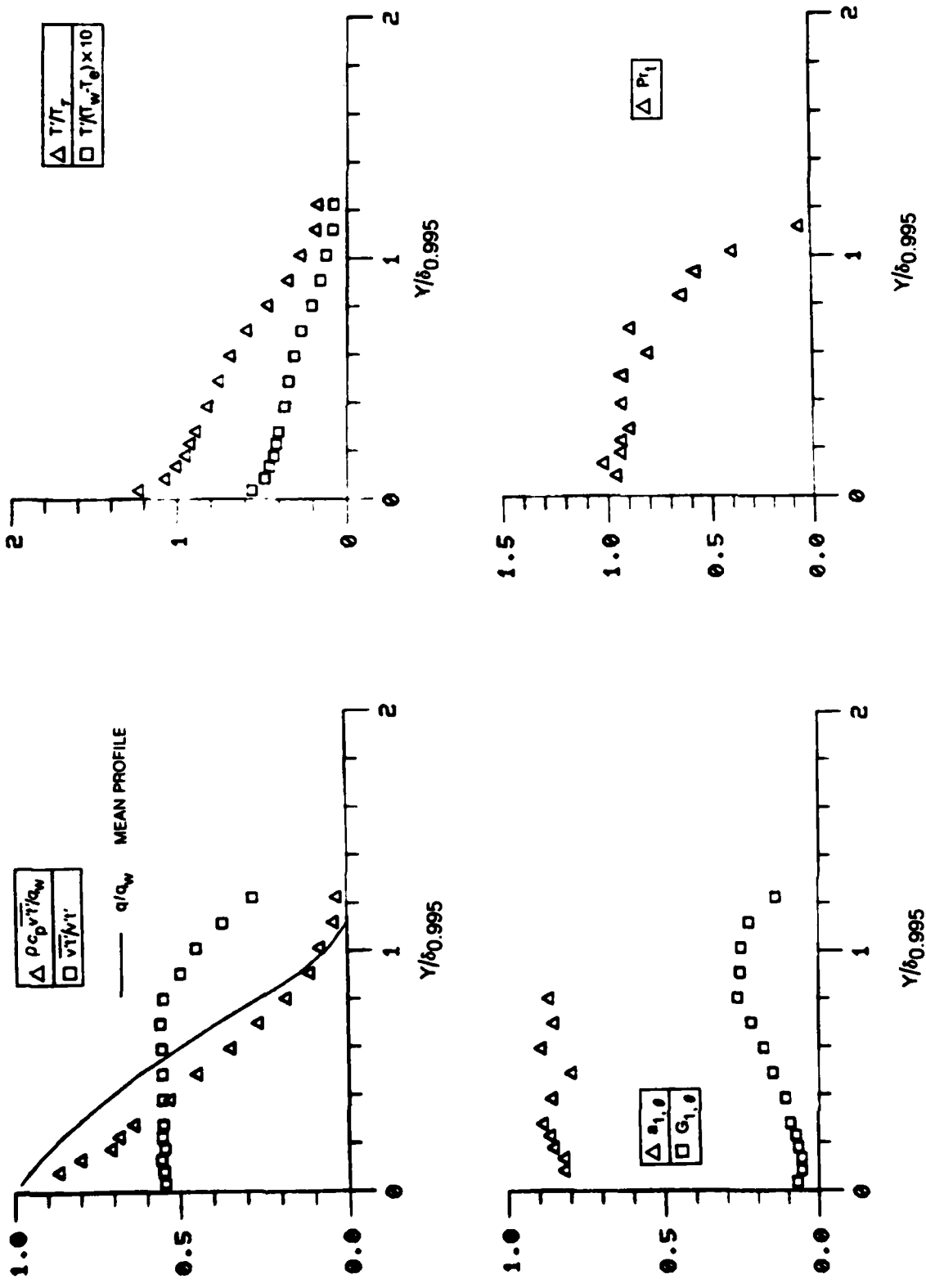


Figure 812B. Boundary Layer Turbulence Quantities $x = 84$ in, $Te = 1.4\%$

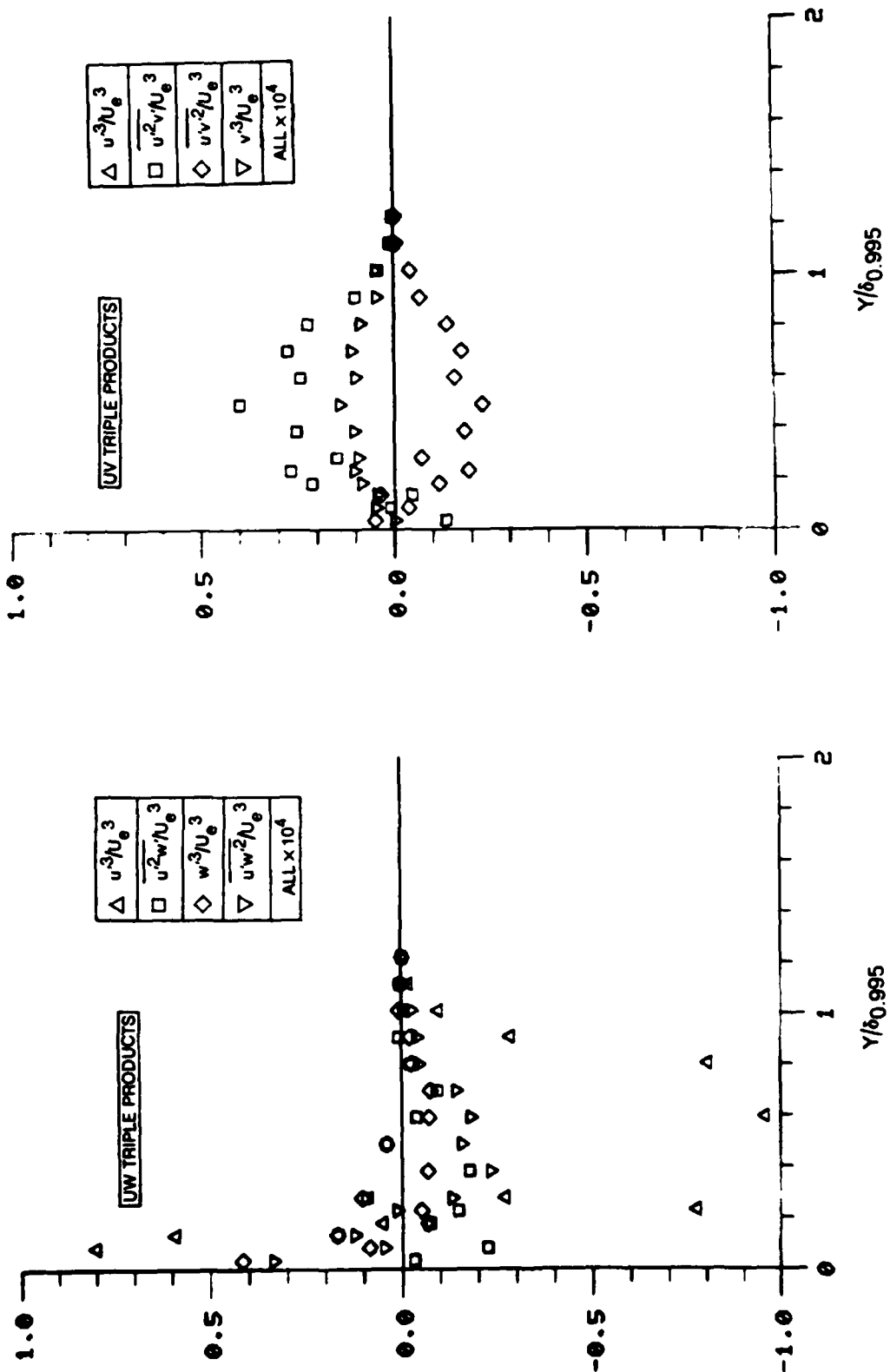


Figure B12C. Boundary Layer Triple Product Distributions $x = 84$ in, $T_e = 1.4\%$

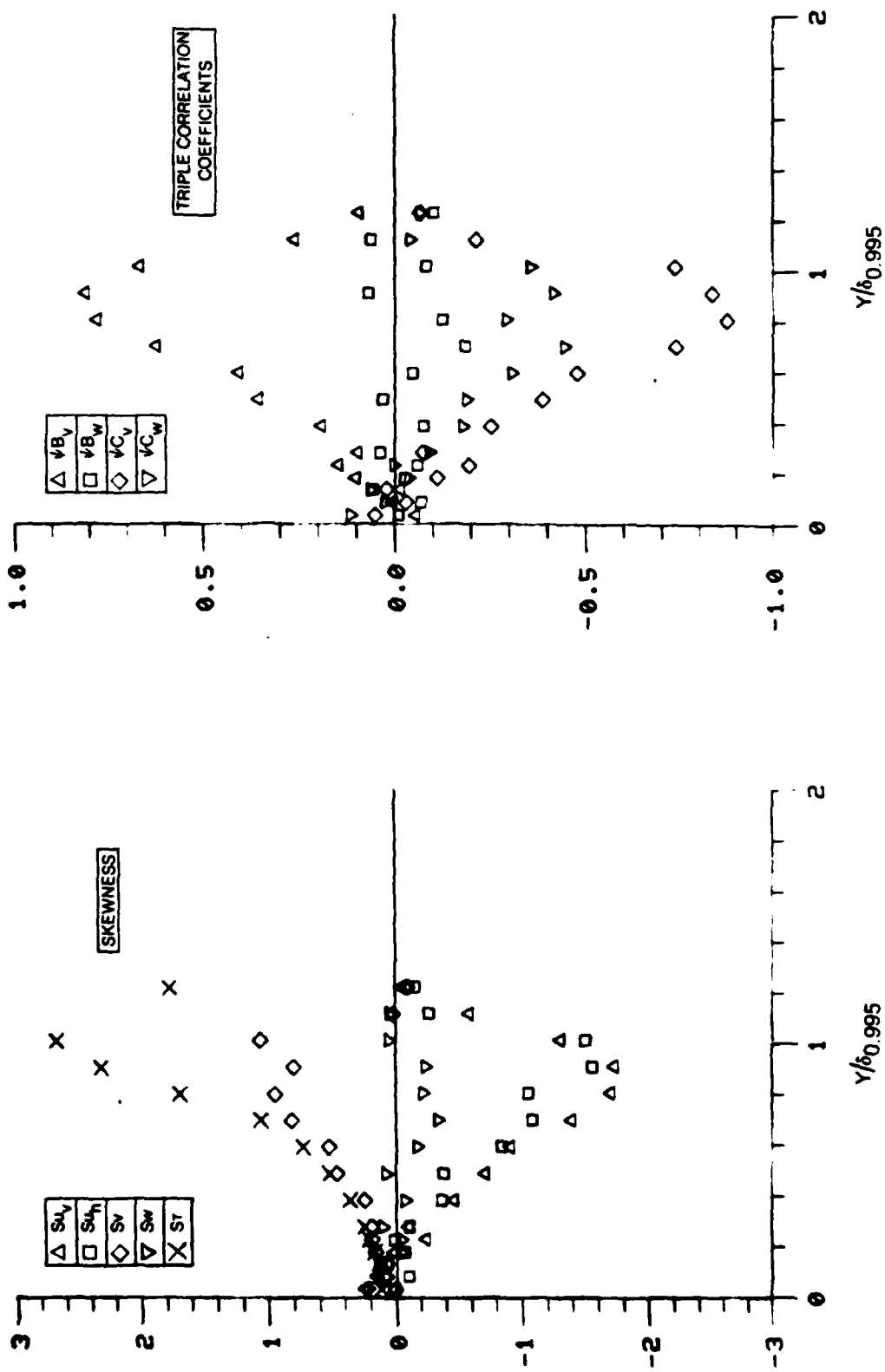


Figure B12D. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 84$ in, $T_e = 1.4\%$

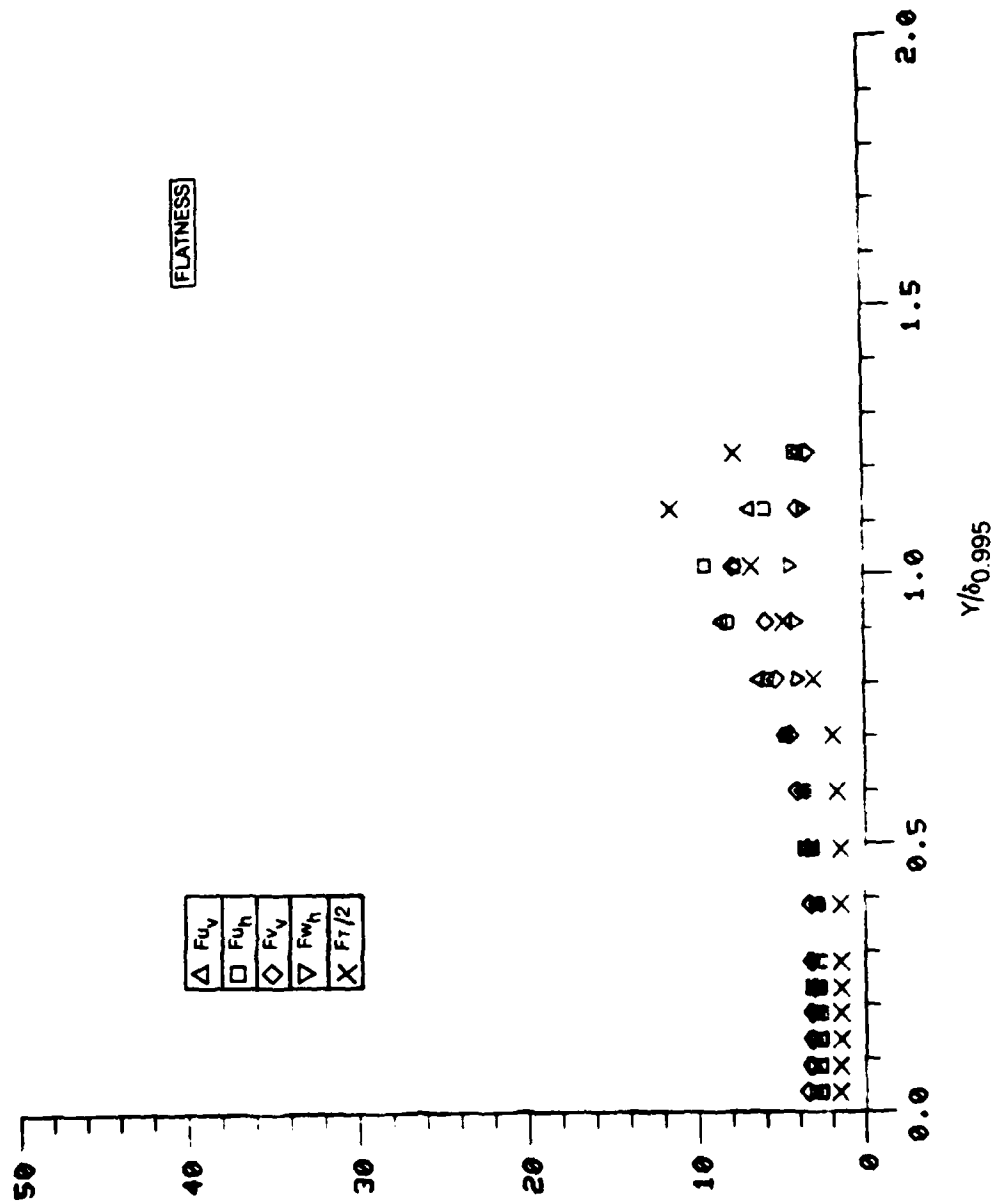


Figure 812E. Boundary Layer Flatness Distributions $x = 84$ in, $Te = 1.4\%$

$$x = 84 \text{ in.}, T_e = 1.4\%$$
$$x = 84 \text{ in.}, T_e = 1.4\%$$

INCHES	DELTA	V.T.V.T.	T.TAU	T.TM-TE	A10	G16	P21
1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6
7	7	7	7	7	7	7	7
8	8	8	8	8	8	8	8
9	9	9	9	9	9	9	9
10	10	10	10	10	10	10	10
11	11	11	11	11	11	11	11
12	12	12	12	12	12	12	12
13	13	13	13	13	13	13	13
14	14	14	14	14	14	14	14
15	15	15	15	15	15	15	15
16	16	16	16	16	16	16	16
17	17	17	17	17	17	17	17
18	18	18	18	18	18	18	18
19	19	19	19	19	19	19	19
20	20	20	20	20	20	20	20
21	21	21	21	21	21	21	21
22	22	22	22	22	22	22	22
23	23	23	23	23	23	23	23
24	24	24	24	24	24	24	24
25	25	25	25	25	25	25	25
26	26	26	26	26	26	26	26
27	27	27	27	27	27	27	27
28	28	28	28	28	28	28	28
29	29	29	29	29	29	29	29
30	30	30	30	30	30	30	30
31	31	31	31	31	31	31	31
32	32	32	32	32	32	32	32
33	33	33	33	33	33	33	33
34	34	34	34	34	34	34	34
35	35	35	35	35	35	35	35
36	36	36	36	36	36	36	36
37	37	37	37	37	37	37	37
38	38	38	38	38	38	38	38
39	39	39	39	39	39	39	39
40	40	40	40	40	40	40	40
41	41	41	41	41	41	41	41
42	42	42	42	42	42	42	42
43	43	43	43	43	43	43	43
44	44	44	44	44	44	44	44
45	45	45	45	45	45	45	45
46	46	46	46	46	46	46	46
47	47	47	47	47	47	47	47
48	48	48	48	48	48	48	48
49	49	49	49	49	49	49	49
50	50	50	50	50	50	50	50
51	51	51	51	51	51	51	51
52	52	52	52	52	52	52	52
53	53	53	53	53	53	53	53
54	54	54	54	54	54	54	54
55	55	55	55	55	55	55	55
56	56	56	56	56	56	56	56
57	57	57	57	57	57	57	57
58	58	58	58	58	58	58	58
59	59	59	59	59	59	59	59
60	60	60	60	60	60	60	60
61	61	61	61	61	61	61	61
62	62	62	62	62	62	62	62
63	63	63	63	63	63	63	63
64	64	64	64	64	64	64	64
65	65	65	65	65	65	65	65
66	66	66	66	66	66	66	66
67	67	67	67	67	67	67	67
68	68	68	68	68	68	68	68
69	69	69	69	69	69	69	69
70	70	70	70	70	70	70	70
71	71	71	71	71	71	71	71
72	72	72	72	72	72	72	72
73	73	73	73	73	73	73	73
74	74	74	74	74	74	74	74
75	75	75	75	75	75	75	75
76	76	76	76	76	76	76	76
77	77	77	77	77	77	77	77
78	78	78	78	78	78	78	78
79	79	79	79	79	79	79	79
80	80	80	80	80	80	80	80
81	81	81	81	81	81	81	81
82	82	82	82	82	82	82	82
83	83	83	83	83	83	83	83
84	84	84	84	84	84	84	84
85	85	85	85	85	85	85	85
86	86	86	86	86	86	86	86
87	87	87	87	87	87	87	87
88	88	88	88	88	88	88	88
89	89	89	89	89	89	89	89
90	90	90	90	90	90	90	90
91	91	91	91	91	91	91	91
92	92	92	92	92	92	92	92
93	93	93	93	93	93	93	93
94	94	94	94	94	94	94	94
95	95	95	95	95	95	95	95
96	96	96	96	96	96	96	96
97	97	97	97	97	97	97	97
98	98	98	98	98	98	98	98
99	99	99	99	99	99	99	99
100	100	100	100	100	100	100	100

Table B18A

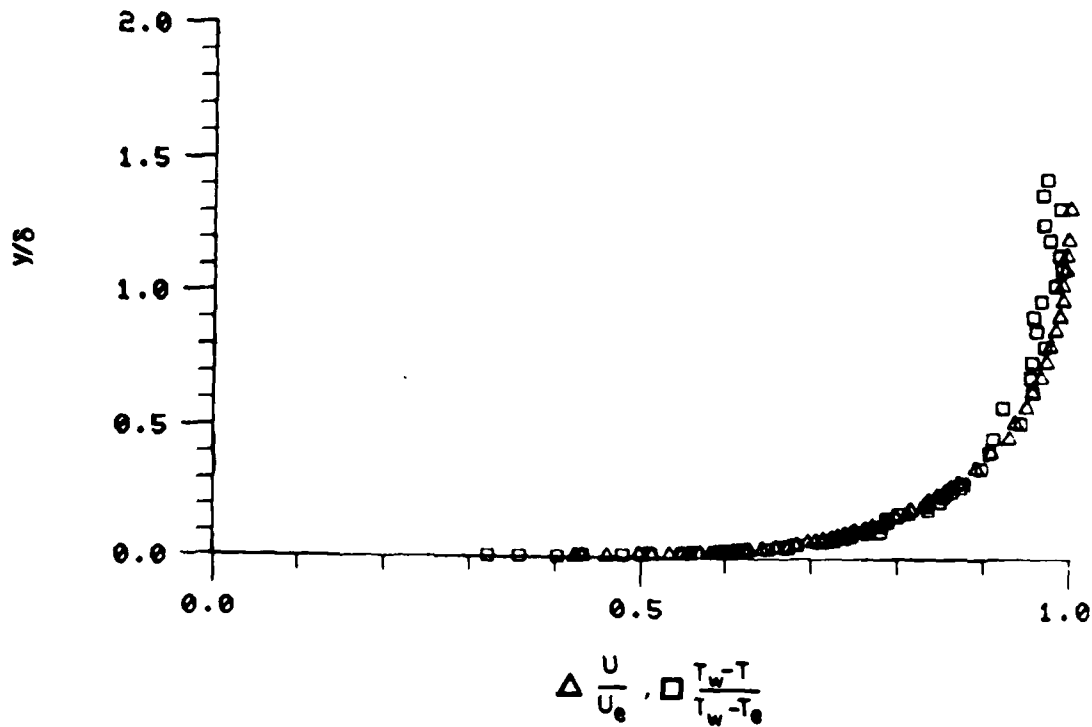
Fluctuating Profile Data

x = 84 in., Te = 1.4%

X INCHES	Y DELTA	U ³ /10000	U ² /10000	U ³ /10000	U ² /10000	U ³ /10000	U ² /10000	U ³ /10000
1	4	2	7	7	7	7	7	7
2	7	7	7	7	7	7	7	7
3	7	7	7	7	7	7	7	7
4	7	7	7	7	7	7	7	7
5	7	7	7	7	7	7	7	7
6	7	7	7	7	7	7	7	7
7	7	7	7	7	7	7	7	7
8	7	7	7	7	7	7	7	7
9	7	7	7	7	7	7	7	7
10	7	7	7	7	7	7	7	7
11	7	7	7	7	7	7	7	7
12	7	7	7	7	7	7	7	7
13	7	7	7	7	7	7	7	7
14	7	7	7	7	7	7	7	7
15	7	7	7	7	7	7	7	7
16	7	7	7	7	7	7	7	7
17	7	7	7	7	7	7	7	7
18	7	7	7	7	7	7	7	7
19	7	7	7	7	7	7	7	7
20	7	7	7	7	7	7	7	7
21	7	7	7	7	7	7	7	7
22	7	7	7	7	7	7	7	7
23	7	7	7	7	7	7	7	7
24	7	7	7	7	7	7	7	7
25	7	7	7	7	7	7	7	7
26	7	7	7	7	7	7	7	7
27	7	7	7	7	7	7	7	7
28	7	7	7	7	7	7	7	7
29	7	7	7	7	7	7	7	7
30	7	7	7	7	7	7	7	7
31	7	7	7	7	7	7	7	7
32	7	7	7	7	7	7	7	7
33	7	7	7	7	7	7	7	7
34	7	7	7	7	7	7	7	7
35	7	7	7	7	7	7	7	7
36	7	7	7	7	7	7	7	7
37	7	7	7	7	7	7	7	7
38	7	7	7	7	7	7	7	7
39	7	7	7	7	7	7	7	7
40	7	7	7	7	7	7	7	7
41	7	7	7	7	7	7	7	7
42	7	7	7	7	7	7	7	7
43	7	7	7	7	7	7	7	7
44	7	7	7	7	7	7	7	7
45	7	7	7	7	7	7	7	7
46	7	7	7	7	7	7	7	7
47	7	7	7	7	7	7	7	7
48	7	7	7	7	7	7	7	7
49	7	7	7	7	7	7	7	7
50	7	7	7	7	7	7	7	7
51	7	7	7	7	7	7	7	7
52	7	7	7	7	7	7	7	7
53	7	7	7	7	7	7	7	7
54	7	7	7	7	7	7	7	7
55	7	7	7	7	7	7	7	7
56	7	7	7	7	7	7	7	7
57	7	7	7	7	7	7	7	7
58	7	7	7	7	7	7	7	7
59	7	7	7	7	7	7	7	7
60	7	7	7	7	7	7	7	7
61	7	7	7	7	7	7	7	7
62	7	7	7	7	7	7	7	7
63	7	7	7	7	7	7	7	7
64	7	7	7	7	7	7	7	7
65	7	7	7	7	7	7	7	7
66	7	7	7	7	7	7	7	7
67	7	7	7	7	7	7	7	7
68	7	7	7	7	7	7	7	7
69	7	7	7	7	7	7	7	7
70	7	7	7	7	7	7	7	7
71	7	7	7	7	7	7	7	7
72	7	7	7	7	7	7	7	7
73	7	7	7	7	7	7	7	7
74	7	7	7	7	7	7	7	7
75	7	7	7	7	7	7	7	7
76	7	7	7	7	7	7	7	7
77	7	7	7	7	7	7	7	7
78	7	7	7	7	7	7	7	7
79	7	7	7	7	7	7	7	7
80	7	7	7	7	7	7	7	7
81	7	7	7	7	7	7	7	7
82	7	7	7	7	7	7	7	7
83	7	7	7	7	7	7	7	7
84	7	7	7	7	7	7	7	7
85	7	7	7	7	7	7	7	7
86	7	7	7	7	7	7	7	7
87	7	7	7	7	7	7	7	7
88	7	7	7	7	7	7	7	7
89	7	7	7	7	7	7	7	7
90	7	7	7	7	7	7	7	7
91	7	7	7	7	7	7	7	7
92	7	7	7	7	7	7	7	7
93	7	7	7	7	7	7	7	7
94	7	7	7	7	7	7	7	7
95	7	7	7	7	7	7	7	7
96	7	7	7	7	7	7	7	7
97	7	7	7	7	7	7	7	7
98	7	7	7	7	7	7	7	7
99	7	7	7	7	7	7	7	7
100	7	7	7	7	7	7	7	7

Table B18B

VELOCITY AND TEMPERATURE RATIOS



VELOCITY AND TEMPERATURE DISTRIBUTIONS IN UNIVERSAL COORDINATES

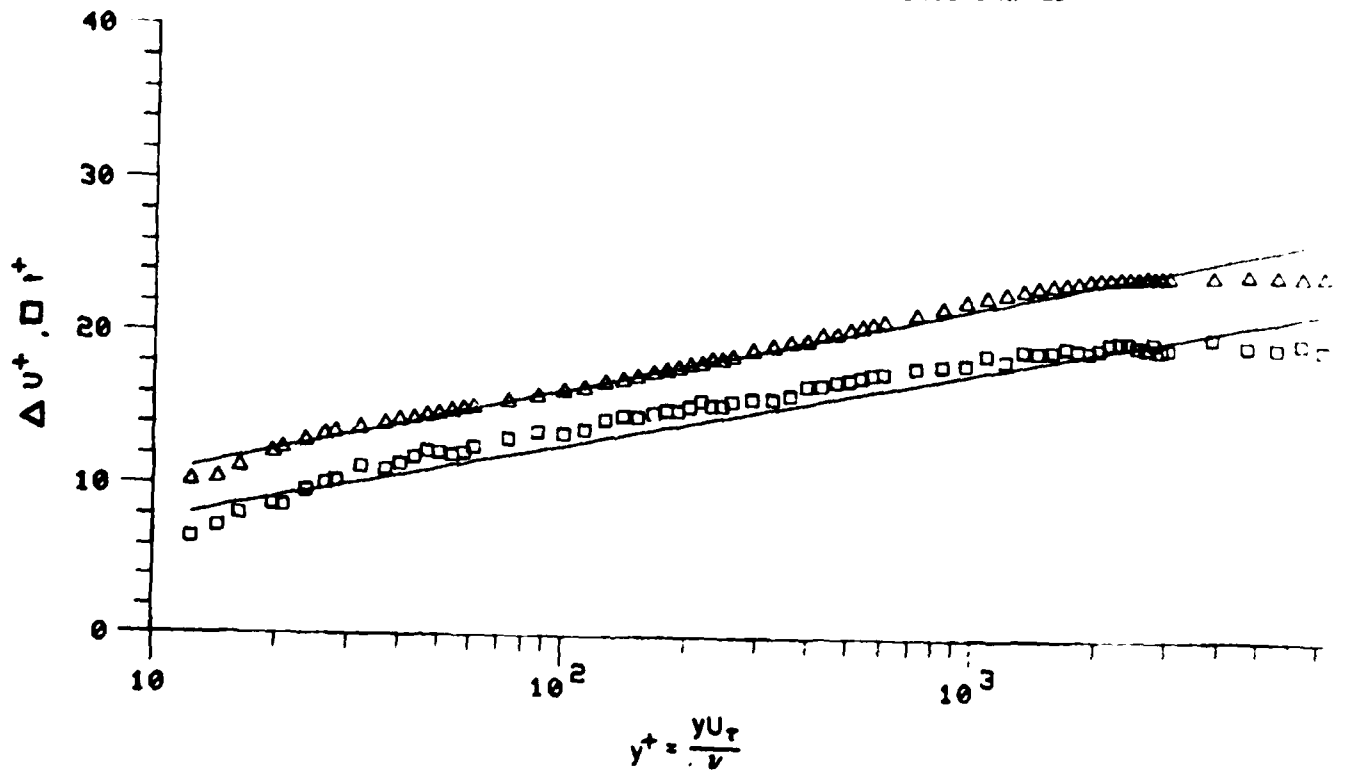


Figure B13. Mean Velocity and Temperature Profiles $x = 52$ in., $Te = 4.7\%$

Mean Profile Data

x = 52 in., Te = 4.7%

N	Y	Y/DELTA	U	T	U/CF	THETA	U-UE	U(1)	T(1)	Y(1)
1	1.0000	1.0000	42.10	87.64	.424	.321	-13.870	10.223	6.451	12.232
2	.0000	.0000	42.10	87.64	.424	.359	-13.682	10.410	7.214	14.228
3	.0000	.0000	42.10	87.64	.424	.403	-12.994	11.097	8.066	16.228
4	.0000	.0000	42.10	87.64	.424	.432	-12.083	12.010	8.675	19.244
5	.0000	.0000	42.10	87.64	.424	.428	-11.736	12.357	8.602	20.700
6	.0000	.0000	42.10	87.64	.424	.480	-11.229	12.864	9.635	23.631
7	.0000	.0000	42.10	87.64	.424	.501	-10.862	13.211	10.069	26.164
8	.0000	.0000	42.10	87.64	.424	.512	-10.676	13.417	10.286	27.917
9	.0000	.0000	42.10	87.64	.424	.558	-10.353	13.740	11.204	32.008
10	.0000	.0000	42.10	87.64	.424	.549	-10.071	14.022	11.017	36.654
11	.0000	.0000	42.10	87.64	.424	.567	-9.822	14.271	11.386	39.666
12	.0000	.0000	42.10	87.64	.424	.588	-9.715	14.376	11.816	43.700
13	.0000	.0000	42.10	87.64	.424	.606	-9.579	14.514	12.205	46.541
14	.0000	.0000	42.10	87.64	.424	.602	-9.427	14.666	12.084	49.541
15	.0000	.0000	42.10	87.64	.424	.594	-9.298	14.795	11.919	53.451
16	.0000	.0000	42.10	87.64	.424	.604	-9.101	14.992	12.120	57.147
17	.0000	.0000	42.10	87.64	.424	.623	-8.956	15.137	12.508	60.647
18	.0000	.0000	42.10	87.64	.424	.649	-8.622	15.471	13.041	73.649
19	.0000	.0000	42.10	87.64	.424	.673	-8.217	15.676	13.521	86.644
20	.0000	.0000	42.10	87.64	.424	.670	-7.871	16.222	13.461	100.644
21	.0000	.0000	42.10	87.64	.424	.683	-7.676	16.417	13.716	112.644
22	.0000	.0000	42.10	87.64	.424	.713	-7.338	16.755	14.309	126.644
23	.0000	.0000	42.10	87.64	.424	.726	-7.120	16.973	14.564	139.644
24	.0000	.0000	42.10	87.64	.424	.724	-6.941	17.152	14.547	151.644
25	.0000	.0000	42.10	87.64	.424	.738	-6.670	17.423	14.629	165.644
26	.0000	.0000	42.10	87.64	.424	.746	-6.520	17.573	14.984	177.644
27	.0000	.0000	42.10	87.64	.424	.745	-6.311	17.782	14.955	190.644
28	.0000	.0000	42.10	87.64	.424	.763	-6.117	17.976	15.319	203.644
29	.0000	.0000	42.10	87.64	.424	.779	-6.019	18.074	15.635	216.644
30	.0000	.0000	42.10	87.64	.424	.766	-5.785	18.307	15.360	229.644
31	.0000	.0000	42.10	87.64	.424	.765	-5.741	18.352	15.366	242.644
32	.0000	.0000	42.10	87.64	.424	.770	-5.536	18.555	15.666	255.644
33	.0000	.0000	42.10	87.64	.424	.788	-5.154	18.939	15.626	268.644
34	.0000	.0000	42.10	87.64	.424	.788	-4.876	19.217	15.616	281.644
35	.0000	.0000	42.10	87.64	.424	.600	-4.560	19.533	16.071	294.644
36	.0000	.0000	42.10	87.64	.424	.634	-4.481	19.612	16.754	307.644
37	.0000	.0000	42.10	87.64	.424	.636	-4.118	19.975	16.763	320.644
38	.0000	.0000	42.10	87.64	.424	.649	-3.960	20.133	17.039	333.644
39	.0000	.0000	42.10	87.64	.424	.853	-3.733	20.360	17.129	346.644
40	.0000	.0000	42.10	87.64	.424	.863	-3.534	20.559	17.325	359.644
41	.0000	.0000	42.10	87.64	.424	.673	-3.367	20.726	17.531	372.644
42	.0000	.0000	42.10	87.64	.424	.875	-3.160	20.933	17.579	385.644
43	.0000	.0000	42.10	87.64	.424	.896	-2.665	21.428	17.956	398.644
44	.0000	.0000	42.10	87.64	.424	.906	-2.222	21.871	18.192	411.644
45	.0000	.0000	42.10	87.64	.424	.909	-1.741	22.352	18.257	424.644
46	.0000	.0000	42.10	87.64	.424	.943	-1.546	22.547	18.929	437.644
47	.0000	.0000	42.10	87.64	.424	.922	-1.229	22.864	19.509	450.644
48	.0000	.0000	42.10	87.64	.424	.956	-1.046	23.047	19.202	463.644
49	.0000	.0000	42.10	87.64	.424	.952	-.862	23.231	19.112	476.644
50	.0000	.0000	42.10	87.64	.424	.954	-.686	23.406	19.166	489.644
51	.0000	.0000	42.10	87.64	.424	.969	-.565	23.528	19.466	502.644
52	.0000	.0000	42.10	87.64	.424	.961	-.464	23.629	19.257	515.644
53	.0000	.0000	42.10	87.64	.424	.986	-.336	23.757	19.353	528.644
54	.0000	.0000	42.10	87.64	.424	.964	-.245	23.848	19.716	541.644
55	.0000	.0000	42.10	87.64	.424	.982	-.241	23.852	19.716	554.644
56	.0000	.0000	42.10	87.64	.424	.989	-.151	23.942	19.657	567.644
57	.0000	.0000	42.10	87.64	.424	.987	-.107	23.986	19.811	580.644
58	.0000	.0000	42.10	87.64	.424	.975	-.087	24.006	19.577	593.644
59	.0000	.0000	42.10	87.64	.424	.968	-.019	24.112	19.441	606.644
60	.0000	.0000	42.10	87.64	.424	.986	-.029	24.064	19.605	619.644
61	.0000	.0000	42.10	87.64	.424	.966	.009	24.102	19.395	632.644
62	.0000	.0000	42.10	87.64	.424	.970	.020	24.113	19.486	645.644
63	.0000	.0000	42.10	87.64	.424	.977	.050	24.143	19.206	658.644
64	.0000	.0000	42.10	87.64	.424	.977	.123	24.216	19.628	671.644
65	.0000	.0000	42.10	87.64	.424	.971	.131	24.224	19.503	684.644
66	.0000	.0000	42.10	87.64	.424	.987	.102	24.195	19.615	697.644
67	.0000	.0000	42.10	87.64	.424	.969	.170	24.263	19.468	710.644
68	.0000	.0000	42.10	87.64	.424	.988	.073	24.166	19.637	723.644

Table B19

BOUNDARY LAYER PROPERTIES	1.	POINT	4.
			STANDARD
			SUBLAYER
			FUNCTION FROM
			WALL TO Y+=30
		LINEAR	
		INTERPOLATION	
		TO WALL	
FREE STREAM VELOCITY =	99.223		99.223
FREE STREAM TEMPERATURE =	72.500		
WALL TEMPERATURE =	94.800		
WALL HEAT FLUX =	.07890		
FREE STREAM DENSITY =	.07489		
FREE STREAM KINEMATIC VISCOSITY =	.0001638		
DENSITY OF FLUID AT WALL =	.07188		
KINEMATIC VISCOSITY OF FLUID AT WALL =	.0001762		
WALL/FREE STREAM DENSITY RATIO =	.95978		
LOCATION REYNOLDS NUMBER (REX) =	2624417.81		
INPUT VALUE OF VELOCITY DELTA =	1.35000		
INPUT VALUE OF TEMPERATURE DELTA =	1.45000		
CALCULATED DELTA =			1.05346
DELTA 99.5% INPUT =	.00000		
DISPLACEMENT THICKNESS (DELSTAR) =	.11874		.11877
MOMENTUM THICKNESS (THETA) =	.08814		.08841
ENERGY-DISSIPATION THICKNESS =	.16040		.16061
ENTHALPY THICKNESS =	.00427		.00428
SHAPE FACTOR 12 (DELSTAR/THETA) =	1.34716		1.34342
SHAPE FACTOR 72 (ENERGY/THETA) =	1.81990		1.81669
MOMENTUM THICKNESS REYNOLDS NUMBER =	4448.29		4461.89
DISPLACEMENT THICKNESS REYNOLDS NUMBER =	5992.57		5994.21
SKIN FRICTION COEFFICIENT =	.003307		
FRICTION VELOCITY =	4.11836		
LAW OF THE WALL CONSTANT (K) =	.41000		
LAW OF THE WALL CONSTANT (C) =	5.00000		
WAKE STRENGTH =			.10069
CLAUSERS 'DELTA' INTEGRAL =	-2.60818		-2.76130
CLAUSERS 'G' INTEGRAL =	14.96252		14.81376
DISPLACEMENT THICKNESS - CONSTANT DENSITY =	.11142		.11461
MOMENTUM THICKNESS - CONSTANT DENSITY =	.08881		.08909
SHAPE FACTOR 12 - CONSTANT DENSITY =	1.25461		1.28645
LOCATION -X-	52.00000		
Te = 4.7%			

Table B20

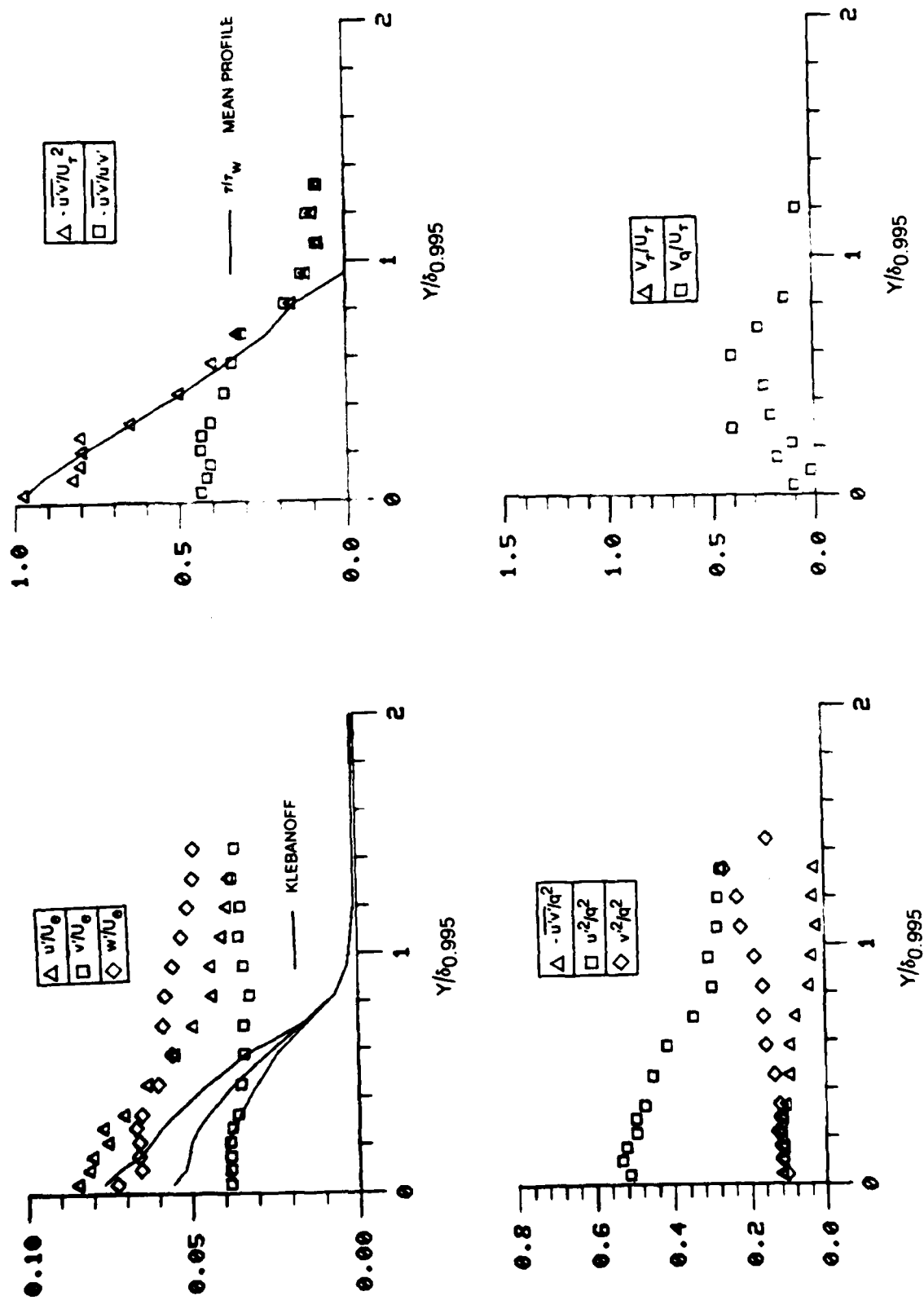


Figure B14A. Boundary Layer Turbulence Quantities, $x = 52$ in, $T_e = 4.7\%$

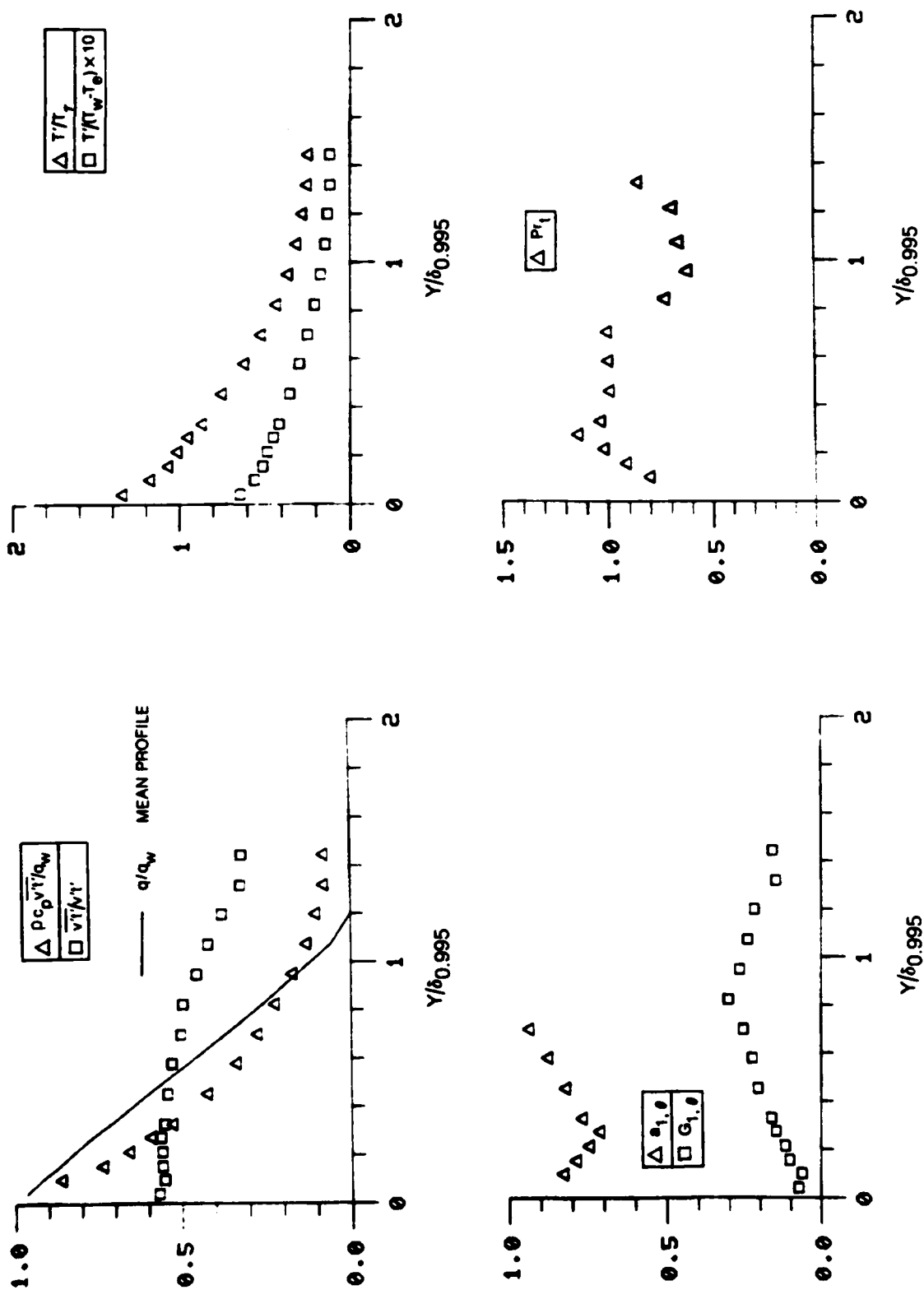


Figure B14B. Boundary Layer Turbulence Quantities, $x = 52$ in, $T_e = 4.7\%$

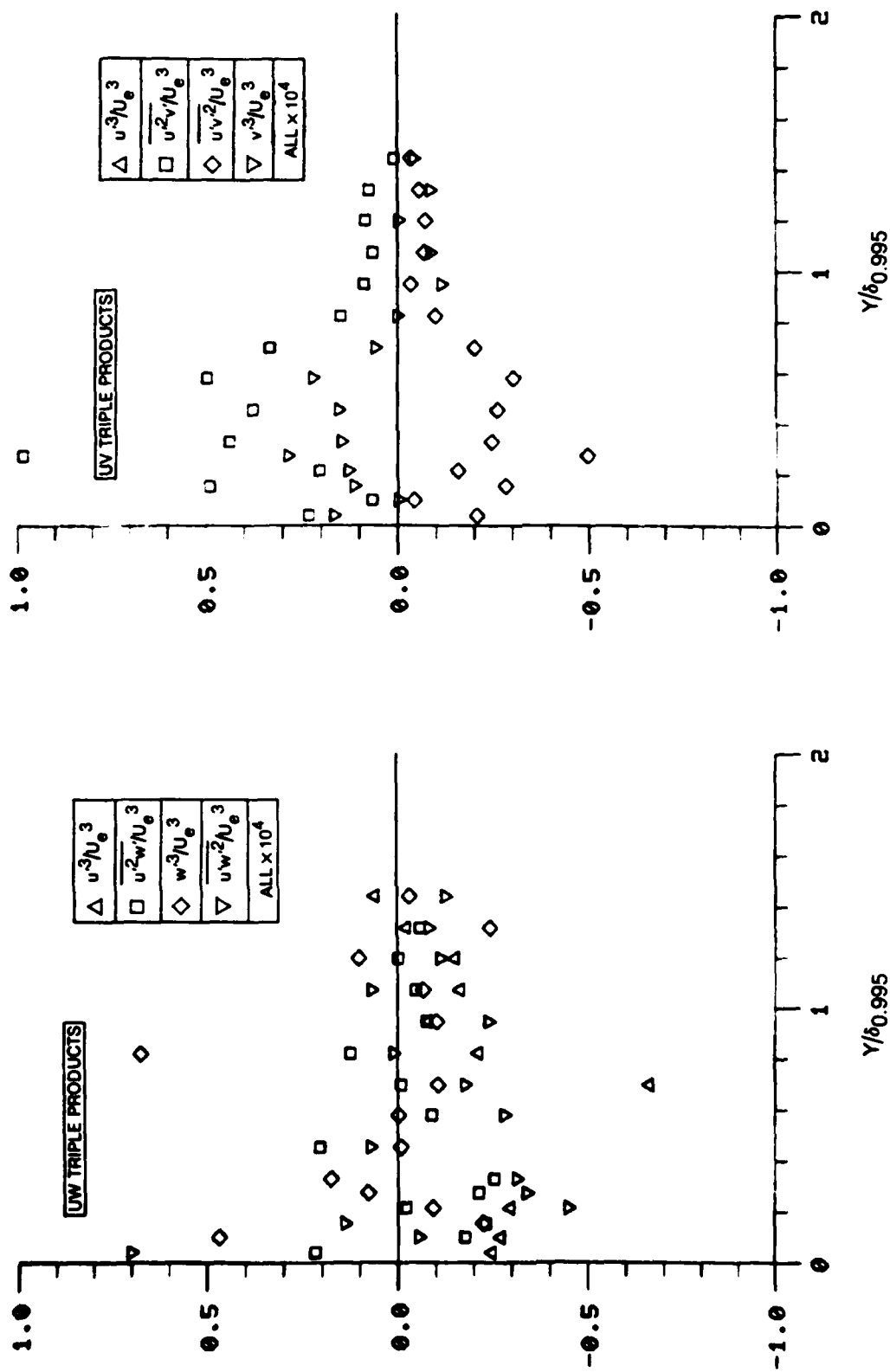


Figure B14C. Boundary Layer Triple Product Distributions $x = 52$ in, $T_e = 4.7\%$

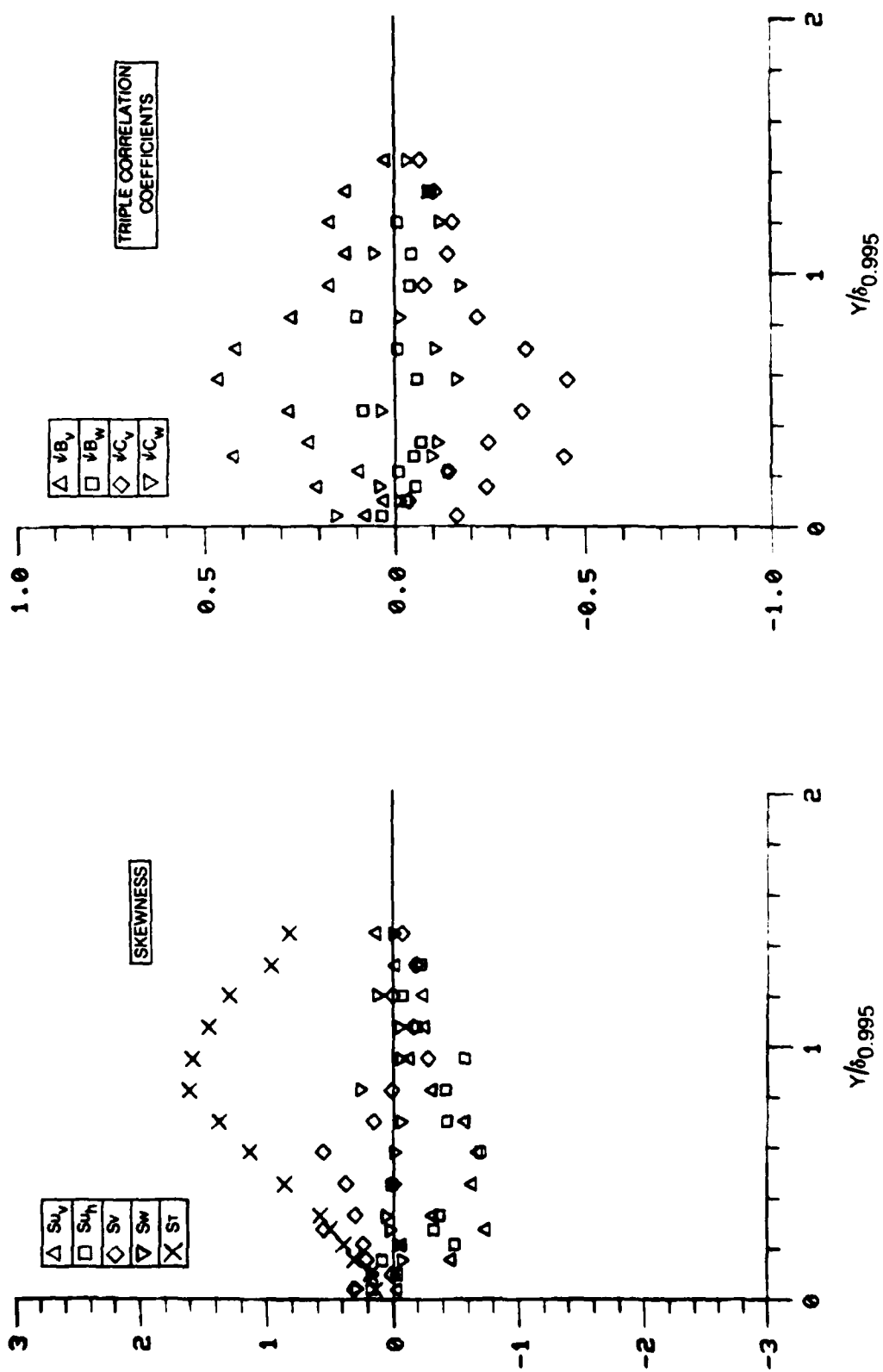


Figure B14D. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 52$ in, $T_g = 4.7\%$

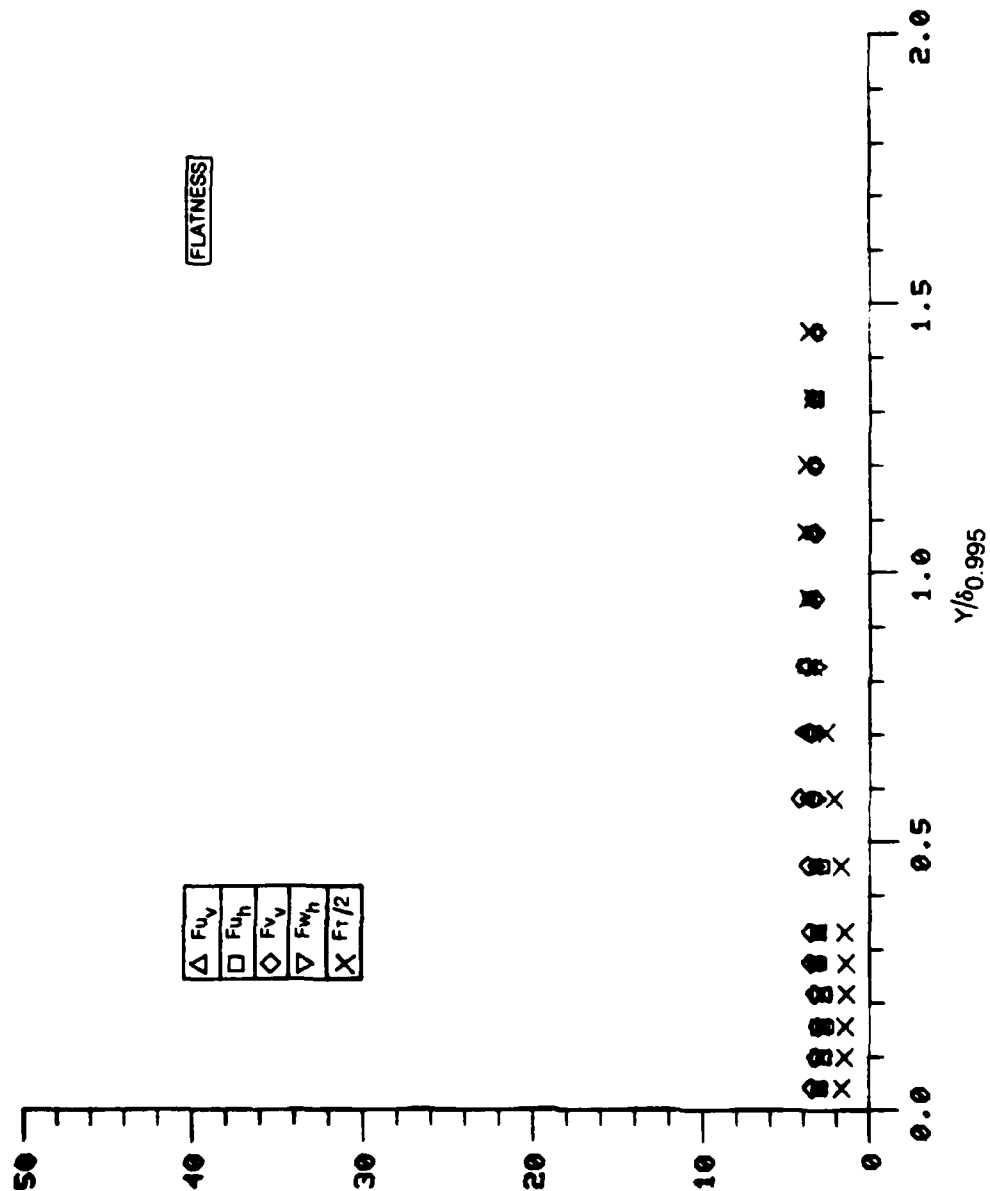


Figure B14E. Boundary Layer Flatness Distributions $x = 52$ in, $T_e = 4.7\%$

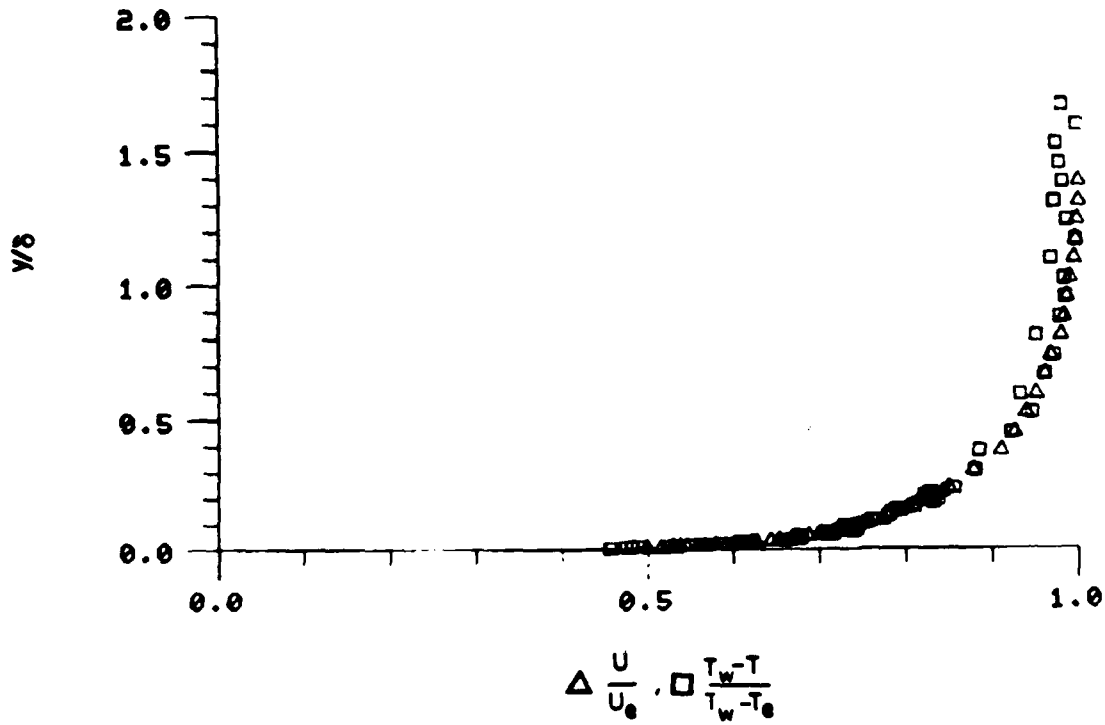
$$x = 52 \text{ in.}, T_e = 4.7\%$$

Table B21A

$x = 52 \text{ in.}, T_e = 4.7\%$

Table B12B

VELOCITY AND TEMPERATURE RATIOS



VELOCITY AND TEMPERATURE DISTRIBUTIONS IN UNIVERSAL COORDINATES

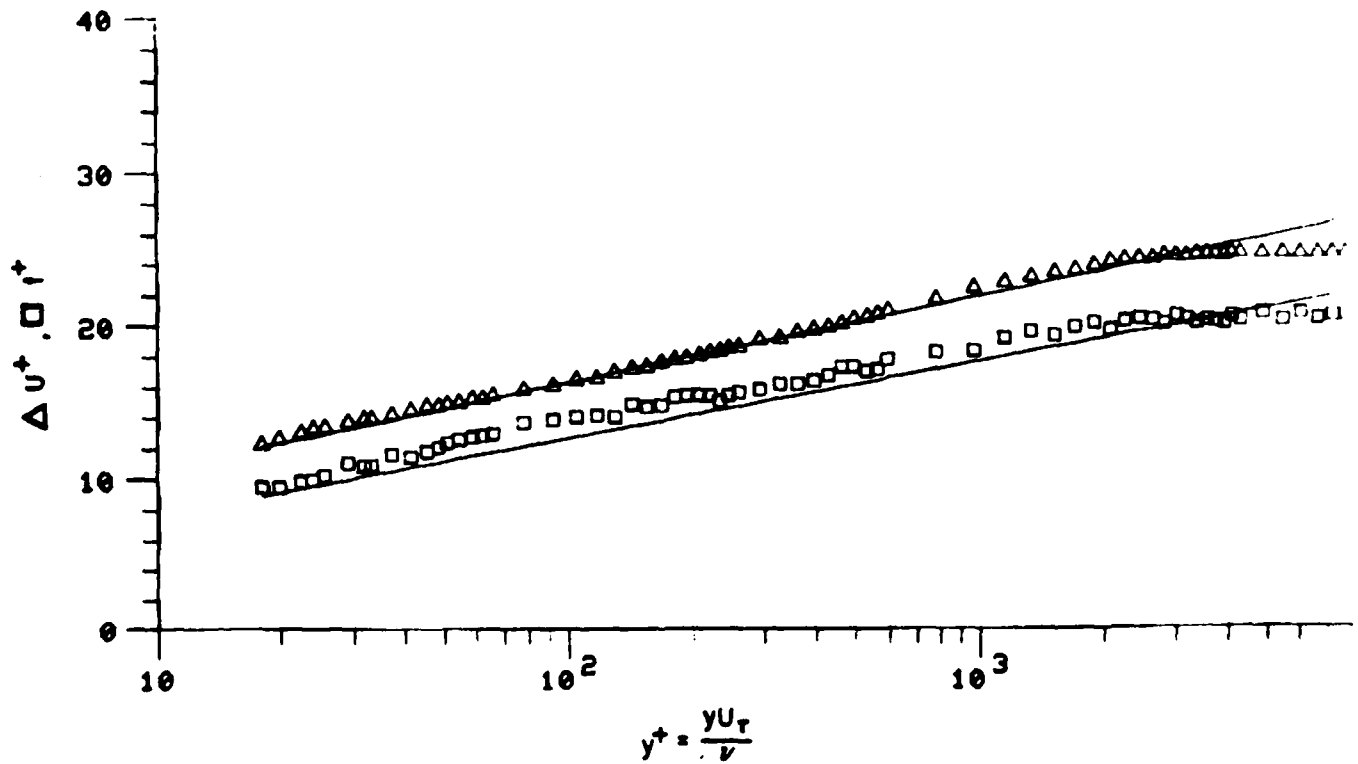


Figure B15. Mean Velocity and Temperature Profiles $x = 68$ in., $Te = 4.2\%$

$x = 68 \text{ in.}, T_e = 4.2\%$

Table B22

RUN NO. 1. POINT 3.
 BOUNDARY LAYER PROPERTIES

LINEAR
 INTERPOLATION
 TO WALL

STANDARD
 SUBLAYER
 FUNCTION FROM
 WALL TO $y^+ = 35$

FREE STREAM VELOCITY	=	99.365	99.365
FREE STREAM TEMPERATURE	=	72.200	
WALL TEMPERATURE	=	95.630	
WALL HEAT FLUX	=	.07913	
FREE STREAM DENSITY	=	.07493	
FREE STREAM KINEMATIC VISCOSITY	=	.0001637	
DENSITY OF FLUID AT WALL	=	.07177	
KINEMATIC VISCOSITY OF FLUID AT WALL	=	.0001766	
WALL/FREE STREAM DENSITY RATIO	=	.95781	
LOCATION REYNOLDS NUMBER (REX)	=	3440281.97	
INPUT VALUE OF VELOCITY DELTA	=	1.80000	
INPUT VALUE OF TEMPERATURE DELTA	=	2.15000	
CALCULATED DELTA	=		1.33179
DELTA 99.5% INPUT	=	.00000	
DISPLACEMENT THICKNESS (DELSTAR)	=	.14511	.14498
MOMENTUM THICKNESS (THETA)	=	.10836	.10894
ENERGY-DISSIPATION THICKNESS	=	.19802	.19856
ENTHALPY THICKNESS	=	.00565	.00567
SHAPE FACTOR 12 (DELSTAR/THETA)	=	1.33910	1.33073
SHAPE FACTOR 32 (ENERGY/THETA)	=	1.82738	1.82262
MOMENTUM THICKNESS REYNOLDS NUMBER	=	5482.26	5511.75
DISPLACEMENT THICKNESS REYNOLDS NUMBER	=	7341.33	7334.64
SKIN FRICTION COEFFICIENT	=	.003181	
FRICTION VELOCITY	=	4.04924	
LAW OF THE WALL CONSTANT (K)	=	.41000	
LAW OF THE WALL CONSTANT (C)	=	5.00000	
WAKE STRENGTH	=		.08475
CLAUSERS 'DELTA' INTEGRAL	=	-3.20155	-3.42684
CLAUSERS 'G' INTEGRAL	=	18.42084	17.96570
DISPLACEMENT THICKNESS - CONSTANT DENSITY	=	.13513	.13965
MOMENTUM THICKNESS - CONSTANT DENSITY	=	.10921	.10961
SHAPE FACTOR 12 - CONSTANT DENSITY	=	1.23740	1.27169

LOCATION -X- 68.00000

Te = 4.2%

Table B23

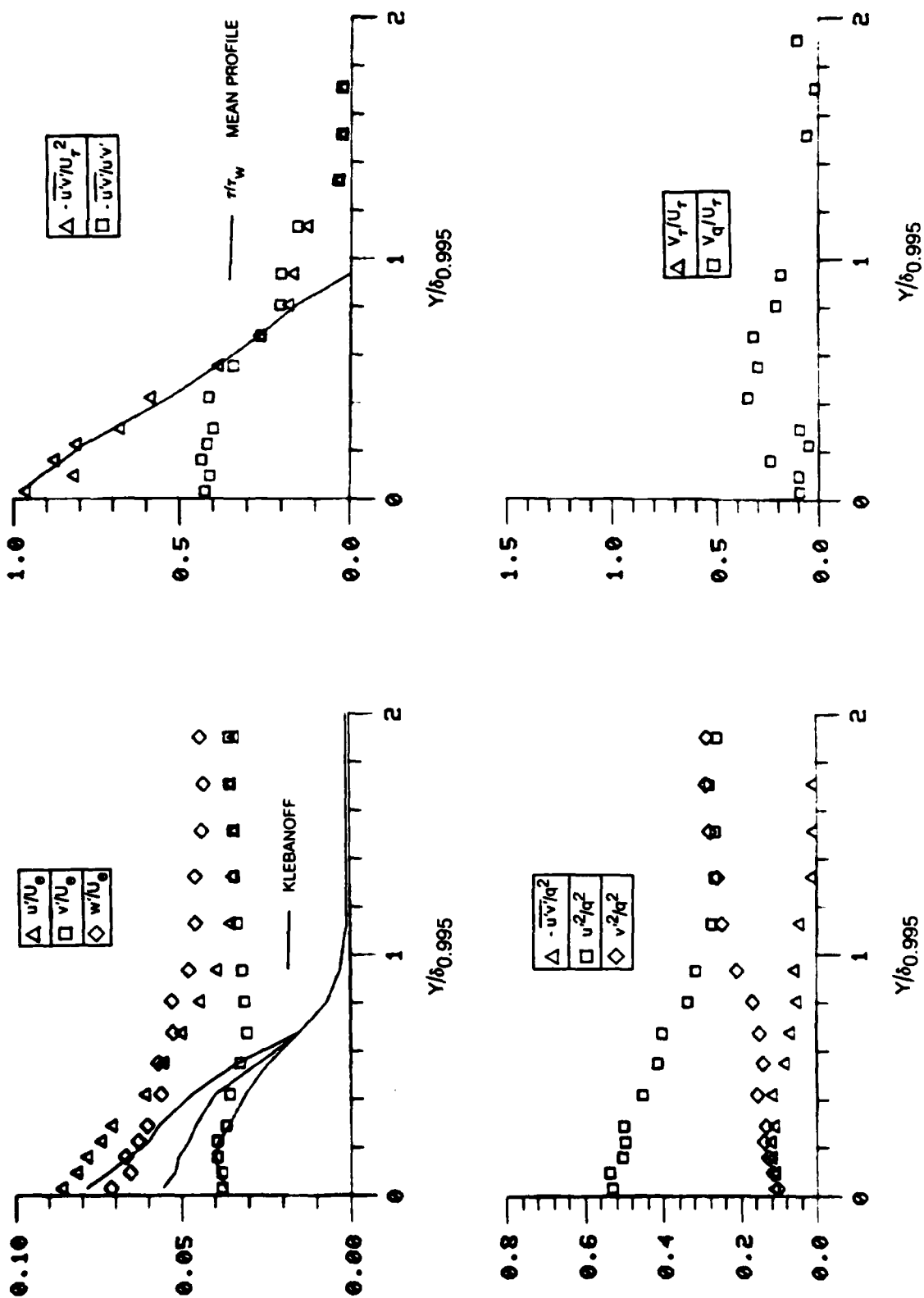


Figure B16A. Boundary Layer Turbulence Quantities, $x = 68$ in, $T_e = 4.2\%$

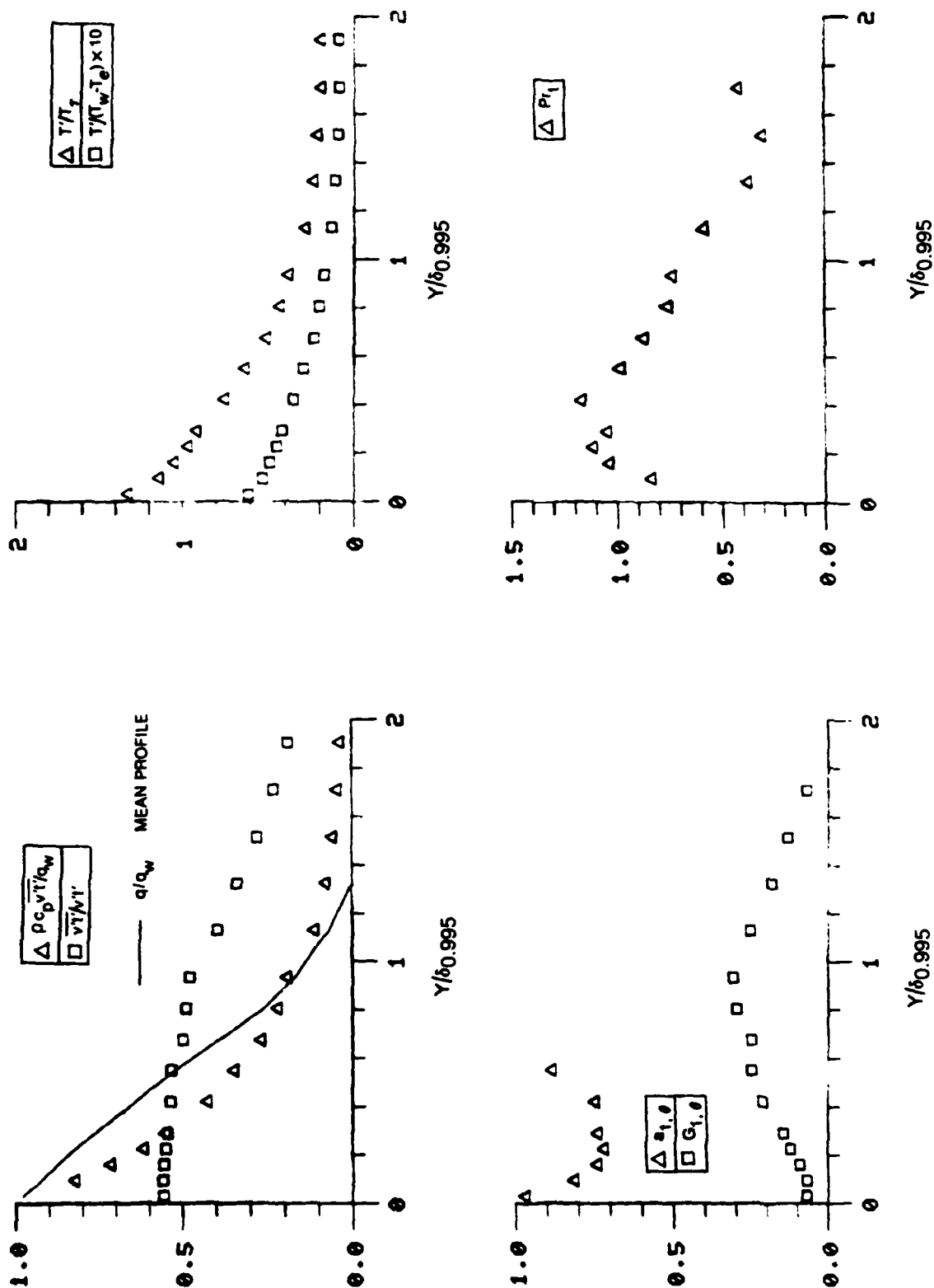


Figure B16b. Boundary Layer Turbulence Quantities, $x = 68$ in, $T_e = 4.2^\circ$

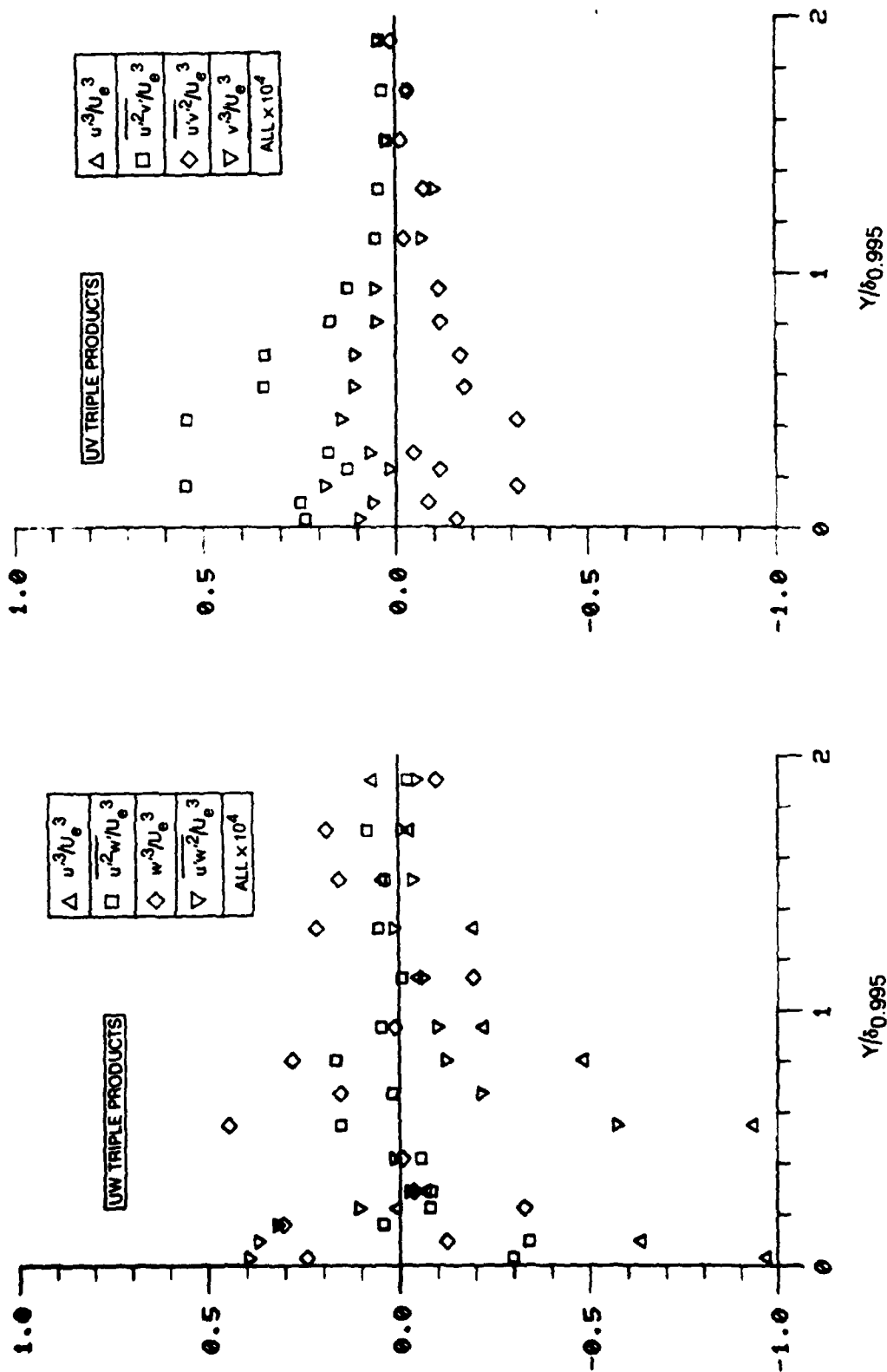


Figure B16C. Boundary Layer Triple Product Distributions $x = 68$ in, $Te = 4.2\%$

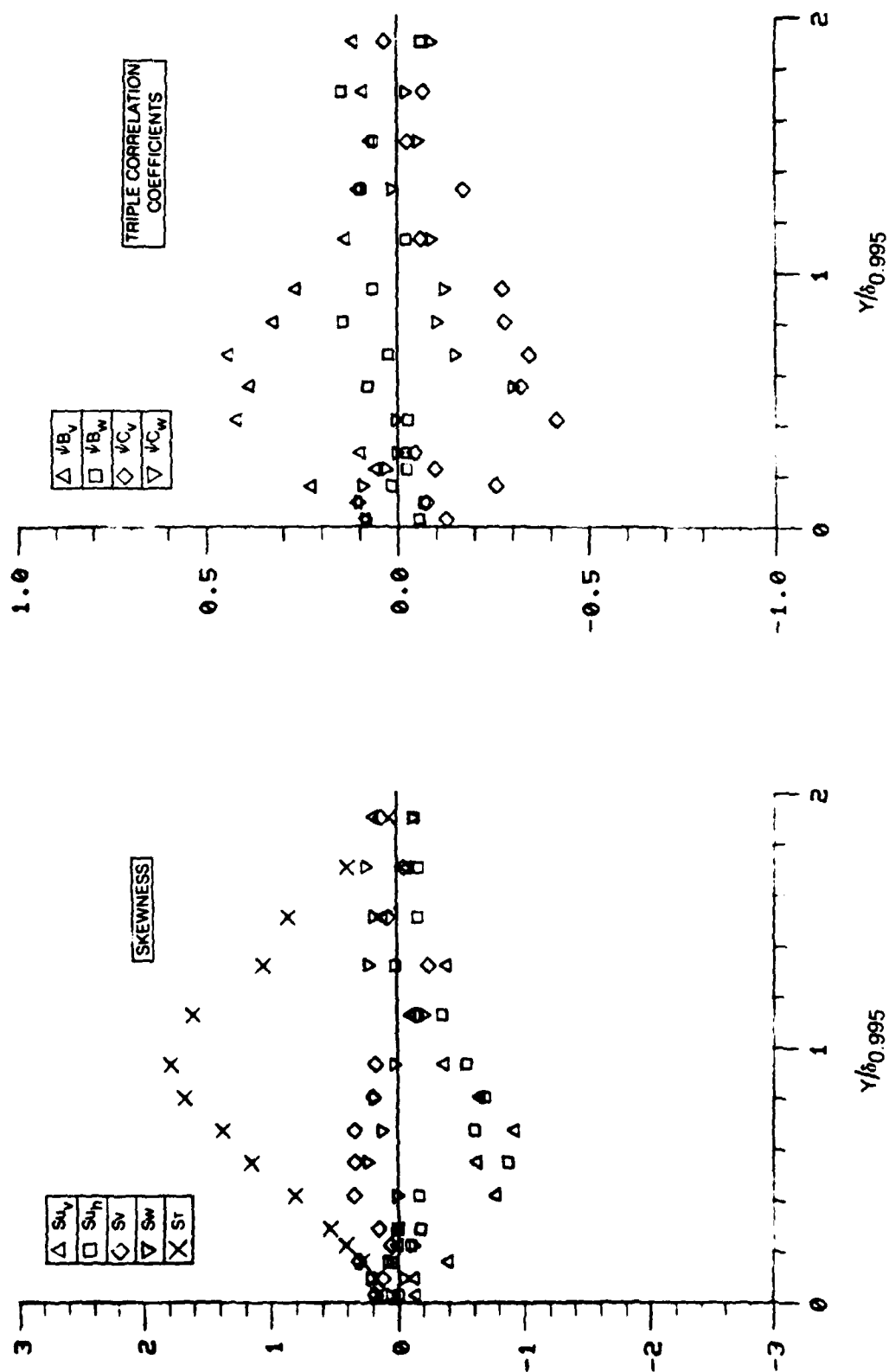


Figure B16D. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 68$ in, $T_e = 4.2^\circ$

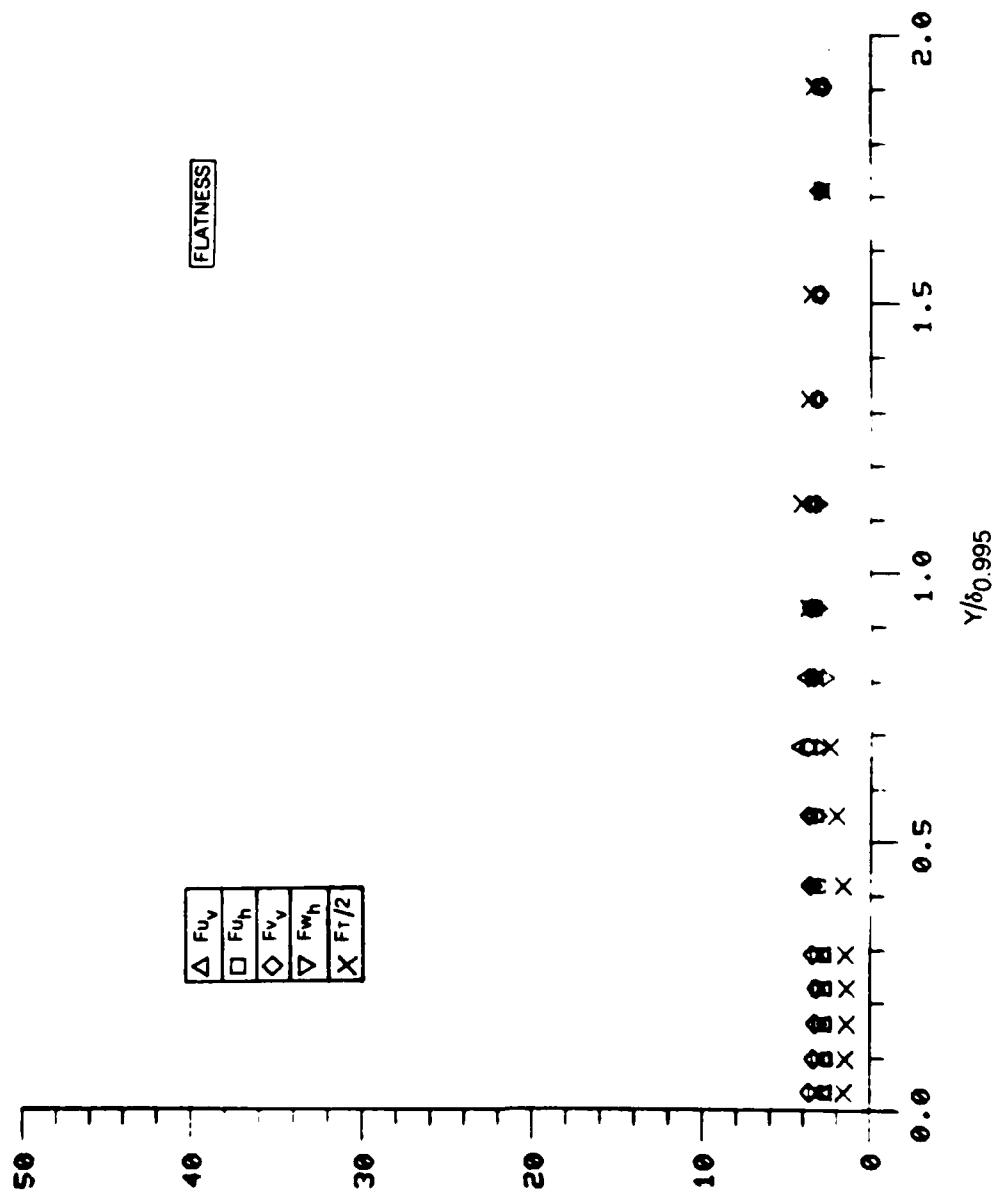


Figure B16E. Boundary Layer Flatness Distributions $x = 68$ in, $T_e = 4.2\%$

$$x = 68 \text{ in.}, T_e = 4.2\%$$
Table B24A

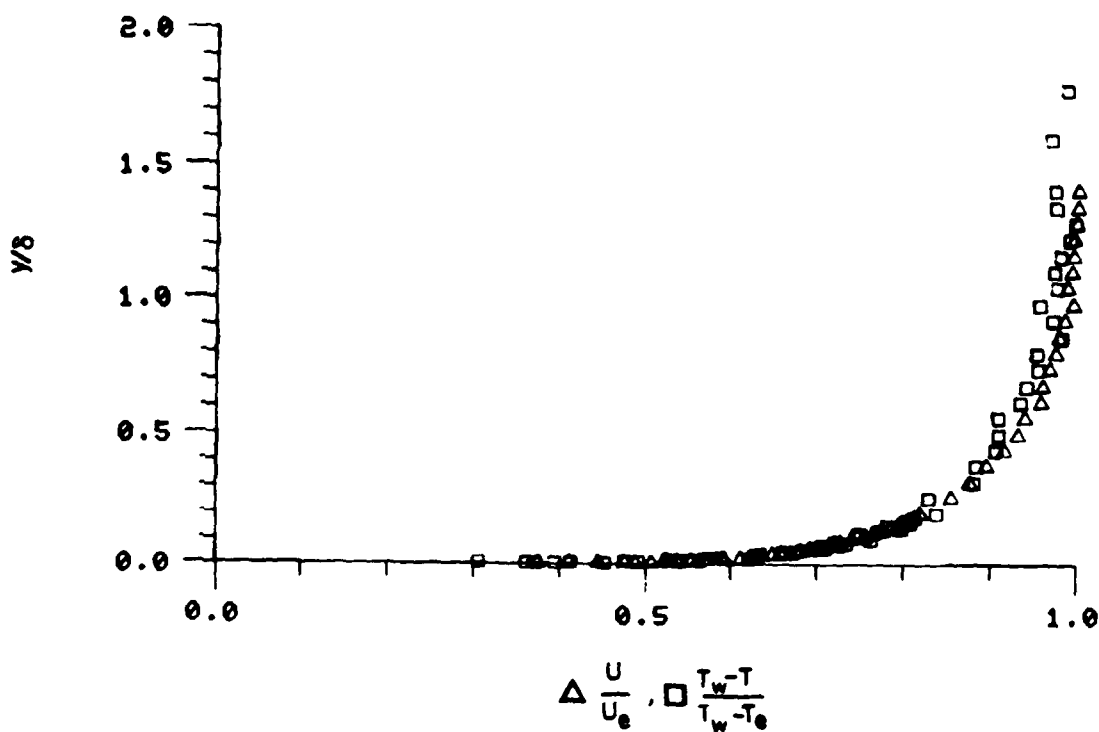
Fluctuating Profile Data

x = 68 in., Te = 4.2%

N INCHES	DELTA	X 10000	X 10000	X 10000	X 10000	X 10000	X 10000	X 10000
1	2							
2	2							
3	2							
4	2							
5	2							
6	2							
7	2							
8	2							
9	2							
10	2							
11	2							
12	2							
13	2							
14	2							
15	2							
16	2							
17	2							
18	2							
19	2							
20	2							
21	2							
22	2							
23	2							
24	2							
25	2							
26	2							
27	2							
28	2							
29	2							
30	2							
31	2							
32	2							
33	2							
34	2							
35	2							
36	2							
37	2							
38	2							
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41	2							
42	2							
43	2							
44	2							
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82	2							
83	2							
84	2							
85	2							
86	2							
87	2							
88	2							
89	2							
90	2							
91	2							
92	2							
93	2							
94	2							
95	2							
96	2							
97	2							
98	2							
99	2							
100	2							

Table B24B

VELOCITY AND TEMPERATURE RATIOS



VELOCITY AND TEMPERATURE DISTRIBUTIONS IN UNIVERSAL COORDINATES

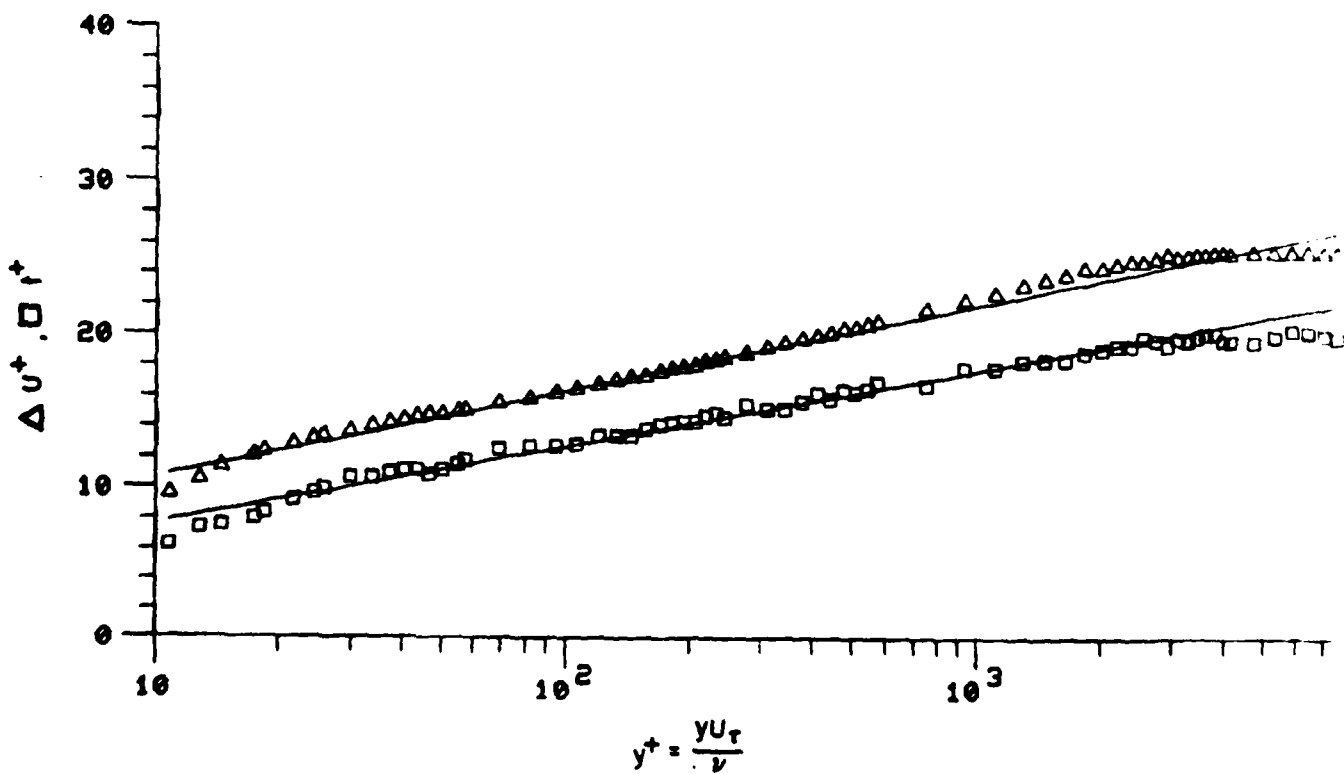


Figure B17. Mean Velocity and Temperature Profiles $x = 84$ in., $Te = 3.9\%$

Mean Profile Data

x = 85 in., Te = 3.9%

N	Y	DELTA	FT/SEC	T	U/UE	THETA	U-UE	U(1)	T(1)	Y(1)
INCHES				°E.F		°TAU				
1	.0000	.0000	37.25	87.96	.376	-15.764	9.523	6.152	10.771	1.771
2	.0000	.0000	37.81	86.62	.412	-14.873	10.434	7.326	12.502	1.502
3	.0000	.0000	40.11	86.39	.446	-14.029	11.276	7.828	14.466	1.466
4	.0000	.0000	47.12	85.87	.476	-13.261	12.046	7.963	17.238	1.238
5	.0000	.0000	48.24	85.41	.467	-12.573	12.334	8.153	16.346	1.346
6	.0011	.0007	50.10	84.47	.506	-12.498	12.609	9.146	21.672	1.672
7	.0013	.0008	51.60	83.93	.476	-12.114	13.193	9.613	25.555	1.555
8	.0013	.0009	51.99	83.57	.525	-12.015	13.292	9.613	25.552	1.552
9	.0016	.0010	53.22	82.69	.538	-11.702	13.605	10.663	29.616	1.616
10	.0016	.0010	53.76	82.73	.553	-11.301	14.006	10.663	33.496	1.496
11	.0021	.0013	55.15	82.42	.561	-11.100	14.206	10.663	37.151	1.151
12	.0021	.0013	55.61	82.13	.567	-10.952	14.355	11.108	40.103	1.103
13	.0023	.0015	56.81	82.16	.574	-10.783	14.524	11.108	43.103	1.103
14	.0023	.0016	57.67	82.46	.583	-10.564	14.743	10.663	46.054	1.054
15	.0023	.0017	57.72	82.18	.583	-10.551	14.756	11.094	49.054	1.054
16	.0023	.0019	58.16	81.69	.586	-10.433	14.674	11.511	52.054	1.054
17	.0030	.0019	58.55	81.41	.592	-10.338	14.964	11.744	55.054	1.054
18	.0033	.0023	60.43	80.47	.610	-9.859	15.448	12.544	68.054	1.054
19	.0044	.0026	61.60	80.29	.622	-9.558	15.749	12.695	71.054	1.054
20	.0506	.0032	62.91	80.34	.636	-9.222	16.084	12.654	74.054	1.054
21	.0577	.0036	64.14	80.18	.646	-8.909	16.398	12.784	77.054	1.054
22	.0644	.0041	65.14	79.49	.656	-8.655	16.652	13.374	80.054	1.054
23	.0711	.0045	66.97	79.56	.669	-8.364	16.942	13.317	83.054	1.054
24	.0772	.0049	66.97	79.55	.677	-8.185	17.121	13.322	86.054	1.054
25	.0844	.0053	67.39	79.04	.681	-8.077	17.229	13.756	89.054	1.054
26	.0911	.0058	68.27	78.70	.690	-7.853	17.454	14.046	92.054	1.054
27	.0977	.0061	69.21	78.35	.699	-7.613	17.694	14.146	95.054	1.054
28	.1033	.0066	69.64	78.39	.703	-7.504	17.603	14.303	98.054	1.054
29	.1111	.0070	70.03	78.42	.708	-7.402	17.905	14.280	101.054	1.054
30	.1177	.0074	71.16	78.01	.719	-7.114	18.193	14.630	104.054	1.054
31	.1244	.0078	71.26	77.79	.720	-7.089	18.216	14.600	107.054	1.054
32	.1300	.0083	71.91	77.12	.726	-6.924	18.383	14.530	110.054	1.054
33	.1477	.0094	73.27	77.11	.740	-6.574	18.733	15.388	113.054	1.054
34	.1655	.0105	74.74	77.43	.755	-6.200	19.107	15.117	116.054	1.054
35	.1833	.0116	75.15	77.49	.763	-5.991	19.316	15.069	119.054	1.054
36	.2011	.0127	76.83	76.90	.776	-5.664	19.642	15.567	122.054	1.054
37	.2189	.0138	77.68	76.28	.785	-5.446	19.659	16.094	125.054	1.054
38	.2367	.0149	78.15	76.69	.792	-5.267	20.040	15.746	128.054	1.054
39	.2545	.0160	79.15	76.07	.802	-5.022	20.285	16.270	131.054	1.054
40	.2723	.0172	79.74	76.16	.806	-4.920	20.387	16.197	134.054	1.054
41	.2901	.0182	80.24	75.93	.811	-4.780	20.526	16.387	137.054	1.054
42	.3079	.0194	80.66	75.36	.816	-4.605	20.702	16.676	140.054	1.054
43	.3257	.0204	84.49	74.28	.827	-3.707	21.600	16.703	143.054	1.054
44	.3435	.0214	86.73	74.25	.836	-3.134	22.173	17.764	146.054	1.054
45	.3613	.0224	88.22	74.25	.844	-2.677	22.630	17.816	149.054	1.054
46	.3791	.0234	88.22	74.25	.854	-2.170	23.137	18.274	152.054	1.054
47	.3969	.0244	92.16	73.65	.861	-1.746	23.561	18.319	155.054	1.054
48	.4147	.0254	92.99	73.64	.868	-1.534	23.773	18.330	158.054	1.054
49	.4325	.0264	94.84	73.04	.876	-1.060	24.247	18.836	161.054	1.054
50	.4503	.0274	94.84	72.85	.883	-1.034	24.273	18.996	164.054	1.054
51	.4681	.0284	95.82	72.53	.891	-.810	24.496	19.219	167.054	1.054
52	.4859	.0294	96.52	72.59	.898	-.630	24.677	19.266	170.054	1.054
53	.5037	.0304	96.77	71.91	.906	-.567	24.740	19.800	173.054	1.054
54	.5215	.0314	97.42	72.14	.914	-.400	24.907	19.600	176.054	1.054
55	.5393	.0324	97.74	72.49	.922	-.320	25.196	19.305	179.054	1.054
56	.5571	.0334	98.56	72.03	.930	-.320	25.498	19.694	182.054	1.054
57	.5749	.0344	98.24	72.11	.938	-.177	25.129	19.624	185.054	1.054
58	.5927	.0354	98.41	71.93	.946	-.147	25.160	19.775	188.054	1.054
59	.6105	.0364	98.41	71.71	.954	-.147	25.159	19.964	191.054	1.054
60	.6283	.0374	98.80	71.33	.962	-.049	25.256	20.119	194.054	1.054
61	.6461	.0384	98.80	72.06	.970	-.014	25.293	19.670	197.054	1.054
62	.6639	.0394	98.93	72.10	.978	-.014	25.293	19.638	200.054	1.054
63	.6817	.0404	99.10	71.20	.986	-.028	25.335	19.548	203.054	1.054
64	.6995	.0414	99.20	71.78	.994	-.054	25.362	19.905	206.054	1.054
65	.7173	.0424	99.20	71.37	.998	-.055	25.377	20.251	209.054	1.054
66	.7351	.0434	99.26	71.43	.999	-.070	25.416	20.201	212.054	1.054
67	.7529	.0444	99.41	71.65	.999	-.109	25.416	20.015	215.054	1.054
68	.7707	.0454	99.22	71.87	.982	-.059	25.366	19.627	218.054	1.054

Table B25

RUN NO. 1. POINT 2.
 BOUNDARY LAYER PROPERTIES

	LINEAR INTERPOLATION TO WALL	STANDARD SUBLAYER FUNCTION FROM WALL TO $Y^+ = 35$
FREE STREAM VELOCITY =	98.987	98.987
FREE STREAM TEMPERATURE =	71.450	
WALL TEMPERATURE =	95.270	
WALL HEAT FLUX =	.07956	
FREE STREAM DENSITY =	.07504	
FREE STREAM KINEMATIC VISCOSITY =	.0001633	
DENSITY OF FLUID AT WALL =	.07182	
KINEMATIC VISCOSITY OF FLUID AT WALL =	.0001764	
WALL/FREE STREAM DENSITY RATIO =	.95708	
LOCATION REYNOLDS NUMBER (REX) =	4244178.31	
INPUT VALUE OF VELOCITY DELTA =	2.05000	
INPUT VALUE OF TEMPERATURE DELTA =	2.10000	
CALCULATED DELTA =		1.58079
DELTA 99.5% INPUT =	.00000	
DISPLACEMENT THICKNESS (DELSTAR) =	.17986	.16012
MOMENTUM THICKNESS (THETA) =	.13446	.13465
ENERGY-DISSIPATION THICKNESS =	.24493	.24498
ENTHALPY THICKNESS =	.00715	.00715
SHAPE FACTOR 12 (DELSTAR/THETA) =	1.33749	1.33772
SHAPE FACTOR 32 (ENERGY/THETA) =	1.82137	1.81943
MOMENTUM THICKNESS REYNOLDS NUMBER =	6794.61	6803.22
DISPLACEMENT THICKNESS REYNOLDS NUMBER =	9087.75	9100.78
SKIN FRICTION COEFFICIENT =	.002989	
FRICTION VELOCITY =	3.91148	
LAW OF THE WALL CONSTANT (K) =	.41000	
LAW OF THE WALL CONSTANT (C) =	5.00000	
WAKE STRENGTH =		.17313
CLAUSERS 'DELTA' INTEGRAL =	-4.22327	-4.37735
CLAUSERS 'G' INTEGRAL =	23.76288	23.81295
DISPLACEMENT THICKNESS - CONSTANT DENSITY =	.16980	.17297
MOMENTUM THICKNESS - CONSTANT DENSITY =	.13561	.13579
SHAPE FACTOR 12 - CONSTANT DENSITY =	1.25212	1.27363

LOCATION -X- 84.00000

Te = 3.9%

Table B26

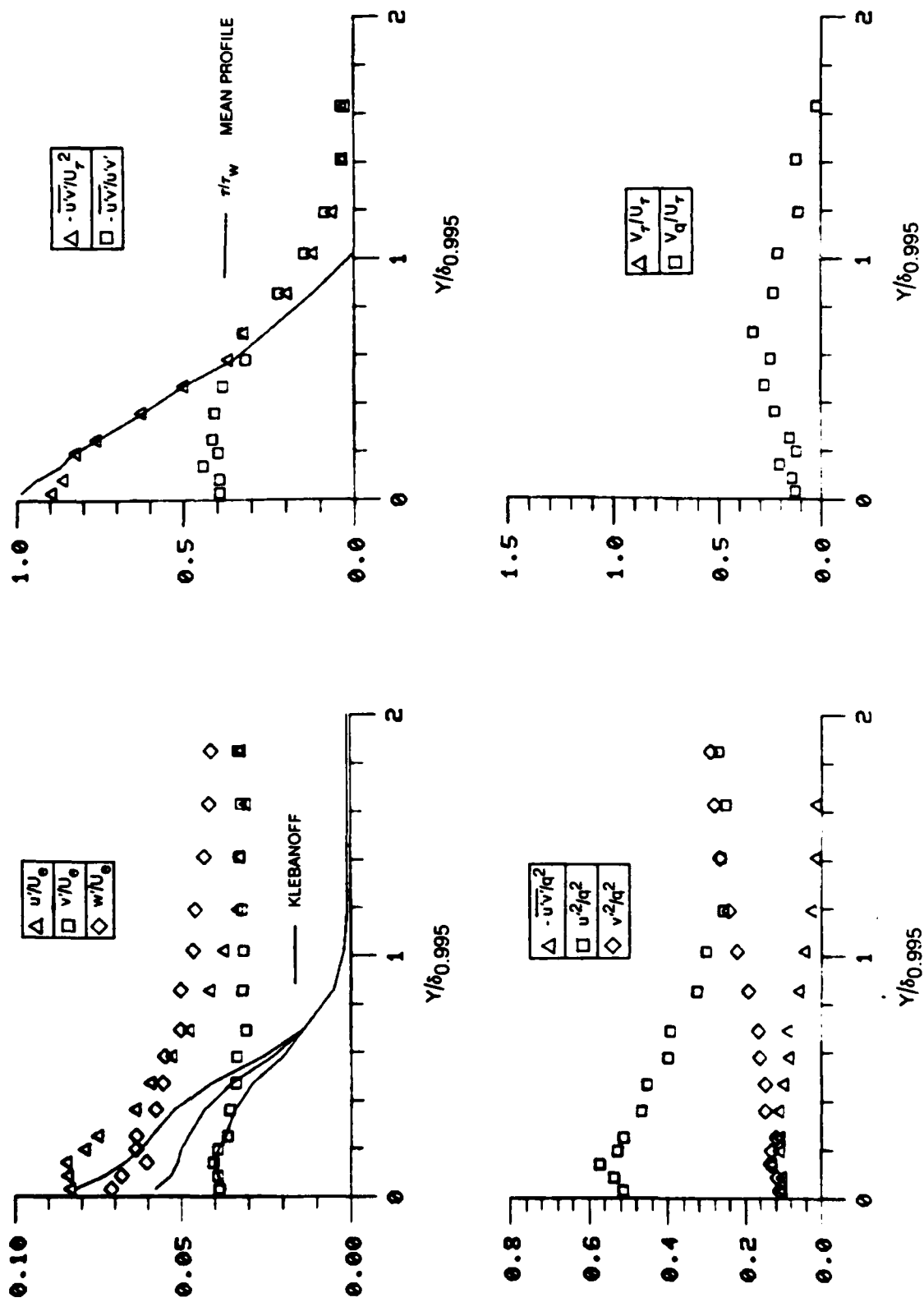


Figure B18A. Boundary Layer Turbulence Quantities, $x = 84$ in, $T_e = 3.9\%$

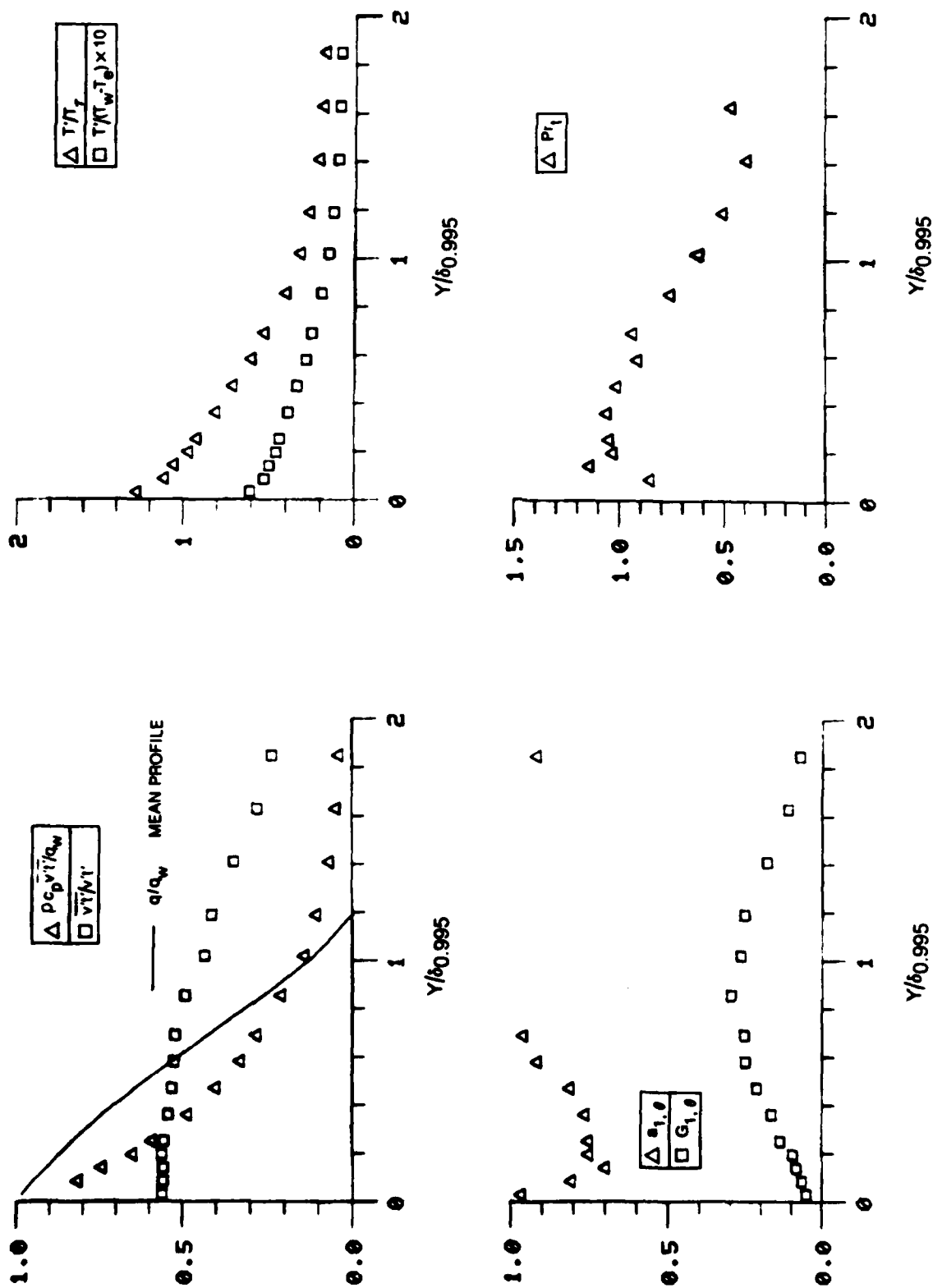


Figure B18B. Boundary Layer Turbulence Quantities $x = 84$ in, $T_e = 3.9^\circ$

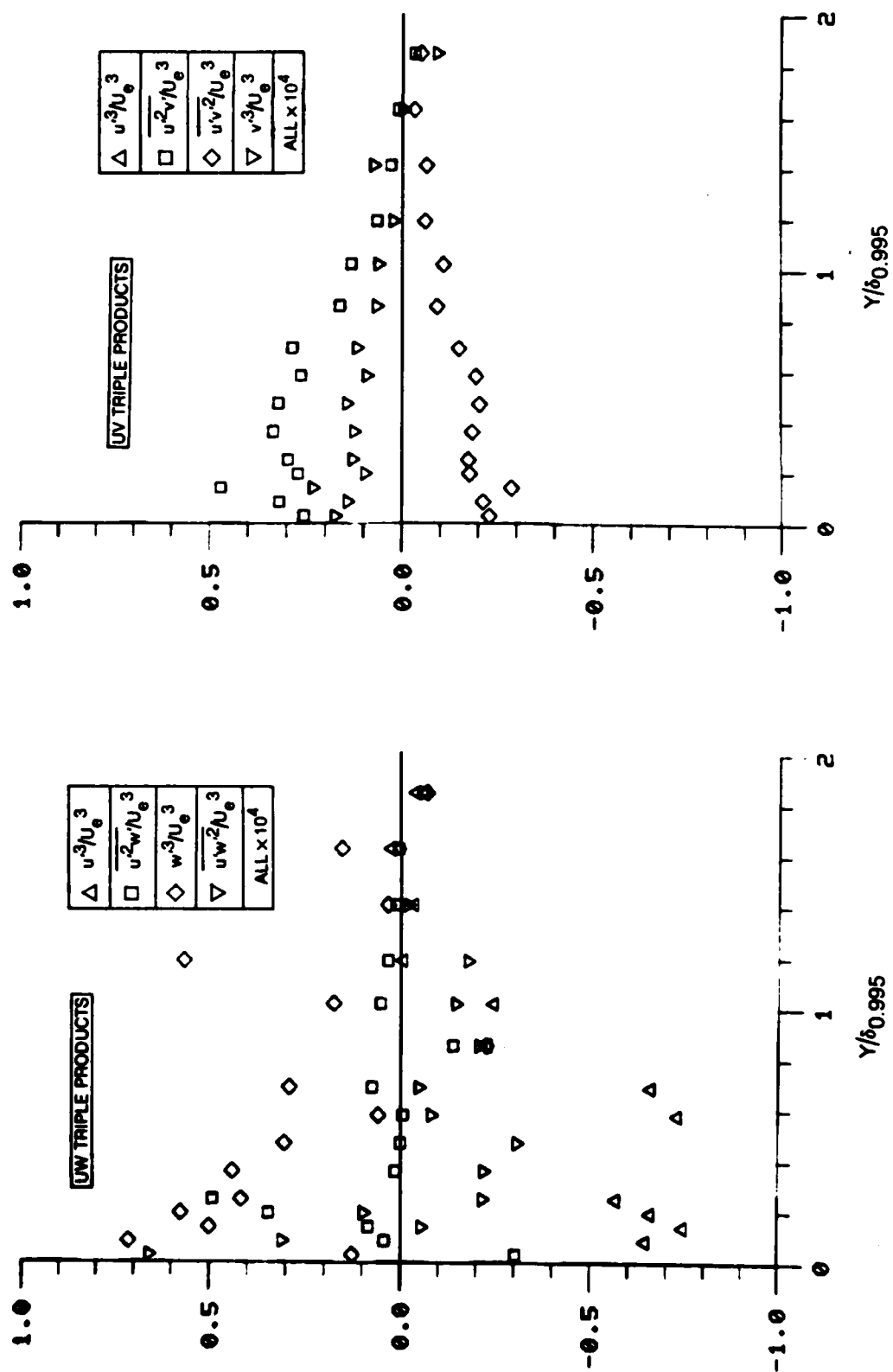


Figure B18C. Boundary Layer Triple Product Distributions $x = 84$ in, $T_e = 3.9\%$

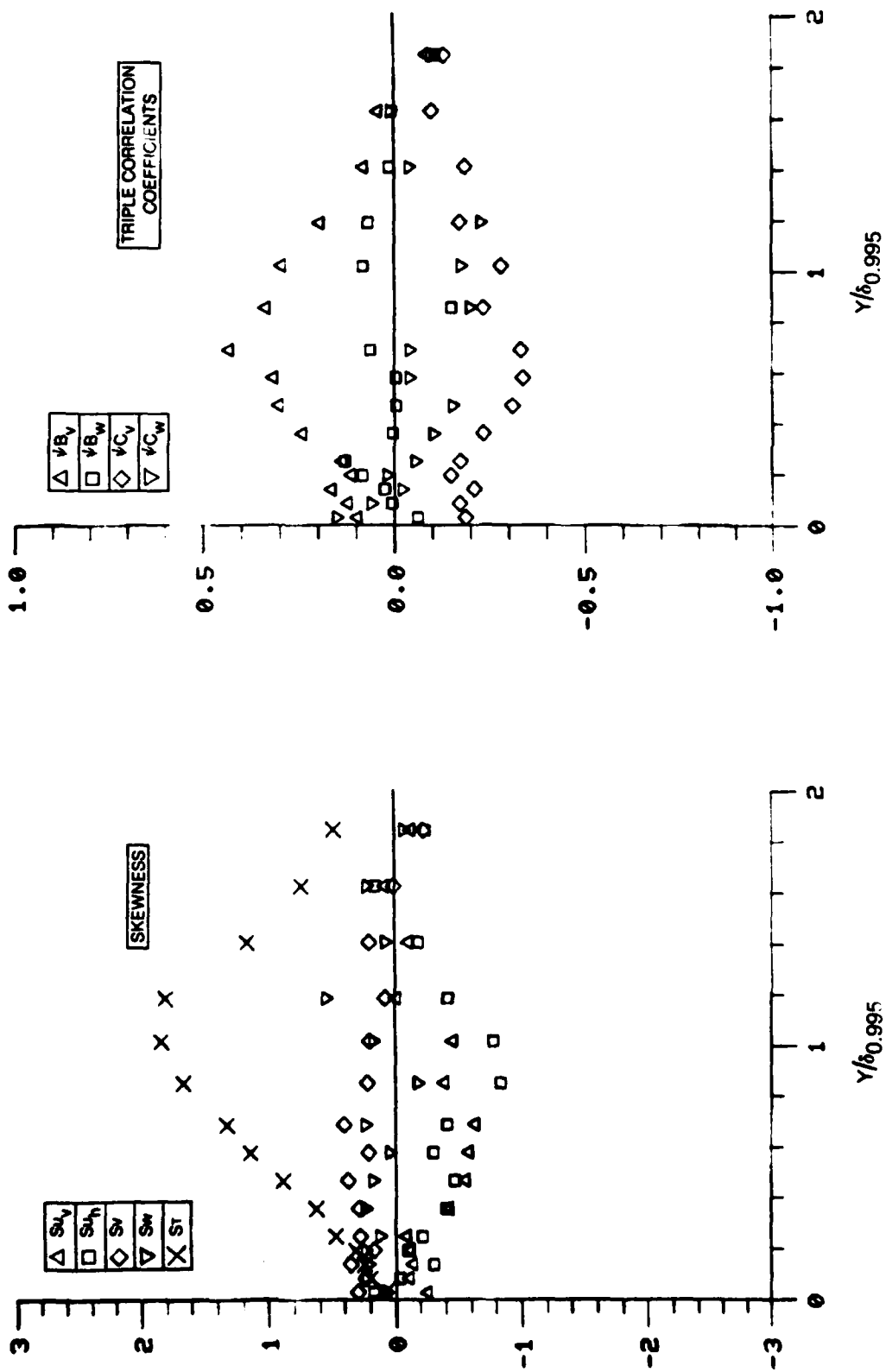


Figure B18D. Boundary Layer Skewness and Triple Product Correlation Coefficient Distributions $x = 84$ in, $T_e = 3.9\%$

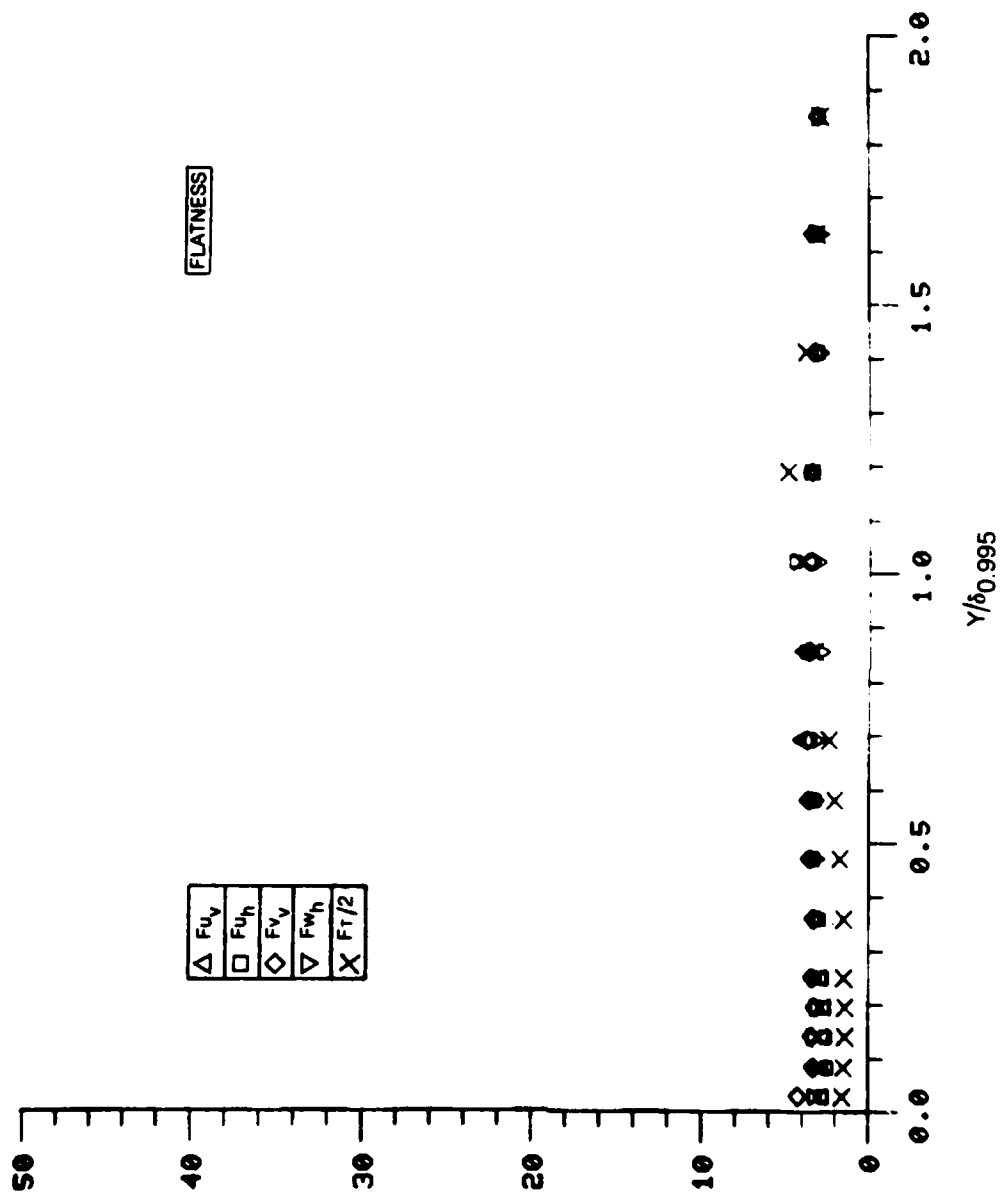


Figure B18E. Boundary Layer Flatness Distributions $x = 84$ in, $T_e = 3.9\%$

$x = 84 \text{ in.}, T_e = 3.9\%$

4 INCHES	Y/ DELTA	U*/UE	V*/U	W*/UE	U*/V*/UE	U*/UE	U*/V*/UE	U*/UE
1	2	3	4	5	6	7	8	9
10	11	12	13	14	15	16	17	18
19	20	21	22	23	24	25	26	27
28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45
46	47	48	49	50	51	52	53	54
55	56	57	58	59	60	61	62	63
64	65	66	67	68	69	70	71	72
73	74	75	76	77	78	79	80	81
82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99
100	101	102	103	104	105	106	107	108
109	110	111	112	113	114	115	116	117
118	119	120	121	122	123	124	125	126
127	128	129	130	131	132	133	134	135
136	137	138	139	140	141	142	143	144
145	146	147	148	149	150	151	152	153
154	155	156	157	158	159	160	161	162
163	164	165	166	167	168	169	170	171
172	173	174	175	176	177	178	179	180
181	182	183	184	185	186	187	188	189
190	191	192	193	194	195	196	197	198
199	200	201	202	203	204	205	206	207
208	209	210	211	212	213	214	215	216
217	218	219	220	221	222	223	224	225
226	227	228	229	230	231	232	233	234
235	236	237	238	239	240	241	242	243
244	245	246	247	248	249	250	251	252
253	254	255	256	257	258	259	260	261
262	263	264	265	266	267	268	269	270
271	272	273	274	275	276	277	278	279
280	281	282	283	284	285	286	287	288
289	290	291	292	293	294	295	296	297
298	299	300	301	302	303	304	305	306
307	308	309	310	311	312	313	314	315
316	317	318	319	320	321	322	323	324
325	326	327	328	329	330	331	332	333
334	335	336	337	338	339	340	341	342
343	344	345	346	347	348	349	350	351
352	353	354	355	356	357	358	359	360
361	362	363	364	365	366	367	368	369
370	371	372	373	374	375	376	377	378
379	380	381	382	383	384	385	386	387
388	389	390	391	392	393	394	395	396
397	398	399	400	401	402	403	404	405
406	407	408	409	410	411	412	413	414
415	416	417	418	419	420	421	422	423
424	425	426	427	428	429	430	431	432
433	434	435	436	437	438	439	440	441
442	443	444	445	446	447	448	449	450
451	452	453	454	455	456	457	458	459
460	461	462	463	464	465	466	467	468
469	470	471	472	473	474	475	476	477
478	479	480	481	482	483	484	485	486
487	488	489	490	491	492	493	494	495
496	497	498	499	500	501	502	503	504
505	506	507	508	509	510	511	512	513
514	515	516	517	518	519	520	521	522
523	524	525	526	527	528	529	530	531
532	533	534	535	536	537	538	539	540
541	542	543	544	545	546	547	548	549
550	551	552	553	554	555	556	557	558
559	560	561	562	563	564	565	566	567
568	569	570	571	572	573	574	575	576
577	578	579	580	581	582	583	584	585
586	587	588	589	590	591	592	593	594
595	596	597	598	599	600	601	602	603
604	605	606	607	608	609	610	611	612
613	614	615	616	617	618	619	620	621
622	623	624	625	626	627	628	629	630
631	632	633	634	635	636	637	638	639
640	641	642	643	644	645	646	647	648
649	650	651	652	653	654	655	656	657
658	659	660	661	662	663	664	665	666
667	668	669	670	671	672	673	674	675
676	677	678	679	680	681	682	683	684
685	686	687	688	689	690	691	692	693
694	695	696	697	698	699	700	701	702
703	704	705	706	707	708	709	710	711
712	713	714	715	716	717	718	719	720
721	722	723	724	725	726	727	728	729
730	731	732	733	734	735	736	737	738
739	740	741	742	743	744	745	746	747
748	749	750	751	752	753	754	755	756
757	758	759	760	761	762	763	764	765
766	767	768	769	770	771	772	773	774
775	776	777	778	779	780	781	782	783
784	785	786	787	788	789	790	791	792
793	794	795	796	797	798	799	800	801
802	803	804	805	806	807	808	809	810
811	812	813	814	815	816	817	818	819
820	821	822	823	824	825	826	827	828
829	830	831	832	833	834	835	836	837
838	839	840	841	842	843	844	845	846
847	848	849	850	851	852	853	854	855
856	857	858	859	860	861	862	863	864
865	866	867	868	869	870	871	872	873
874	875	876	877	878	879	880	881	882
883	884	885	886	887	888	889	890	891
892	893	894	895	896	897	898	899	900
901	902	903	904	905	906	907	908	909
910	911	912	913	914	915	916	917	918
919	920	921	922	923	924	925	926	927
928	929	930	931	932	933	934	935	936
937	938	939	940	941	942	943	944	945
946	947	948	949	950	951	952	953	954
955	956	957	958	959	960	961	962	963
964	965	966	967	968	969	970	971	972
973	974	975	976	977	978	979	980	981
982	983	984	985	986	987	988	989	990
991	992	993	994	995	996	997	998	999
1000	1001	1002	1003	1004	1005	1006	1007	1008
1009	1010	1011	1012	1013	1014	1015	1016	1017
1018	1019	1020	1021	1022	1023	1024	1025	1026
1027	1028	1029	1030	1031	1032	1033	1034	1035
1036	1037	1038	1039	1040	1041	1042	1043	1044
1045	1046	1047	1048	1049	1050	1051	1052	1053
1054	1055	1056	1057	1058	1059	1060	1061	1062
1063	1064	1065	1066	1067	1068	1069	1070	1071
1072	1073	1074	1075	1076	1077	1078	1079	1080
1081	1082	1083	1084	1085	1086	1087	1088	1089
1090	1091	1092	1093	1094	1095	1096	1097	1098
1099	1100	1101	1102	1103	1104	1105	1106	1107
1108	1109	1110	1111	1112	1113	1114	1115	1116
1117	1118	1119	1120	1121	1122	1123	1124	1125
1126	1127	1128	1129	1130	1131	1132	1133	1134
1135	1136	1137	1138	1139	1140	1141	1142	1143
1144	1145	1146	1147	1148	1149	1150	1151	1152
1153	1154	1155	1156	1157	1158	1159	1160	1161
1162	1163	1164	1165	1166	1167	1168	1169	1170
1171	1172	1173	1174	1175	1176	1177	1178	1179
1180	1181	1182	1183	1184	1185	1186	1187	1188
1189	1190	1191	1192	1193	1194	1195	1196	1197
1198	1199	1200	1201	1202	1203	1204	1205	1206
1207	1208	1209	1210	1211	1212	1213	1214	1215
1216	1217	1218	1219	1220	1221	1222	1223	1224
1225	1226	1227	1228	1229	1230	1231	1232	1233
1234	1235	1236	1237	1238	1239	1240	1241	1242
1243	1244	1245	1246	1247	1248	1249	1250	1251
1252	1253	1254	1255	1256	1257	1258	1259	1260
1261	1262	1263	1264	1265	1266	1267	1268	1269
1270	1271	1272	1273	1274	1275	1276	1277	1278
1279	1280	1281	1282	1283	1284	1285	1286	1287
1288	1289	1290	1291	1292	1293	1294	1295	1296
1297	1298	1299	1300	1301	1302	1303	1304	1305
1306	1307	1308	1309	1310	1311	1312	1313	1314
1315	1316	1317	1318	1319	1320	1321	1322	1323
1324	1325	1326	1327	1328	1329	1330	1331	1332
1333	1334	1335	1336	1337	1338	1339	1340	1341
1342	1343	1344	1345	1346	1347	1348	1349	1350
1351	1352	1353	1354	1355	1356	1357	1358	1359
1360	1361	1362	1363	1364	1365	1366	1367	1368
1369	1370	1371	1372	1373	1374	1375	1376	1377
1378	1379	1380	1381	1382	1383	1384	1385	1386
1387	1388	1389	1390	1391	1392	1393	1394	1395
1396	1397	1398	1399	1400	1401	1402	1403	1404
1405	1406	1407	1408	1409	1410	1411	1412	1413
1414	1415	1416	1417	1418	1419	1420</		

Table 827A

$x = 84 \text{ in.}, T_e = 3.9\%$

[illegible]

Table B27B

DATE
ILME