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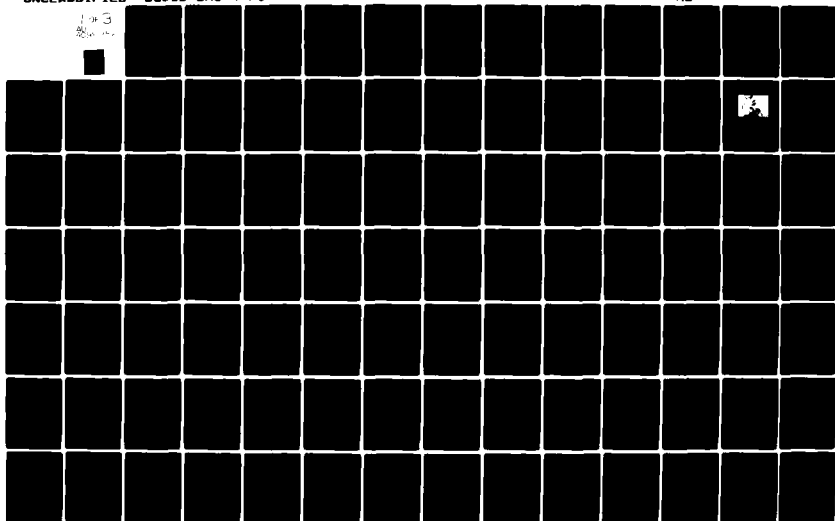
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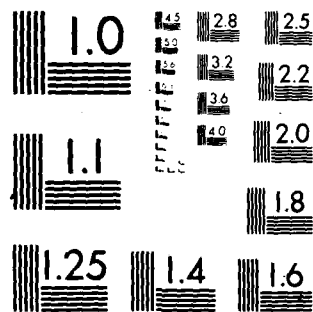
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The experimental results described in this report are concerned with a nominally two-dimensional separating turbulent boundary layer for an airfoil-type flow in which the flow was accelerated and then decelerated until separation. Upstream of separation single and cross-wire hot-wire anemometer measurements are also presented. Measurements obtained in the separated zone with a directionally-sensitive laser anemometer system are presented, for U , V , $\overline{u^2}$, $\overline{v^2}$, $-\overline{uv}$, $\overline{u^3}$, $\overline{u^4}$, $\overline{v^3}$, $\overline{v^4}$, the fraction of time that the flow moves downstream, the fraction of time that the flow moves away from the wall, and u spectra.

In addition to confirming the earlier conclusions of Simpson et al. (1977) regarding a separating airfoil-type turbulent boundary layer, much new information about the separated region has been gathered. (1) The backflow mean velocity profile scales on the maximum negative mean velocity U_N and its distance from the wall N . A U^+ vs. y^+ law-of-the-wall velocity profile is not consistent with this result. (2) The turbulent velocities are comparable with the mean velocity in the backflow, although low turbulent shearing stresses are present. (3) Mixing length and eddy viscosity models are physically meaningless in the backflow. (4) Negligible turbulence energy production occurs in the backflow.

These and other results lead to significant conclusions about the nature of the separated flow when the thickness of the backflow region is small as compared with the shear layer thickness. The backflow is controlled by the large-scale outer region flow. The small mean backflow does not come from far downstream, but appears to be supplied intermittently by large-scale structures as they pass through the separated flow. Downstream of fully-developed separation, the mean backflow appears to be divided into three layers: a viscous layer nearest the wall that is dominated by the turbulent flow unsteadiness but with little Reynolds shearing stress effects; a rather flat intermediate layer that seems to act as an overlap region between the viscous wall and outer regions; and the outer backflow region that is really part of the large-scaled outer region flow. The Reynolds shearing stress must be modeled by relating it to the turbulence structure and not to local mean velocity gradients. The mean velocities in the backflow are the results of time-averaging the large turbulent fluctuations and are not related to the source of the turbulence.

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MEASUREMENTS OF A SEPARATING
TURBULENT BOUNDARY LAYER

by

Roger L. Simpson, Y.-T. Chew, and B. G. Shivaprasad
SOUTHERN METHODIST UNIVERSITY

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by

Roger L. Simpson*, Y.-T. Chew**, and B.G. Shivaprasad***
Southern Methodist University

ABSTRACT

The problem of turbulent boundary layer separation due to an adverse pressure gradient is an old but still important problem in many fluid flow devices. Until recent years little quantitative experimental information was available on the flow structure downstream of separation because of the lack of proper instrumentation. The directionally-sensitive laser anemometer now provides the ability to accurately measure the instantaneous flow direction and magnitude.

The experimental results described in this report are concerned with a nominally two-dimensional separating turbulent boundary layer for an airfoil-type flow in which the flow was accelerated and then decelerated until separation. Upstream of separation single and cross-wire hot-wire anemometer measurements are also presented. Measurements obtained in the separated zone with a directionally-sensitive laser anemometer system are presented for U , V , $\overline{u^2}$, $\overline{v^2}$, $\overline{-uv}$, $\overline{u^3}$, $\overline{u^4}$, $\overline{v^3}$, $\overline{v^4}$, the fraction of time that the flow moves downstream, the fraction of time that the flow moves away from the wall, and u spectra.

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NOMENCLATURE

a	$\equiv \tau/\rho q^2$
a_1	$\equiv -\overline{uv}/(\overline{u^2} + \overline{v^2})$
a_2	$\equiv aF^{4/3}$, defined in equation (36)
$B(y/\delta)$	$\equiv RU_\infty/ U_N $, normalized backflow function
C	$\equiv \int_0^\infty f_2(\eta_2)d\eta_2$, Perry and Schofield constant
C_1	defined in equation (34)
C_2	$\equiv C_1F^{1/3}$, defined in equation (35)
$C_f/2$	$\equiv \tau_0/\rho U_\infty^2$, local skin-friction coefficient
C_p	$\equiv 2(P - P_i)/\rho U_\infty^2$, pressure coefficient
e	$\equiv LU_\tau^2/U_{MP}^2$, Perry and Schofield inner layer length scale, equation (12).
F	ratio of total turbulence energy production to shear production, equation (33)
F_u, F_v	$\overline{u^4}/(\overline{u^2})^2, \overline{v^4}/(\overline{v^2})^2$, kurtosis or flatness factor for u and v fluctuations, respectively.
$F(n)$	$(1/\overline{u^2})(d\overline{u^2}/dn)$; $1 = \int_0^\infty F(n)dn$; spectrum function for u .
f_1, f_2	Perry and Schofield correlation functions, defined in equations (14) and (10), respectively.
G	Bradshaw large eddy diffusion function, defined in equation (28)
H_{12}	$\equiv \delta_1/\delta_2$, velocity profile shape factor

L	distance from the wall to the maximum pseudo-shear stress
ℓ	mixing length, defined in equation (20)
M	distance from the wall to the maximum
N	number of signal bursts in equation (4); distance from wall to minimum velocity in backflow.
n_b	peak frequency of $nF(n)$ spectral distribution
P, p	mean and fluctuation pressure
PL,PR	left and right sides of equation (8)
$P(U)$	velocity probability distribution, equation (5)
$\overline{q^2}$	$\overline{u^2} + \overline{v^2} + \overline{w^2}$
$R(y/\delta)$	"backflow" function defined by equation (19)
Re_{δ_2}	$\equiv U_\infty \delta_2 / \nu$, momentum thickness Reynolds number
S_u, S_v	$\overline{u^3}/(\overline{u^2})^{3/2}$, $\overline{v^3}/(\overline{v^2})^{3/2}$, skewness factors for u and v fluctuations, respectively
U, V, W	instantaneous velocity components in x, y, z directions, respectively
U, V, W	mean velocities in x, y, z directions, respectively
u, v, w	instantaneous fluctuations velocities in x, y, z directions
u', v', w'	rms fluctuation velocities in x, y, z directions, respectively
U_τ	$\equiv (\tau_0/\rho)^{1/2}$, shear velocity

U^+	$\equiv U/U_\tau$
U_M	$(-\overline{uv})_{\max}^{1/2}$
U_{MP}	maximum pseudo-shearing stress, equation (16)
U_0	$2U(1/2) - U_\infty$ at x_0 in equation (17)
U_s	Perry and Schofield velocity scale, defined in equation (10)
V_p	entrainment velocity
x, y, z	streamwise, normal, and spanwise coordinates
x_0	streamwise distance from reference point in equation (17)
$y_{1/2}$	perpendicular distance from reference streamwise line to where U is $U_\infty/2$ for mixing layer of Wygnanski and Fiedler.

Greek Symbols

γ_{pu}, γ_{pv}	fraction of time the flow moves downstream and away from the wall, respectively.
Δ	$\equiv U_\infty \delta_1 / CU_s$, length scale in Perry and Schofield correlation
δ	y where $U = 0.99 U_\infty$
$\delta_{0.995}$	y where $U = 0.995 U_\infty$
δ_1	$\equiv \int_0^\infty (1 - U/U_\infty) dy$, displacement thickness
δ_2	$\equiv \int_0^\infty (U/U_\infty)(1 - U/U_\infty) dy$, momentum thickness

ϵ	rate of turbulent energy dissipation in equation (31)
η_1	$\equiv y/e$
η_2	$\equiv y/\Delta$
θ	angle of inclination of principal axis to the flow direction
ν	kinematic viscosity
ν_e	eddy viscosity, defined in equation (23)
ρ	density
σ'	mixing layer parameter in equation (17)
τ	shearing stress
$\omega(y/\delta)$	wake function in equation (18)

Subscripts

i	denotes initial value
$\max$	denotes maximum value
$\min$	denotes minimum value
0	denotes wall value
∞	denotes free-stream condition

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ABSTRACT

NOMENCLATURE

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I. INTRODUCTION

The problem of turbulent boundary layer separation due to an adverse pressure gradient is an important factor in the design of many devices such as jet engines, rocket nozzles, airfoils and helicopter blades, and the design of fluidic logic systems. Until the last five years little quantitative experimental information was available on the flow structure downstream of separation because of the lack of proper instrumentation.

In 1974 after several years of development, a one velocity component directionally-sensitive laser anemometer system was used to reveal some new features of a separating turbulent boundary layer (Simpson et al., 1974). The directional sensitivity of the laser anemometer system was necessary since the magnitude and direction of the flow must be known when the flow moves in different directions at different instants in time. In addition to much turbulence structure information, it was determined: (1) that the law-of-the-wall velocity profile is apparently valid up to the beginning of intermittent separation; (2) that the location of the beginning of intermittent separation or the upstreammost location where separation occurs intermittently is located close to where the freestream pressure gradient begins to rapidly decrease; (3) that the normal stress terms of the momentum and turbulent kinetic energy equations are important near separation; and (4) that the separated flowfield shows some similarity of the streamwise velocity U , of the velocity fluctuation u' , and of the fraction of time that the flow moves downstream (Simpson et al., 1977).

Based upon these results, modifications (Simpson and Collins, 1978; Collins and Simpson, 1978) to the Bradshaw et al. (1967) boundary layer prediction method were made with significant improvements. However, this prediction effort pointed to the need to understand the relationship between the pressure gradient

relaxation and the intermittent separation region structure. A number of other workers have tried to predict this type flow, but with questionable assumptions about the turbulence structure near the wall. In nearly all efforts, the workers have simply extended the velocity and turbulence profile correlations that apply to attached flows to the backflow region. Even though turbulent fluctuations near the wall in the backflow region are as large as or larger than mean velocities, these predictors use a turbulence model that is tied to the mean velocity gradient. Even with adjustment of turbulence model "constants" to fit one feature or another, these models do not predict simultaneously the backflow velocity profile, the streamwise pressure distribution, and the fact that length scales increase along the flow. Clearly then, a limiting factor for further improvement of the prediction of separated flows is the lack of fundamental experimental velocity and turbulence structure information with which to develop adequate models, especially for the backflow region. Such data are presented here.

The experimental results described in this report are concerned with a nominally two-dimensional separating turbulent boundary layer for an airfoil-type flow in which the flow was accelerated and then decelerated until separation. Upstream of separation single and cross-wire hot-wire anemometer measurement results are presented. Measurements obtained in the separated zone with a directionally-sensitive laser anemometer system are presented for U , V , $\overline{u^2}$, $\overline{v^2}$, $-\overline{uv}$, $\overline{u^3}$, $\overline{v^3}$, $\overline{u^4}$, $\overline{v^4}$, the fraction of time that the flow moves downstream γ_u , fraction of time that the flow moves away from the wall γ_v , and u spectra. The implications of these results to flow models are discussed.

II EXPERIMENTAL EQUIPMENT

II.1 Basic Wind Tunnel

The mainstream flow of the blown open-circuit wind tunnel is introduced into the test section after first passing through a filter, blower, a fixed-setting damper, a plenum, a section of honeycomb to remove the mean swirl of the flow, seven screens to remove much of the turbulence intensity, and finally through a two-dimensional 4:1 contraction ratio nozzle to further reduce the longitudinal turbulence intensity while accelerating the flow to test speed. These same components were in an earlier version of this wind tunnel with a shorter test section that was used in previous research (Simpson et al., 1977; Simpson and Wallace, 1975; Simpson and Shackleton, 1977).

Fig. 1 is a side view schematic of the 25 feet long, 3 feet wide test section of the wind tunnel. The upper wall is adjustable such that the free-stream velocity or pressure gradient can be adjusted. The side walls are made of plexiglass. The test wall is constructed from 3/4 inches thick fin-form plywood, reinforced every 11 inches with 3 x 1½ x ¼ inches cross section steel channel.

The active boundary layer control system, which is described in section II.2 below, is used to eliminate preferential separation of the curved top wall boundary layer. Highly two-dimensional wall jets of high velocity air are introduced at the beginning of each of the eight feet long sections. At the latter two streamwise locations the oncoming boundary layer is partially removed by a highly two-dimensional suction system. In order to accommodate the increased energy dissipation in the wind tunnel laboratory due to the boundary layer control system, a new 3 ton air conditioner was added.

The inviscid core flow is uniform within 0.05% in the spanwise direction and within 1% in the vertical direction with a turbulence intensity of 0.1% at 60 fps. The test wall boundary layer is tripped by the blunt leading edge of the



FIGURE 1. SIDEVIEW SCHEMATIC OF THE TEST SECTION. MAJOR DIVISIONS ON SCALES:
10 INCHES. NOTE BAFFLE PLATE UPSTREAM OF BLUNT LEADING EDGE ON
BOTTOM TEST WALL AND SIDE AND UPPER WALL JET BOUNDARY LAYER CONTROLS.

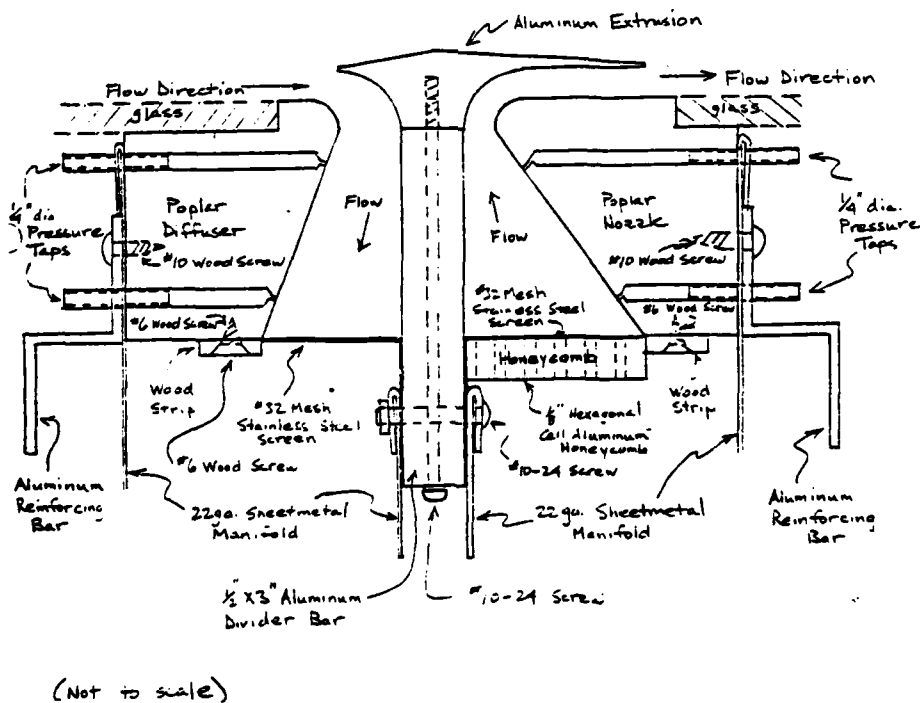


Figure 2. Cross sectional view of wall jet-wall suction assembly.

plywood floor, the height of the step from the wind tunnel contraction to the test wall being $\frac{1}{4}$ inches. Smoke can be introduced uniformly into the boundary layer just upstream of this trip for use with the laser doppler anemometer.

II.2 Boundary Layer Control System

An active boundary layer control system was installed on the nontest walls of the test section to inhibit undesirable flow three-dimensionality and to prevent separation. Because the static pressure in the test section is time varying in a series of unsteady experiments at the same mean conditions as in the case reported here (Simpson et al., 1980), no passive boundary layer control can be used that depends on a steady test section pressure higher than the pressure outside the tunnel. In previous steady freestream separated flow experiments in the old tunnel test section (Simpson et al., 1977), a perforated plate was located at the test section exit to produce static pressures in the test section that were above atmospheric pressure. In that case, the upper wall boundary layer was bled from the test section just upstream of the separation zone.

In the current case, the active boundary layer control system removes low momentum fluid by sucking off the boundary layer and supplies high momentum fluid through tangential wall jets. Its performance is less influenced by the fluctuating test section static pressure in the unsteady experiments than that of the previous passive system. Fig. 2 is a cross-sectional view of the wall suction and wall jet units located at 100 inches and 200 inches on the non-test walls. Only the wall jet portion of this unit is installed at the test section entrance. Only the essential features of this system are summarized here; other details are contained in Simpson et al. (1980) and in an unpublished report by Bowles (1977).

A fan supplies the wall jets with air sucked through the suction slots and with additional makeup air. Sheet metal ducting, flow dampers, resistance baffles, and manifolds that contain the wall suction and wall jet units are used to direct

and control the air distribution. All of the wall suction and wall jet units have identical cross sections. As much care as possible was taken to make these units geometrically and aerodynamically two-dimensional. As shown in Fig. 2 the wall jet portion is a 6:1 area ratio nozzle that accelerates the fluid before it is injected along the glass tunnel sides walls or plexiglas top. The suction portion is a 1:3.6 area ratio diffuser that decelerates the removed flow. An aluminum divider plate separates the wall jet and suction flows, forming one wall of the jet nozzle and one wall of the diffuser. The specially extruded aluminum deflector directs the jet flow parallel to the tunnel wall and scoops the suction flow from the upstream tunnel flow. Shims were placed between the aluminum divider plate and the extruded aluminum deflector to make the jet flow exit gap uniform within 0.0016 inches along a given unit. The gap was nominally 0.25 inches, but was slightly different for each unit. The suction side flow entrance gap was less uniform, being within 0.01 inches of the nominal 5/16 inches.

As also shown in Fig. 2, 32 mesh stainless steel screen and 1/8 inches cell hexagonal aluminum honeycomb are located at the nozzle entrance to evenly distribute and straighten the flow from the jet manifold. After initial system testing, additional screen was mounted on top of the honeycomb opposite the manifold duct entrance from the supply duct. This eliminated preferential flow due to impingement of the incoming flow. In one case a flow deflector was required at the manifold entrance to further distribute the flow. 32 mesh screen was also placed over the diffuser exit to distribute the suction flow more evenly over the flow cross-sectional area. A small gap between the screen and each endplate was used to induce a greater flow along the endplates. This greater flow benefits the momentum deficient wind tunnel corner flows.

Two pressure taps were located in the nozzle and in the diffuser. After calibration, the measured pressure difference between these taps allowed the nozzle and the diffuser to be used as jet flow and suction flow meters, respectively. Excellent linear calibrations were found between measured dynamic pressures and the respective differential pressures.

The average dynamic pressure of the jet exit flow was measured along the length of each unit with a 0.25 inches dia. impact probe. The standard deviation of the dynamic pressure variation was less than 2.5% along each of the jet units. The dynamic pressure in the 3/4 inches nearest the end of each unit was about 2/3 of that for the midsection. The jets at the test section entrance were operated at an average velocity of 90 fps; at the 100 inches location the wall jet velocity was 120 fps for the upper wall and 72 fps for the side walls; at the 200 inches location the upper wall and side wall jet velocities were 75 fps and 57 fps.

Fig. 3 shows the mean velocity and streamwise turbulence intensity profiles in the midplane along the second streamwise upper wall jet that were obtained from a hot-wire anemometer. Note that the velocity profile is asymmetric with more high velocity flow near the freestream side of the jet. Saripalli and Simpson (1979) have shown that such an asymmetric jet is more effective in preventing boundary layer separation than a uniform jet with a greater momentum flow rate. This is due to the fact that less of the asymmetric jet momentum is wasted on increased wall drag while greater mixing occurs with the outer region flow.

The variation of the dynamic pressure of the suction flow was measured along the length of each unit. The difference between the static pressure inside the diffuser at a particular location and atmospheric pressure had a standard

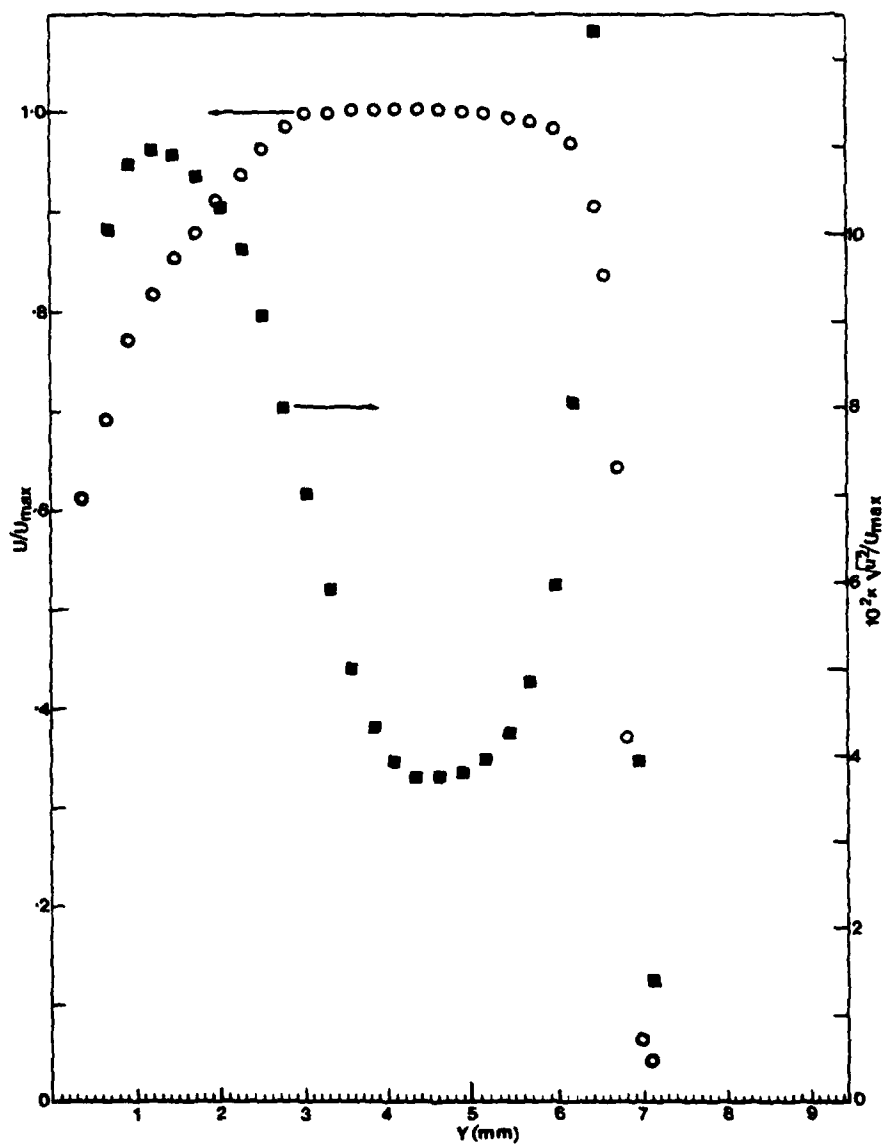


Figure 3. Wall jet mean velocity and streamwise turbulence intensity profiles, upper wall jet at 100 inches.

deviation of no more than 2% along each suction unit. Most of the departure from uniformity occurred near the ends where, fortunately, about 20% greater suction dynamic pressure occurred. Thus a greater amount of momentum deficient wind tunnel corner fluid could be removed, partly overcoming the effect of the dynamic pressure deficiency at the ends of the wall jet sections. The average suction velocity at the 100 inches location was 45 fps while for the 200 inches location it was 75 fps for the upper wall and 56 fps for the side walls.

The hot-wire anemometer mean velocity and streamwise turbulence intensity profiles in the midplane along the first streamwise upper wall suction unit were almost uniform. This indicates that some of the upstream flow is deflected toward the wall by the suction since the boundary layer velocity profile is not uniform. Immediately downstream the asymmetric velocity profile jet momentum is then rapidly mixed with the remaining upstream boundary layer flow.

It should be noted that the flows in this control system are relatively insensitive to the ± 1 cm of water static pressure oscillation in the test section in the unsteady experiments. The large volume of the control system and the 12 inches of water static pressure loss in its components act as a large low-pass-frequency filter. Dynamic pressure oscillations of the wall jet flow were of the order ± 0.016 inches of water.

II.3 Hot-wire Anemometers

Miller-type (1976) integrated circuit hot-wire anemometers and linearizers, as modified by Simpson et al. (1979) were constructed and used. A TSI Model 1050 anemometer was used with the surface hot-wire element that is described in section II.4 below. The frequency response was flat up to 7.5 kHz for an overheat ratio

of 0.7. this moderately high overheat ratio was used since Wood (1975) showed that the range of flat frequency response is improved with a higher overheat ratio.

Standard TSI model 1274-TI.4 normal wire and model 1248-TI.5 cross-wire probes were used for boundary layer measurements. The closest to the wall that these probes could safely make measurements was about 0.002 inches and 0.035 inches, respectively. The sensing elements are 0.00015 inches diameter, 0.050 inches length platinum-plated tungsten wires.

The traversing mechanism used for the boundary layer velocity measurements was mounted on the supporting frame for the upper wall and provided for precise positioning of the probe sensors as described by Strickland and Simpson (1973). A cathetometer was used to accurately locate the probe sensor from the wall within an uncertainty of about ± 0.002 inches. The detailed streamwise free-stream velocity distributions were obtained using a the Model 1274-TI.5 probe mounted on the toy racing car shown in Fig. 3 of Simpson and Wallace (1975). The car was easily positioned along the flow by fishing line.

Calibrations were made in a TSI Model 1127 calibrator. There was no detectable drift of the anemometer; the function-module type linearizers had a small amount of DC drift. Each linearized calibration had a low level of dispersion from a straight line, with a product moment correlation coefficient (Bragg, 1974) in excess of 0.09999. The slope of each calibration varied no more than about 4% over the life of a given probe.

A standard TSI model 1015C correlator was used to obtain sum and difference values for u and v from cross-wire signals. Electronic multipliers (Analog Devices AD533JH) were used to produce the turbulence quantities uv , u^2v , and v^3 . These were trimmed to within $\pm 1\%$ fullscale nonlinearity error. True inte-

grating voltmeters, consisting of a voltage-controlled oscillator (Tektronix FG501 Function Generator) and a digital counter (Tektronix DC503 Universal Counter), were used to obtain true time-averaged results.

II.4 Surface Hot-wire Skin Friction Gage

Because a single universal calibration is valid in both laminar and turbulent flow and is insensitive to pressure gradients (Murthy and Rose, 1978; Higuchi and Peake, 1978), a Rubesin et al. (1975) type surface hot-wire skin friction gage was constructed and used. The basic advantages of this type gage are that the surface-heating-element dimension in the streamwise direction is very small and that conduction losses to a very low thermal conductivity substrate are minimized.

A 0.001 inches diameter platinum - 10% rhodium wire was mounted between 0.052 inches diameter nickel electrodes located 0.4 inches apart whose ends were flush with the flat polystyrene surface. Conduction losses to the electrodes are small since the wire length-to-diameter ratio of 400 is large. Several drops of ethyl acetate were used to dissolve the polystyrene in the vicinity of the wire and imbed it in the surface. The ends of the wire were then soldered to the electrodes. A 0.00015 inches diameter wire was tried but was too fragile for use with simple construction techniques. The polystyrene was mounted on a thin portable plexiglas plate. The resulting surface was sanded and polished flat and smooth before the wire was mounted. This plate allows a single element to be moved to various measurement locations with a minimum of flow disturbance. The element is sufficiently downstream of the end of the small ramp and sufficiently upstream of the trailing edge to avoid sensing local disturbances generated by the plate. A 0.001 inches diameter platinum and platinum-10% rhodium thermocouple was mounted 3/32 inches downstream of the hot-wire element.

Rubesin et al. found that overheat temperatures of at least 80°F were needed to make the heat loss from a wire proportional to its temperature rise, or $E^2/R\Delta T$ a constant. Peake and Higuchi found that overheats greater than 176°F caused the wire to melt the substrate and separate from the surface. Here the cold resistance at 77°F was $3.70\ \Omega$ and $0.5\ \Omega$ overheat resistance was used, so with a temperature coefficient of resistivity of $0.89 \times 10^{-3}\ ^{\circ}\text{F}^{-1}$ then ΔT was 152°F . The wire was not observed to separate from the surface.

A simple stainless steel cone with 0.5° angle between the cone and the plate surface was constructed for calibration of this gage. A brass housing held the cone in place on the plate. The hot-wire was aligned with a radial line from the cone apex. The velocity gradient at the plate surface was independent of the radial position since the cone surface velocity, ωr , and the spacing between the cone and the plate, $r \tan (0.5^{\circ})$, each vary linearly with the radius. Because the maximum surface velocity gradient of interest was about $9.6 \times 10^4\ \text{sec}$, a high-speed grinder motor (Sears and Roebuck, Model 315.17440, 26000 RPM) and a Variac power control were used to produce $600\ \text{rpm} < f < 8000\ \text{rpm}$. A vinyl tubing flexible connector was used between the cone shaft and the grinder to minimize misalignment. The angular speed f was measured by reflecting a light from the hexagonal grinder chuck nut into a photomultiplier tube and counting the signal pulse rate f_p on a digital counter; thus $f = f_p/6$. Heating of the calibrator flow occurred above 8000 rpm due to substantial frictional heating in the steel-brass bearing. Since the air temperature was measured with the thermocouple, corrections could be made. After calibration, a Miller-type exponential electronic linearizer was used to linearize the bridge output voltage.

II.5 Laser Anemometer and Signal Processing

The laser anemometer used in these experiments and shown in Fig. 4 is

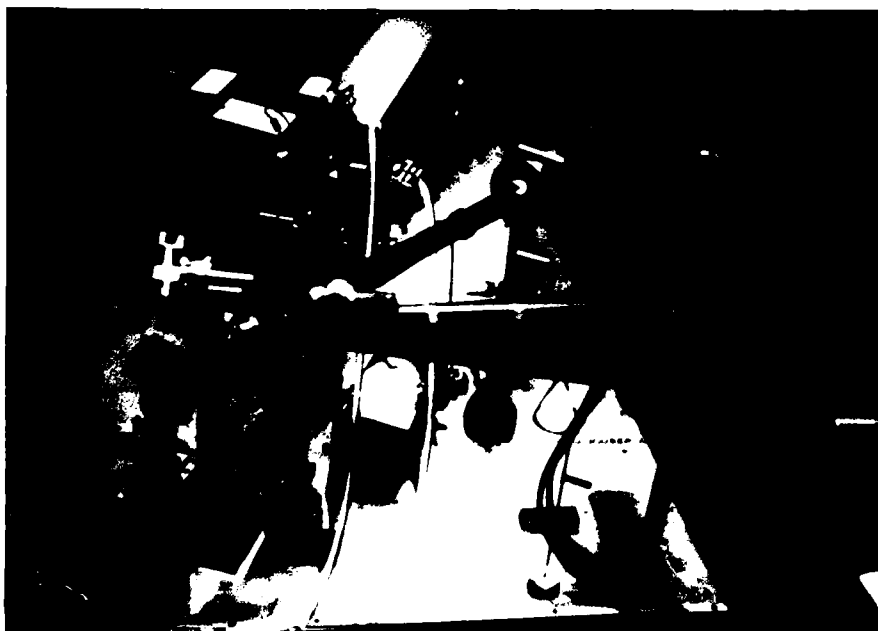


Figure 4. Photograph of current two-velocity component directionally-sensitive fringe-type laser anemometer.

described in some detail by Simpson and Chew (1979). In essence this is a two-velocity-component (U, V) directionally-sensitive fringe type system that has been used in earlier work (Simpson et al., 1977). The unshifted and 25 MHz Bragg-cell shifted beams lie in an almost horizontal plane and measure the streamwise velocity with vertical fringes. The unshifted and 15 MHz Bragg-cell shifted beams lie in a vertical plane and measure $(V \cos 4.4^\circ + W \sin 4.4^\circ)$ with almost horizontal fringes. The 25 MHz and 15 MHz beams form a third fringe pattern that measures $(U - V \cos 4.4^\circ - W \sin 4.4^\circ) / \sqrt{2}$ around 10 MHz. Since $\overline{u^2}$ and $(V \cos 4.4^\circ + W \sin 4.4^\circ)^2$ were measured independently and $\overline{uw}$ was presumed very small, the Reynolds shearing stress $-\overline{uv}$ resulted from this measurement. Signal processing was by fast-sweep-rate sampling spectrum analysis, as described by Simpson and Barr (1975).

The 1 micron dioctal phthalate particles follow the highly turbulent oscillations found in separated regions (Simpson and Chew, 1979). It should be noted that it is impossible to seed a highly turbulent flow in any prescribed manner. Highly turbulent flows are characterized by intense mixing with the flow. In this case there is also significant entrainment of freestream fluid into the turbulent motions. This would progressively dilute the particle concentration if only the shear flow has been seeded. Instead of needless worry over prescribed particle concentration, we have been concerned with proper averaging of available signals as described below, with enough particles to provide a high data rate, and with sufficiently small particles to accurately follow the flow. In fact, without any seeding we were able to obtain signals from ambient dust. However, we used minimal seeding to produce a signal data rate of about 400 per second.

Since the particle number density in a highly turbulent flow cannot be

made uniform, the time between the passage of successive signal generating particles will be unequal. This effect alone presents no particular signal processing problem if the time intervals between successive signal bursts are small compared to $1/f_{\max}$, the time period of the highest flow oscillation frequency $f_{\max}$ to be detected, i.e., if the signal is almost continuous. One can simply treat the signal as a continuous hot-wire anemometer signal to obtain the averages

$$U = \frac{1}{T} \int_0^T U(t) dt \quad (1)$$

$$\overline{U^n} = \frac{1}{T} \int_0^T (U(t) - U)^n dt \quad (2)$$

where $n = 2, 3, 4 \dots$. When the time intervals between successive signal bursts are long compared to $1/f_{\max}$ (high signal dropout rate) and are unequal, these equations should also be used in the fashion explained below.

First, let us look at the commonly used method of particle averaging for individual particle velocity measurements. The averages are made over the number of signal bursts N obtained during the time period T :

$$U_N = \frac{\sum_{i=1}^N U_i}{N} \quad (3)$$

$$\overline{U_N^n} = \frac{\sum_{i=1}^N (U_i - U_N)^n}{N} \quad (4)$$

where $n = 2, 3, 4 \dots$. These averages are not made with respect to time and are biased unless the time intervals between signal bursts are equal. McLaughlin and Tiederman (1973) proposed a biasing correction that is based upon the idea

that higher velocity flow carries more particles through the focal volume per unit time. Thus, more high velocity signal bursts will be obtained and U_N will be too high. However, high velocity particles spend less time in the focal volume so that in the case of sampling spectrum analysis signal processing, the chance of detecting a given signal burst varies as $(U^2 + V^2 + W^2)^{-1/2}$. Thus, this effect tends to cancel the above mentioned bias for particle averaging. Durão and Whitelaw (1975) showed that if the Doppler bursts are randomly sampled before particle averaging, the bias effects are reduced significantly. Even so, particle averaging is not fundamentally a time average.

Consider now time-averaging of signals according to equations (1) and (2), even though the signal dropout rate may be large. Only ergodic flows, whose averaged quantities in equations (1) and (2) become independent of time for large T , are considered. This restriction is also required for particle averaging. The last sampled signal must be held by a sample-and-hold circuit until a new signal is detected for time-averaging. With exception of the instant at which a new signal is detected, the sampled-and-held voltage does not correspond to the actual instantaneous velocity. However, the voltage value at each instant corresponds to the instantaneous velocity at some instant during a record time T for an ergodic flow. Since any averaging process removes time domain dependency, it does not matter when during the time period T that it is averaged. It is unlikely that a given signal voltage will be averaged too long (Simpson and Chew, 1979). This method of averaging eliminates the need for the high velocity flow bias correction.

The mechanics of evaluating a true time average in this research made use of a velocity probability histogram, such as shown in Figure 5. A SAICOR Model 41 Correlator and Probability Analyzer was used.

$$1 = \int_{-\infty}^{+\infty} P(U) dU \quad (5)$$

$$U = \int_{-\infty}^{+\infty} U P(U) dU \quad (6)$$

$$\overline{U^n} = \int_{-\infty}^{+\infty} (U - U)^n P(U) dU \quad (7)$$

where $n = 2, 3, 4 \dots$. The histogram $P(U)$ is constructed by sampling the $U(t)$ sample-and-held signal at equal intervals in time Δt for the period T . Thus the histogram reflects a true time integral and the results from equations (5-7) will be equivalent to those from equations (1-2). The time interval Δt between digital samples should be no larger than the shortest time between signal bursts, otherwise some data will be lost. For example, $\Delta t = 10^{-4}$ sec for about 400 new signals per second. The averaging time T was at least a half minute, so at least 12,000 new data signals and 3×10^5 equal time interval samples were involved for one histogram. An added benefit of the histogram approach is that noise can be detected while $P(U)$ is being constructed. If one has an oscilloscope display, the noise will cause the base level of $P(U)$ to grow. Thus, the resulting $P(U)$ can be corrected for noise or the discriminator level in the signal processor can be adjusted on-line and a new $P(U)$ constructed. The histograms were stored on digital tape and analyzed by a digital computer.

These results are not believed to suffer strongly from bias errors. First, there is no bias in the duration of a detected signal due to the flow velocity. In other words, the time that the highest velocity particle spends in the focal volume is always large enough to produce a sufficiently large vertical voltage output from the spectrum analyzer. Minimal particle seeding was used for the

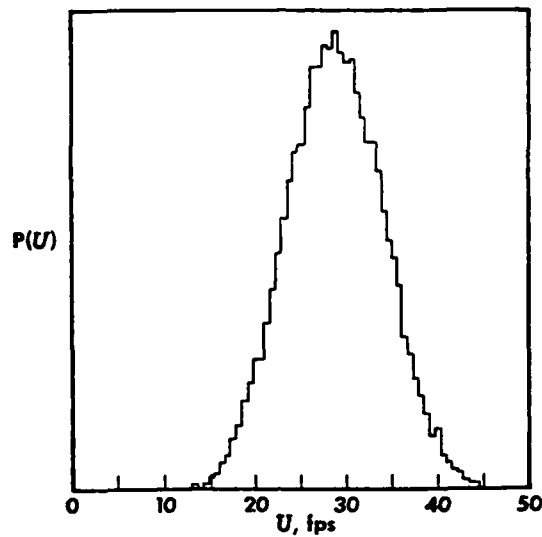


Figure 5. Typical velocity probability histogram: $U = 29.1 \text{ fps}$, $\overline{u^2} = 27.0 (\text{fps})^2$
 $S_u = 0.047$, $F_u = 2.66$. Discrete velocity bins due to probability analyzer.

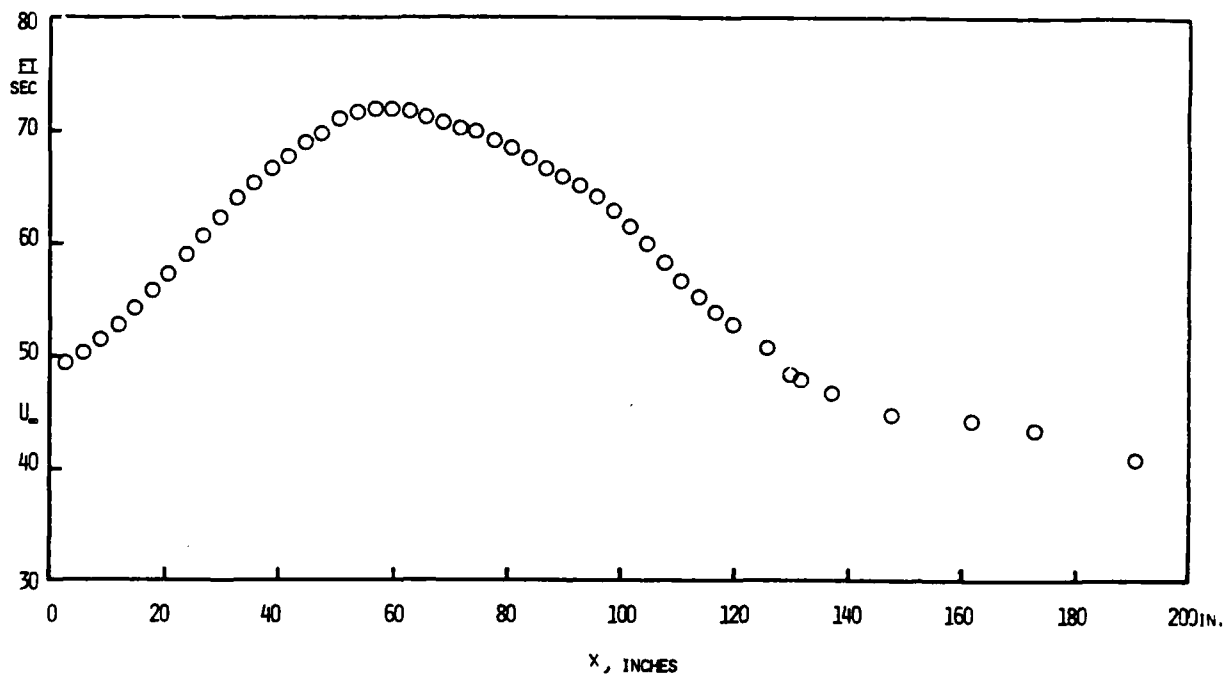


Figure 6. Freestream velocity distribution along the tunnel centerline.

best SNR and data sample rate, so significant finite transit time broadening is unlikely.

Velocity gradient broadening is not significant for any data presented here (Simpson, 1976). The focal volume diameter 0.012 inches and length 0.140 inches are small compared to the boundary layer thickness. In addition, signals from the center of the focal volume are the most likely since the scattered signals are the most intense. Large-scaled motions, which scale on the boundary layer thickness, appear to dominate the structure of highly turbulent flows, so strong instantaneous spatial velocity variations are unlikely. In any event as shown below, these results compare favorably with hot-wire anemometer data obtained in regions that do not contain significant time variation of the flow direction.

Since no spectra has previously been measured in the separated flow zone, low frequency spectra of u from the laser anemometer were measured using a Princeton Applied Research Model 4512 Fast-Fourier-Transform Spectrum Analyzer.

II. DESCRIPTION OF THE TEST FLOW

All data were obtained at atmospheric pressure and $77 \pm \frac{1}{2}^{\circ}\text{F}$ flow conditions. Figure 6 shows the free-stream velocity distributions obtained along the tunnel centerline using the single-wire probe. This distribution was repeatable within 2.9% over the duration of these experiments, which is only a little greater than uncertainty in measuring the mean velocity with a hot-wire anemometer ($\pm 2.4\%$). Figure 7 shows the non-dimensional pressure gradient dC_p/dx along the centerline of the test wall. Here $C_p \equiv 2(p - p_i)/\rho U_{\infty i}^2 = 1 - (U_{\infty}/U_{\infty i})^2$, where i denotes the free-stream entrance conditions at $x = 3"$. A five-point local least-squares curve fit of C_p data was used at each streamwise location to determine this derivative.

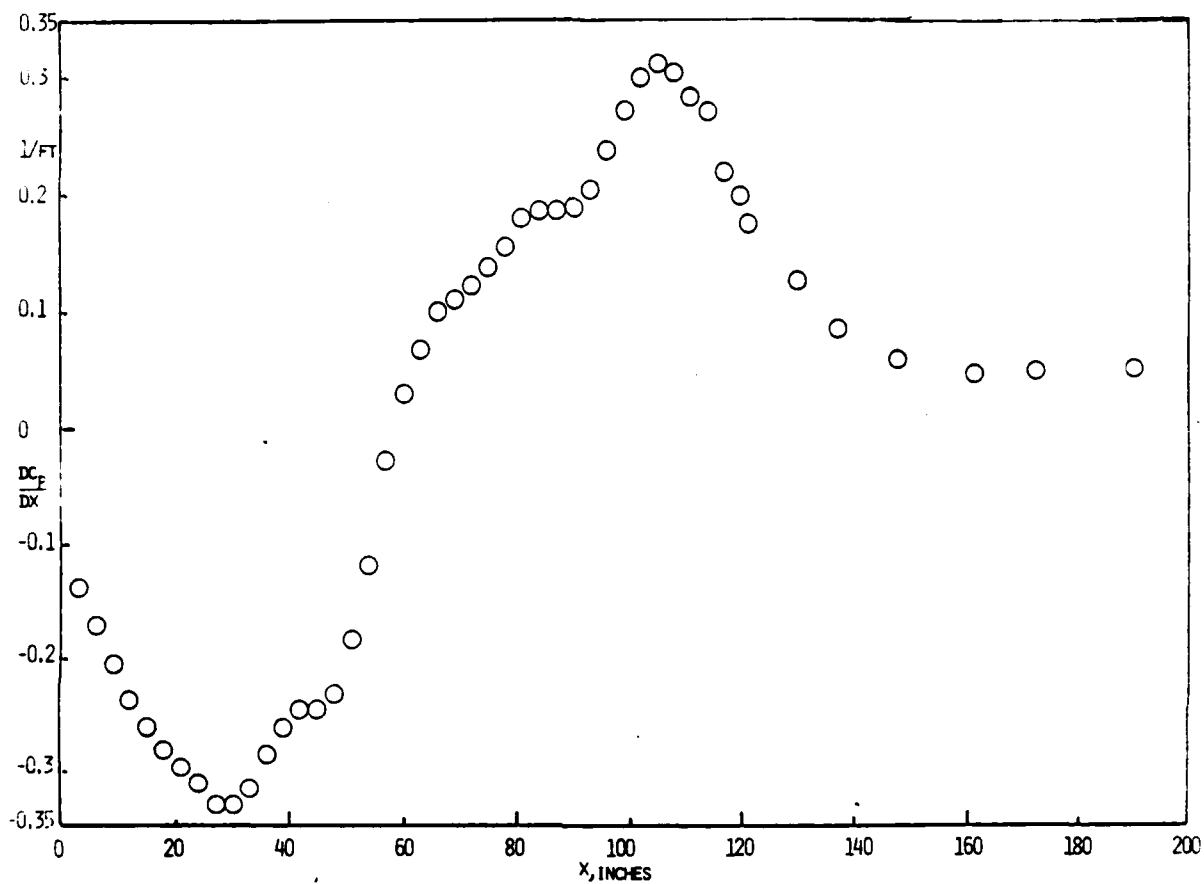


Figure 7. Non-dimensional pressure gradient along the test wall,
 $C_p = 2(P - P_i) / \rho U_{\infty i}^2 = 1 - (U_{\infty} / U_{\infty i})^2$, $U_{\infty i} = 49.4$ fps.

Just downstream of the location of the second wall jet boundary layer control unit (100 inches), the slope of the static pressure gradient changes sign. Near 145 inches the pressure gradient drops to an approximately constant value downstream.

To examine the two-dimensionality of the mean boundary layer flow, smoke was introduced only in a spanwise portion of the test wall boundary layer at a given time. A sheet of laser light produced by a cylindrical lens was used to illuminate the smoke across the tunnel. Upstream of separation, negligible spanwise diffusion of the smoke was observed, indicating no gross flow three-dimensionality. Mean velocity profiles at several spanwise locations indicated that the mean velocity was two-dimensional within 1%. Downstream of separation greater spanwise diffusion occurred, so that downstream of 170 inches no nominally two-dimensional flow remained. On the basis of these observations, the wall jet and suction boundary layer controls were adjusted to produce a nearly two-dimensional flow pattern downstream of separation. Smoke flow patterns in the sidewall and corner flows were symmetric about the channel centerline.

After laser and hot-wire anemometer data were available, examination of the two-dimensionality was done by evaluating the terms in the two-dimensional continuity equation and the momentum integral equation. In the first method, the differential continuity equation was written as

$$R = 1 + (U_x + \Delta x - U_x) / \left(\frac{\partial V}{\partial y} \right) \Delta x$$

R was computed by finding the gradient of V with respect to y and also the change in U with respect to X at a constant y location. Only where LDV data

were available was this method useful, because it requires good V data.

For many streamwise locations R lies between +0.5 and -0.5 in the middle region of the boundary layer, with an uncertainty of ± 0.46 . Nearer the wall, ΔU becomes relatively more uncertain while $\partial V/\partial y$ is more uncertain in the outer region. As a result one can expect greater uncertainties in R in these regions. Thus, at least in the middle region of the boundary layer, the flow is two-dimensional within the uncertainty of evaluating R . This is a stringent test since it is based only on the local flow field, but it suffers from the disadvantage of needing to differentiate experimental velocity distributions.

On the other hand, the momentum integral equation provides a global test based on conservation of momentum over a large flow volume. In this method, the momentum integral equation was again integrated in the x -direction to yield

$$U_{\infty}^2 \theta \Big|_{x_0}^x + \int_{x_0}^x (U_{\infty} \delta_1^+) \frac{dU_{\infty}}{dx} dx = \int_{x_0}^x \frac{C_f}{2} U_{\infty}^2 dx + \int_{x_0}^x \left[\int_0^{\infty} \frac{\partial}{\partial x} (u'^2 - v'^2) \right] dx \quad (8)$$

where the l.h.s. is PL and the r.h.s. is PR. The last term of PR is due to the normal stresses and its effect in the vicinity of separation has been shown (Simpson et al., 1977) to be significant. Using the experimental data, PL and PR of eqn. (8) were evaluated with and without the normal stress term and the ratio, $\frac{PL}{PR} - 1$, was computed for both the cases. The distributions on the ratio in the streamwise direction are shown in Fig. 8 along with estimated uncertainty bands. The ratio computed without the normal stress term is within ± 0.16 up to 122 inches, indicating that the flow is reasonably two-dimensional.

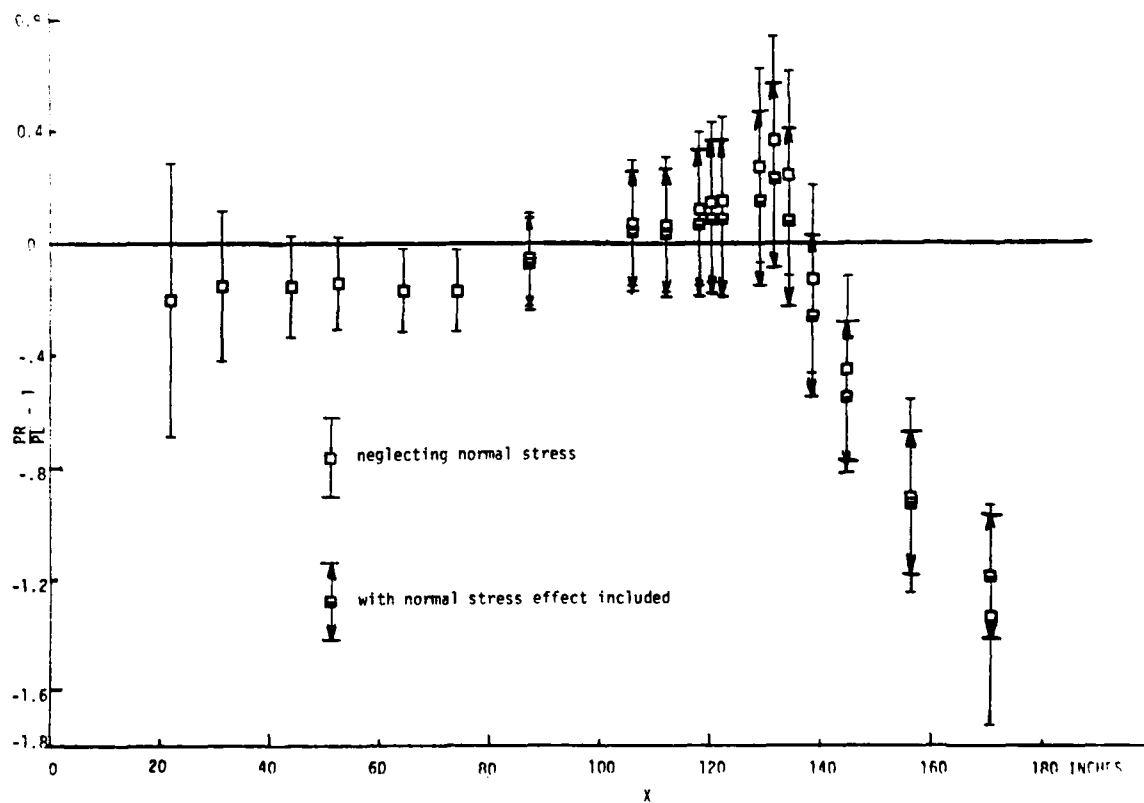


Figure 8. Fractional imbalance of the momentum integral equation, $PL/PR - 1$, vs. X . Associated uncertainty denoted by vertical band.

Downstream the normal stresses play an more important role, although they are not large enough to account for the imbalance far downstream of separation.

IV. EXPERIMENTAL RESULTS FOR THE MEAN FLOW

IV.1 Mean Velocity Profiles

Mean velocity profiles were obtained in the unseparated upstream boundary layer and the outer part of the separated flow using single wire and cross-wire hot-wire anemometer probes. The directionally-sensitive laser anemometer provided velocity profiles in the separated zone and the region immediately upstream.

Figures 9a and 9b show the streamwise mean velocity profiles for steady flow for a few typical stations in the near separation and the separated regions obtained using all three different techniques. There is good agreement among these measurements, with the maximum discrepancy among them being about 6 to 7%. In the separated region only the laser anemometer measurements are meaningful. Table 1 presents the experimental uncertainties for each measured quantity as determined by the method of Kline and McClintock (1953). As shown by Simpson and Chew (1979), the laser anemometer results obtained on different days at the same location indicate a high level of data repeatability.

Figures 10 and 11 show non-dimensional streamwise mean velocity profiles across the boundary layer at various streamwise stations in linear and semi-logarithmic co-ordinates. These results were obtained by smoothing a curve between the laser and valid cross-wire data. While the smoothing was a somewhat subjective procedure, one can see from Figures 9a and 9b that this procedure basically just eliminated a few scattered data points.

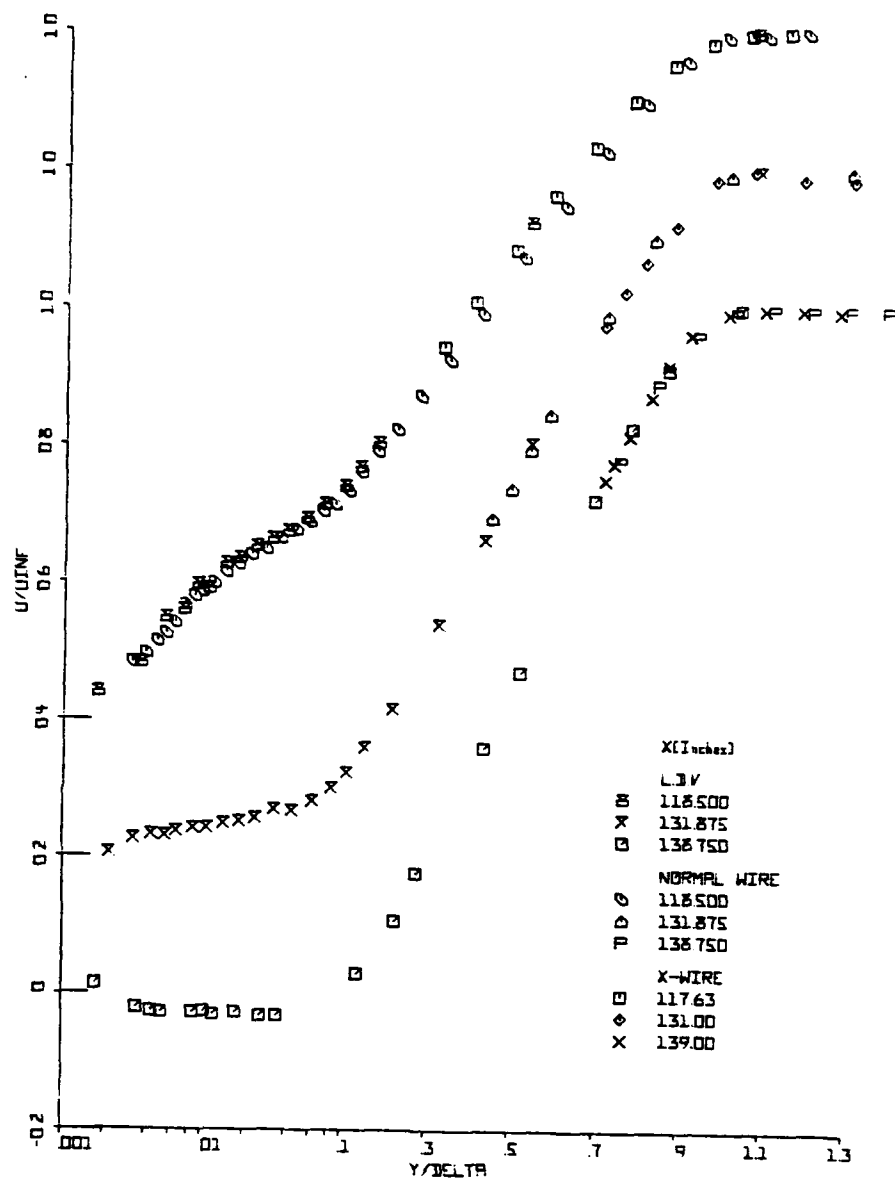


Figure 9 (a). Non-dimensional streamwise mean velocity profile data from the laser and hot-wire anemometers. Note displaced ordinates.

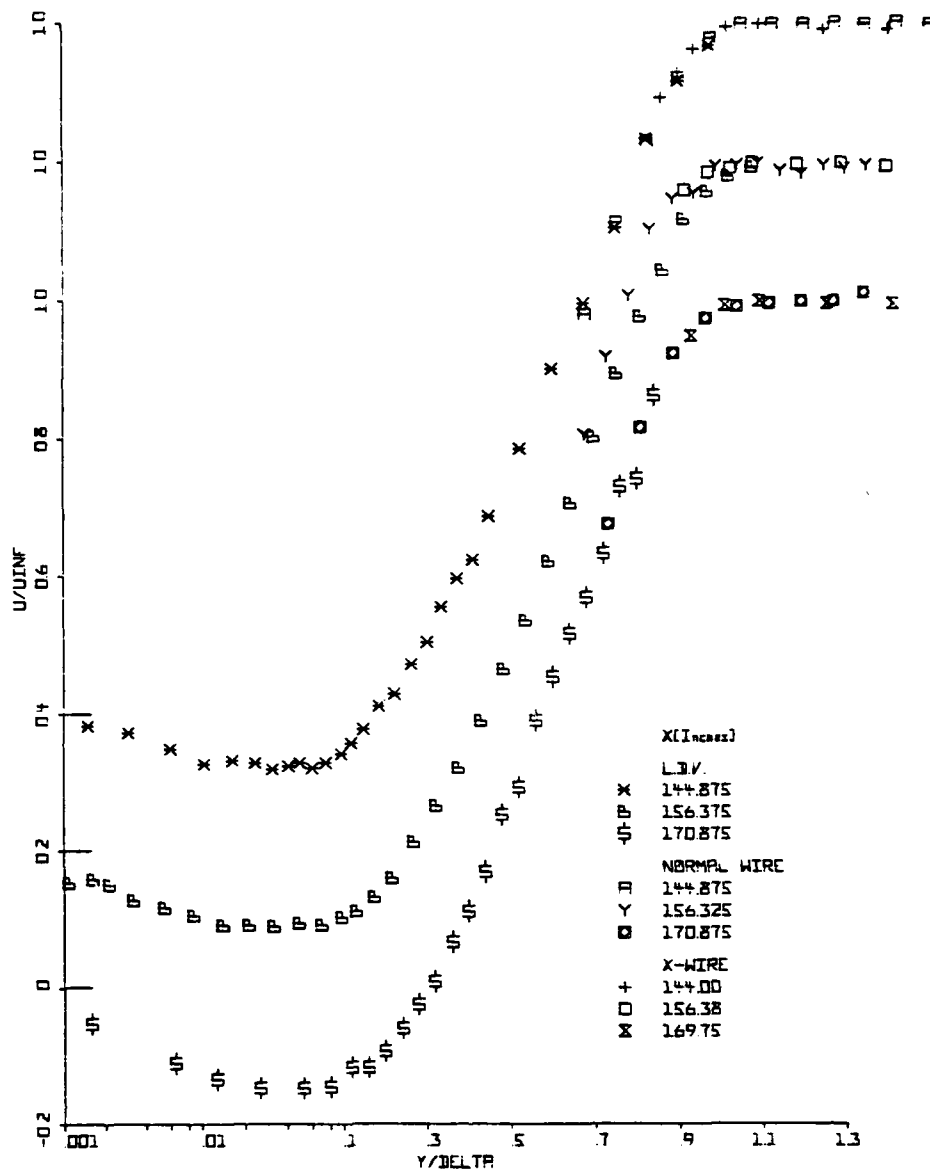


Figure 9 (b). Non-dimensional streamwise mean velocity profile data from the laser, single hot-wire, and cross hot-wire anemometers. Note displaced ordinates.

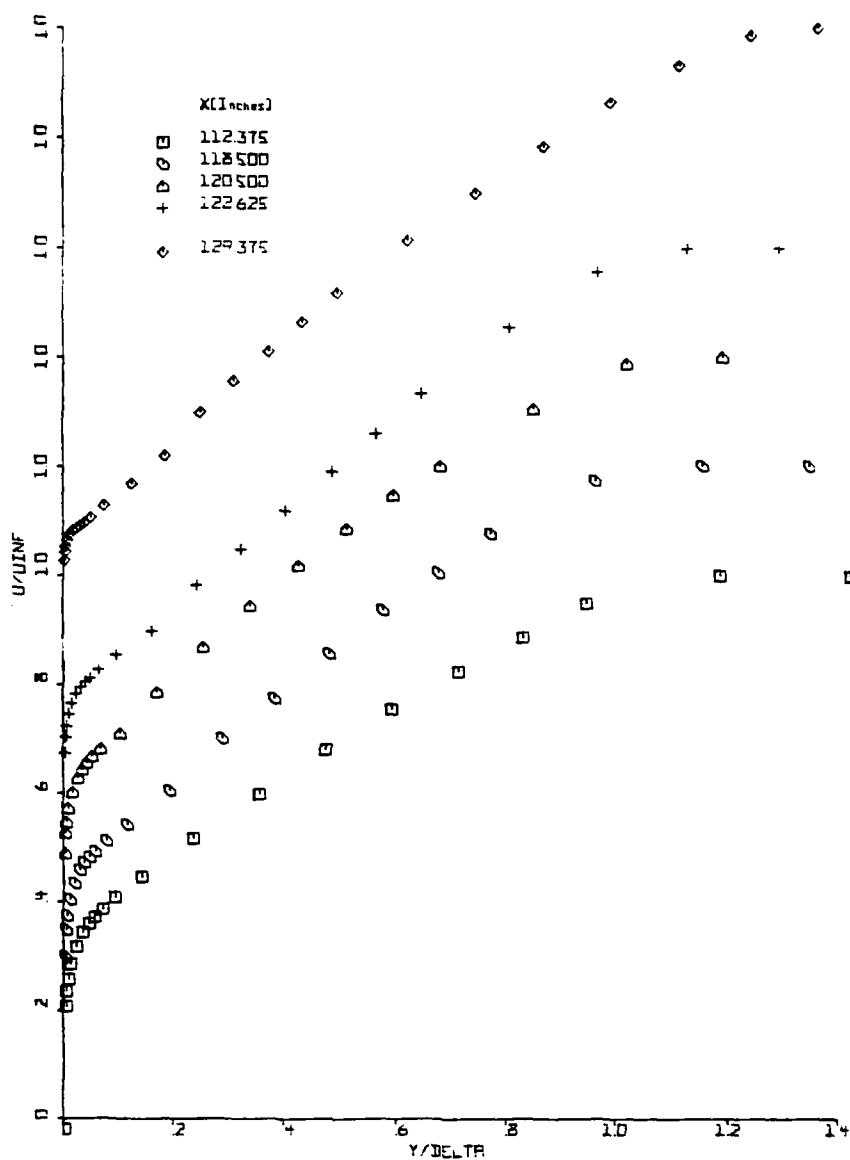
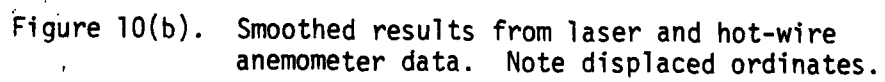


Figure 10(a). Smoothed results from laser and hot-wire anemometer data. Note displaced ordinates.



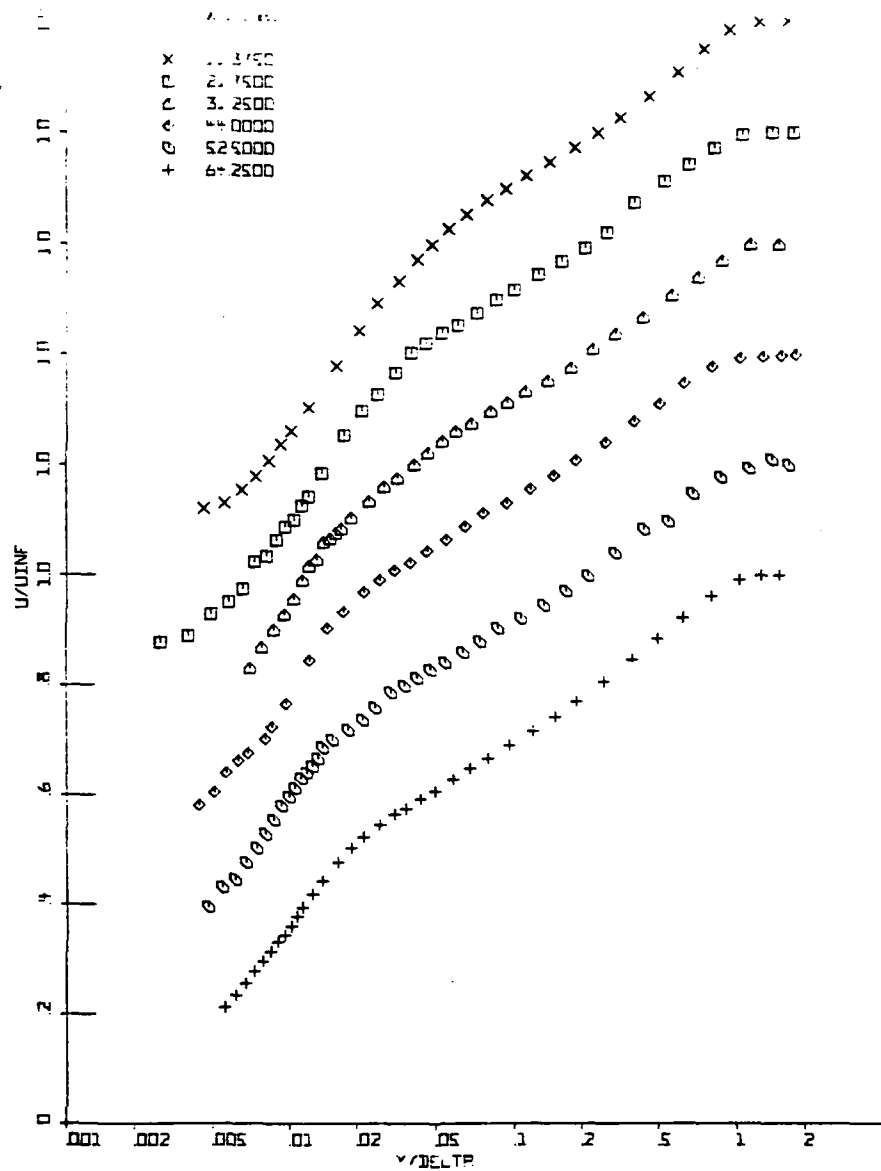


Figure 11(a). Non-dimensional streamwise mean velocity profiles: single hot-wire results.

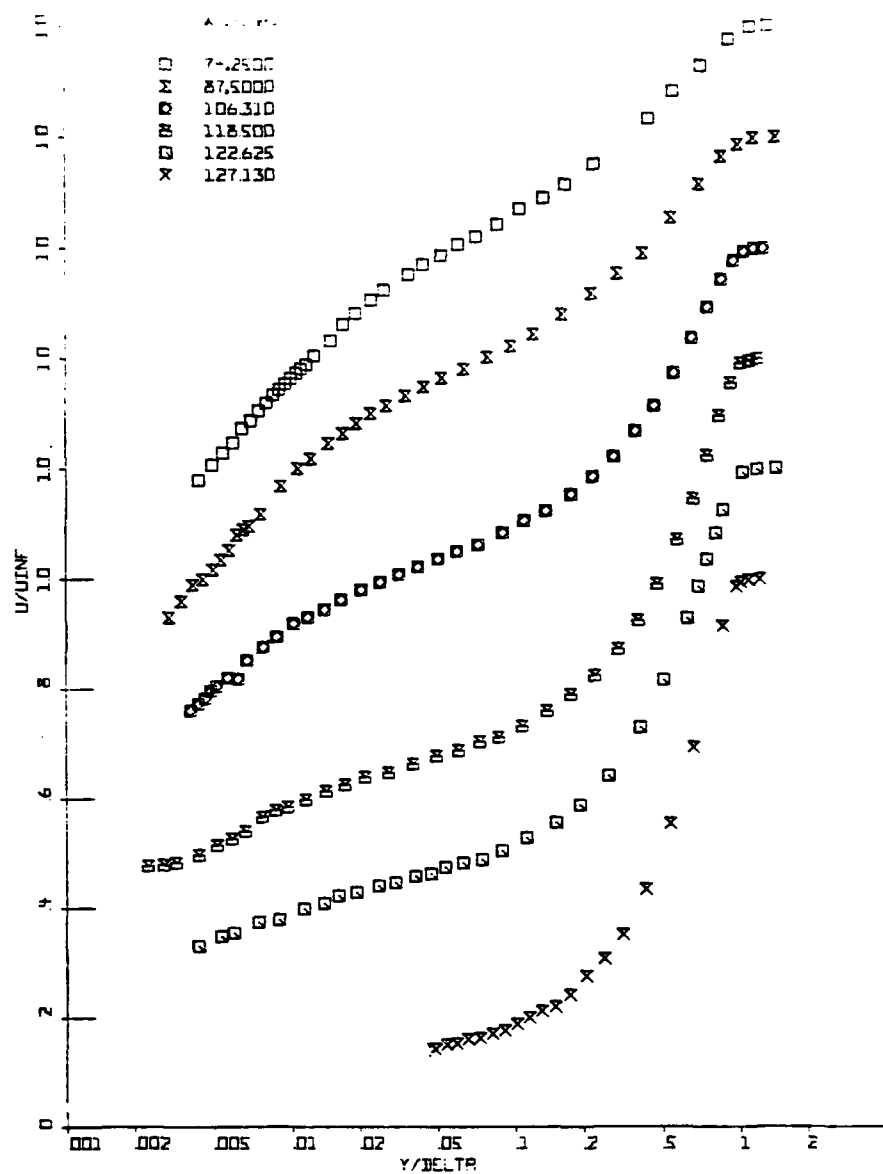


Figure 11(b). Non-dimensional streamwise mean velocity profiles: single hot-wire results.

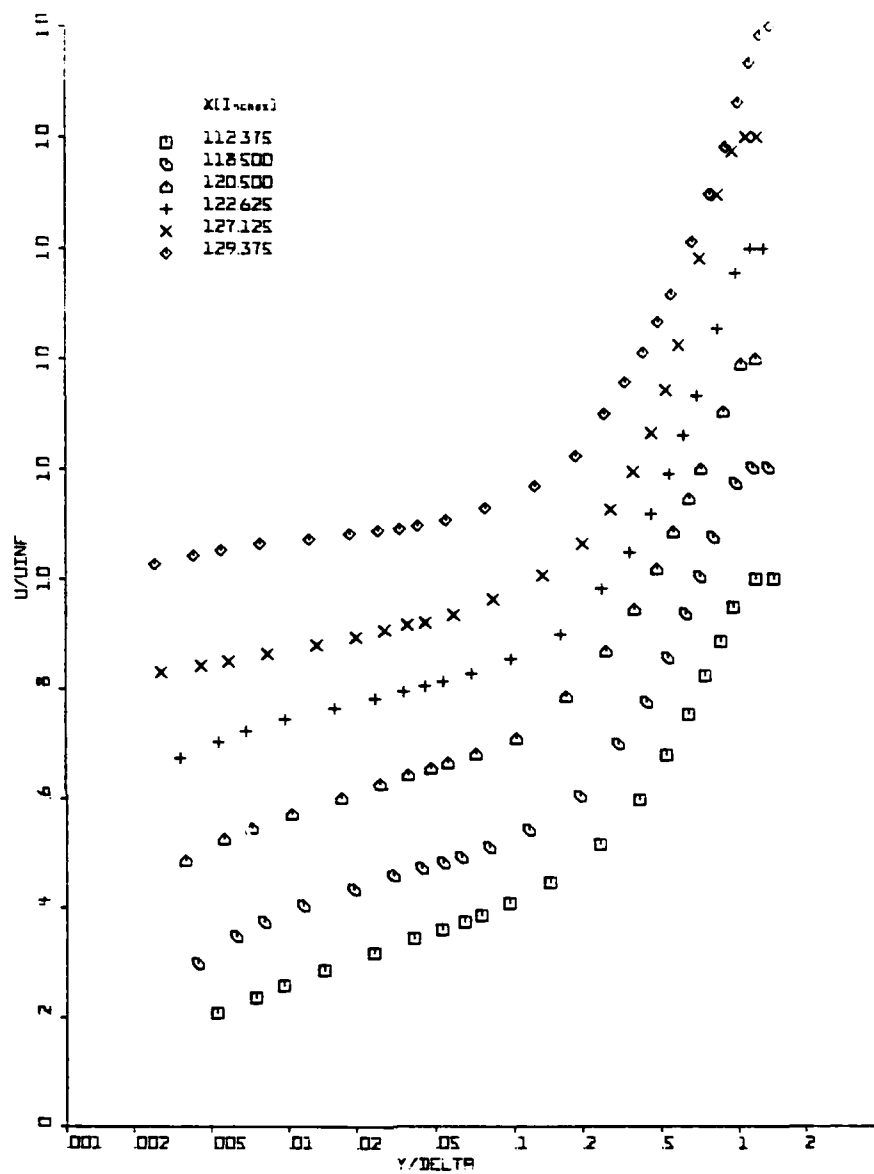


Figure 11(c). Non-dimensional streamwise mean velocity profiles: smoothed laser and valid single hot-wire anemometer results.

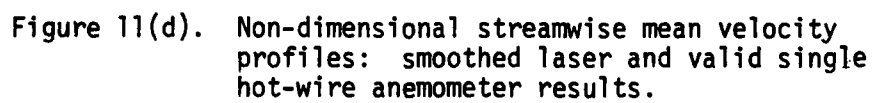


Figure 12 shows non-dimensional laser anemometer and cross-wire anemometer results for the normal velocity component V just upstream of separation and in the separated region. At most streamwise locations, there is good agreement. However, as shown in Table 1, there is a fairly large uncertainty in the cross-wire result, mainly because of the uncertainty of the probe orientation with respect to the test wall. Therefore, the laser anemometer results are more reliable.

IV.2 Turbulence Quantities

Figures 13, 14, and 15 show u'/U_∞ , v'/U_∞ , and $-\overline{uv}/U_\infty^2$ vs. y/δ , respectively. The agreement between the laser and cross-wire anemometer results is good with the apparent discrepancies being due to the experimental uncertainties shown in Table 1. The discrepancies in the $-\overline{uv}/U_\infty^2$ plots are the greatest due to the uncertainty in orientation of the cross-wire probe with respect to the test wall. Since $\overline{u^2}$ and $\overline{v^2}$ are much larger than $-\overline{uv}$, only a very small misalignment is required to produce a much different $-\overline{uv}$ result. Figures 16 (a-e) show profiles obtained by smoothing a curve between the laser anemometer and valid cross-wire data. Figure 17 shows u'/U_∞ , v'/U_∞ , and $-\overline{uv}/U_\infty^2$ profiles upstream of the near separation zone. Figures 18 (a) and (b) show u'/U_∞ obtained from the single wire anemometer.

IV.3 Upstream-downstream Intermittency

Only the directionally-sensitive laser anemometer results from these measurements give information on the fraction of time that the flow moves downstream or γ_{pu} . This quantity is the fraction of the area of the velocity probability histogram that has a positive velocity. The directionally-insensitive hot-wire anemometer cannot yield γ_{pu} values (Simpson, 1976).

Normal hot-wire:	$U \pm 2.4\%, \overline{u^2} \pm 7\%$
Cross hot-wire: (including misalignment uncertainty)	$U \pm 3.2\%, \overline{u^2} \pm 10\%$ $v^2 \pm 11\%, -\overline{uv} \pm 17\%, S_v \pm 0.1$
Laser anemometer:	$U, V \pm 0.2 \text{ fps}; \overline{u^2} \text{ and } \overline{v^2}$ $\pm 4\% \text{ max. profile value}; \overline{uv} \pm 6\%$ $\text{max. profile value}; \text{skewness} \pm 0.1;$ $\text{flatness} \pm 0.2; \gamma_{pu} \pm 0.1 \exp(-U^2/2\overline{u^2});$ $\gamma_{pv} \pm 0.1 \exp(-V^2/2\overline{v^2})$
Position from wall:	$\pm 0.002 \text{ inches}$
Skin friction coefficient C_f :	Ludwig-Tillman, $\pm 6.5\%;$ Preston tube, $\pm 8.5\%;$ Surface hot-wire, $\pm 12\%.$

Table 1. Estimated uncertainties of measured quantities.

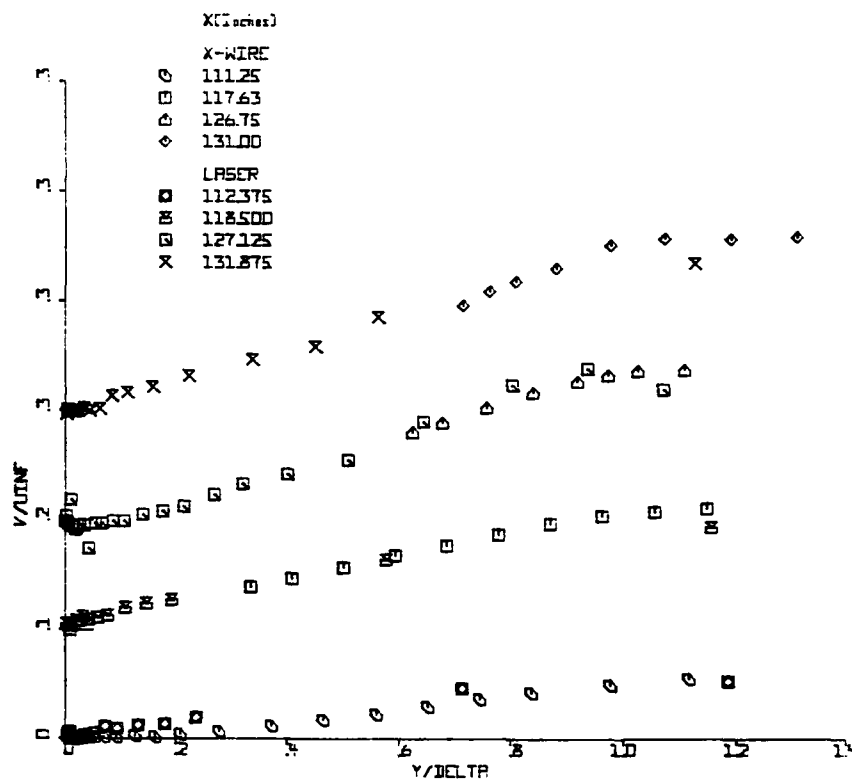


Figure 12(a). Mean velocity V/U_∞ vs. y/δ profiles, laser and cross hot-wire anemometer data.

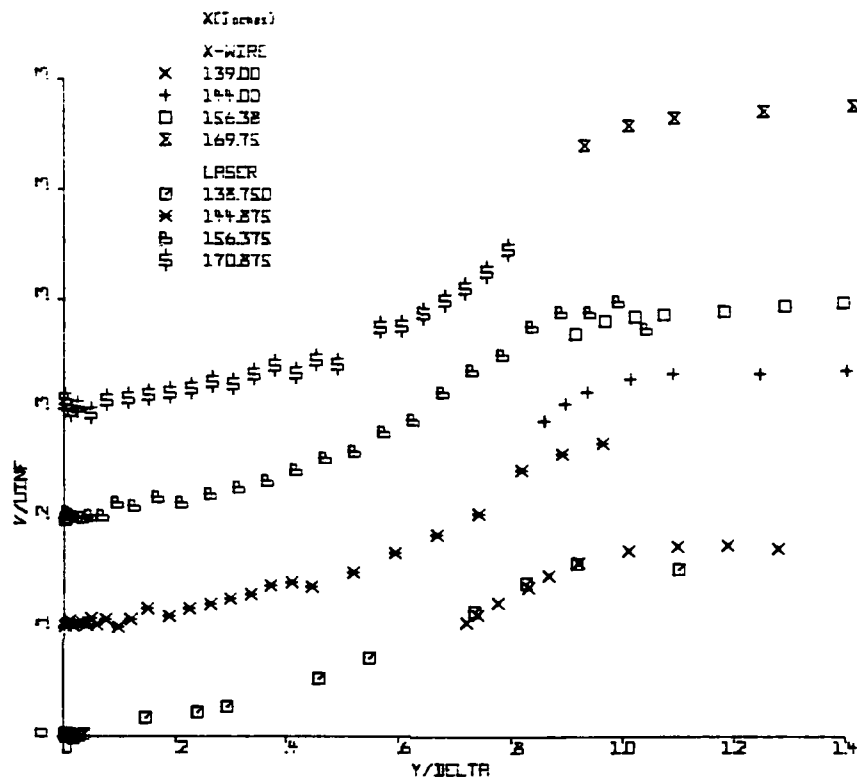


Figure 12(b). Mean velocity V/U_∞ vs. y/δ profiles, laser and cross hot-wire anemometer data.

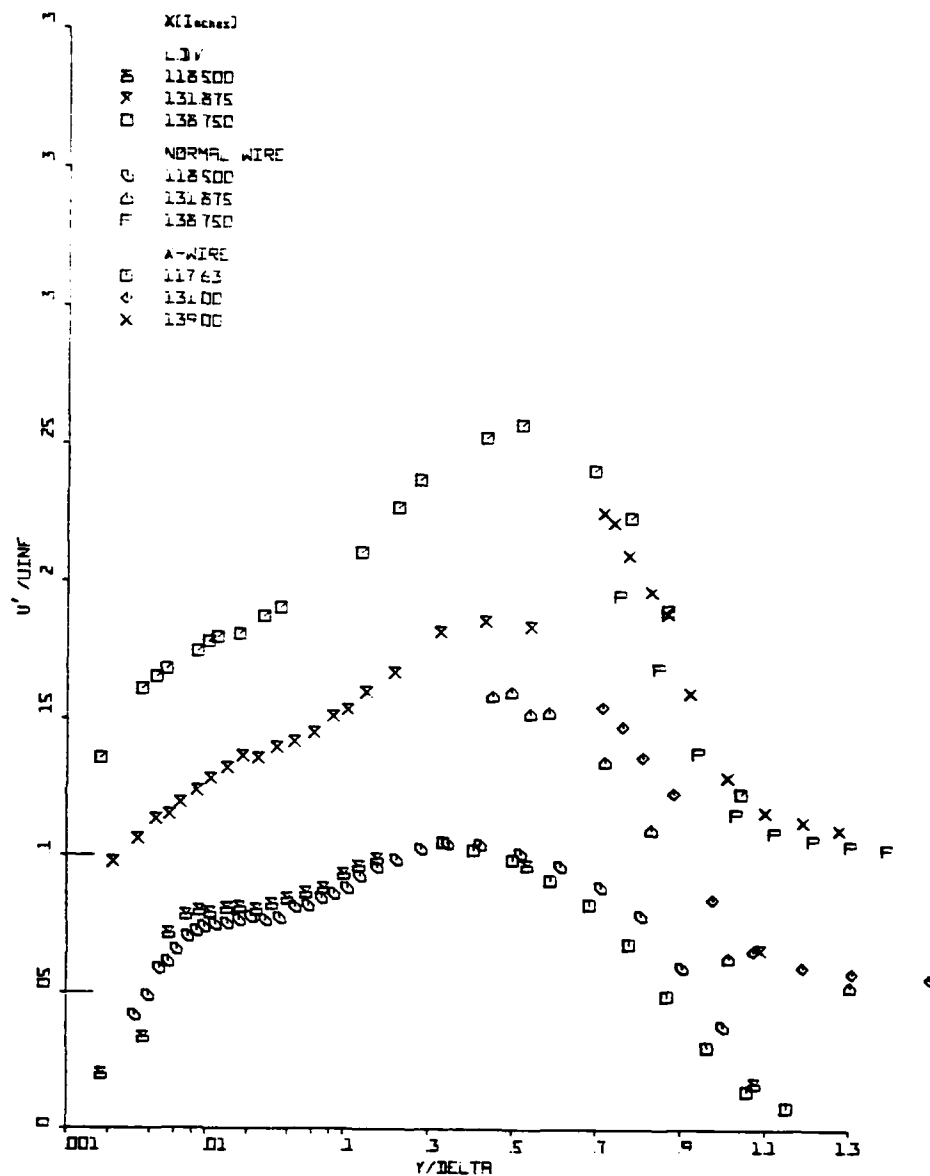


Figure 13(a). Streamwise turbulence intensity u'/U_{∞} vs. y/δ profiles: laser, single hot-wire, and cross hot-wire anemometer results. Note displaced ordinates.

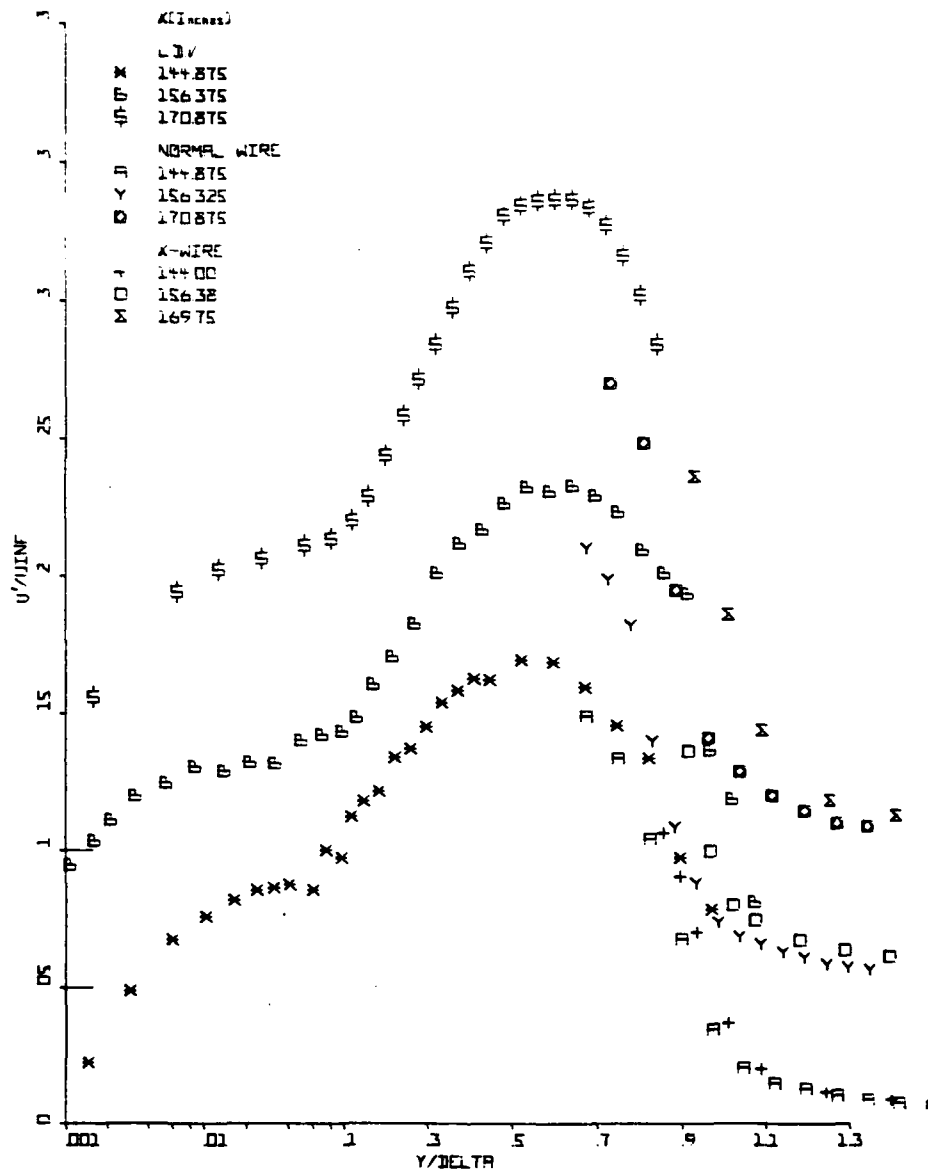


Figure 13(b). Streamwise turbulence intensity u'/U_{∞} vs. y/δ profiles: laser, single hot-wire, and cross hot-wire anemometer results. Note displaced ordinates.

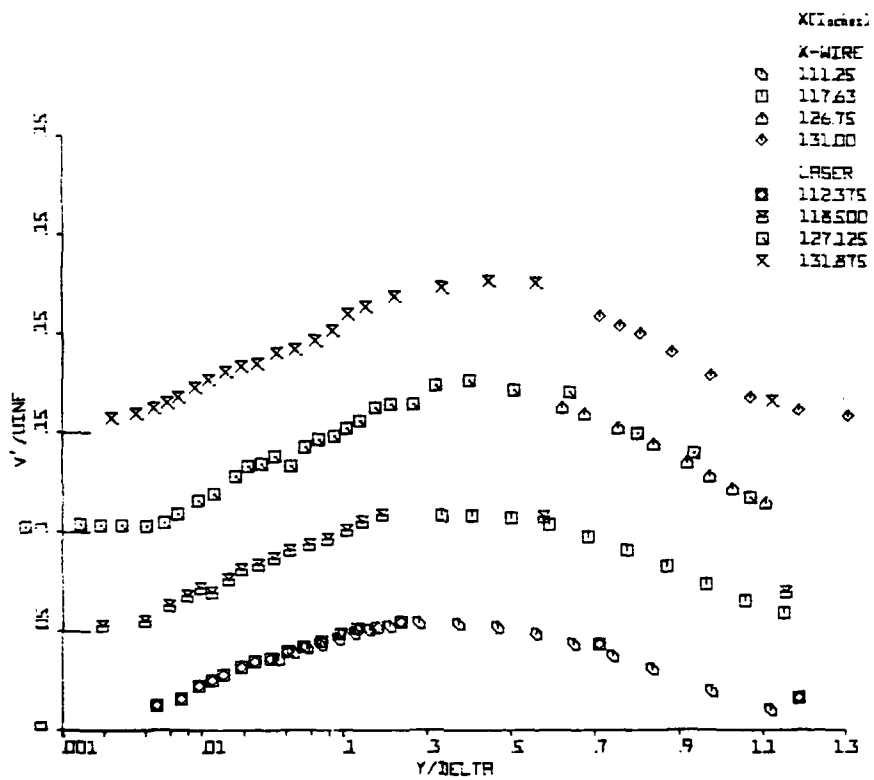


Figure 14(a). v'/U_{∞} vs. y/δ profiles: laser and cross hot-wire anemometer results. Note displaced ordinates.

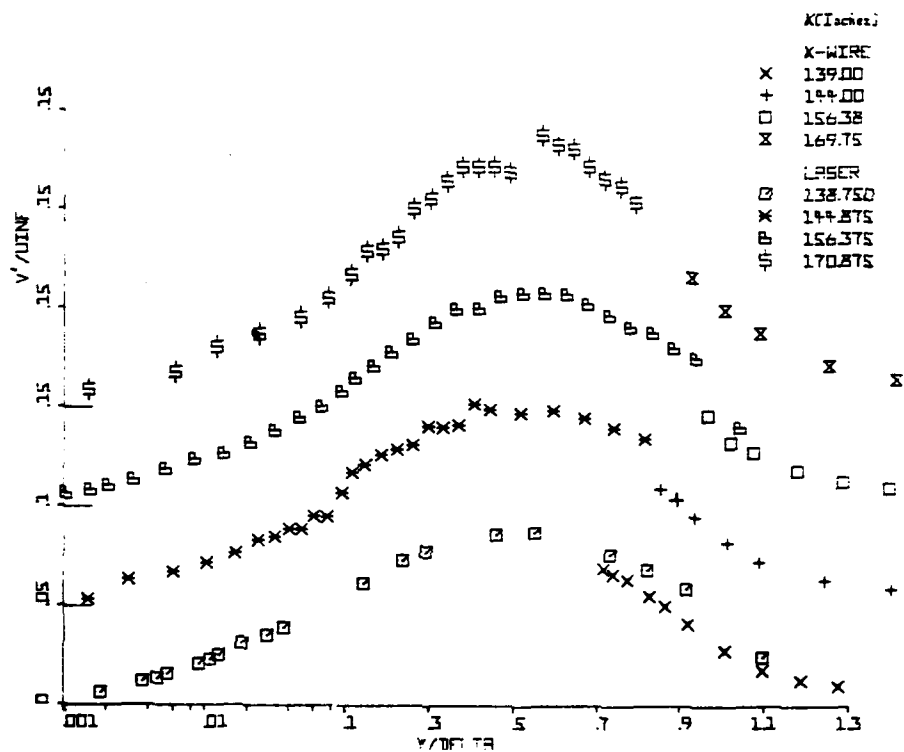


Figure 14(b). v'/U_{∞} vs. y/δ profiles: laser and cross hot-wire anemometer results. Note displaced results.

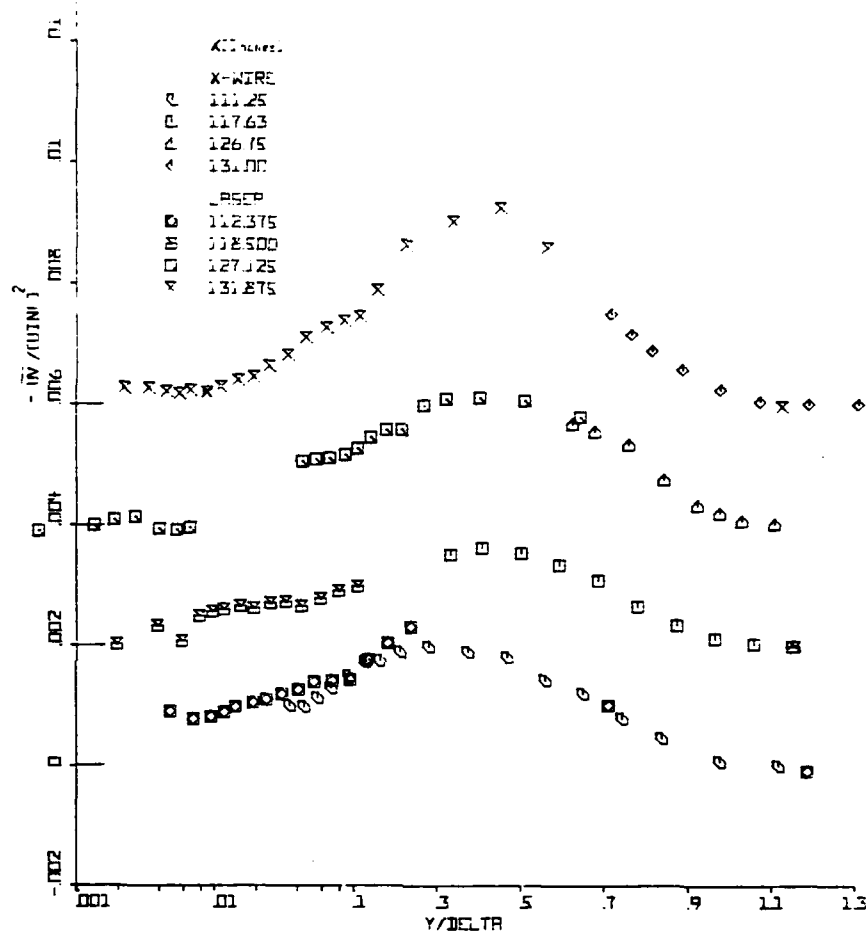


Figure 15(a). Reynolds shearing stress $-\overline{uv}/U^2$ vs. y/δ profiles: laser and cross hot-wire anemometer results. Note displaced ordinates.

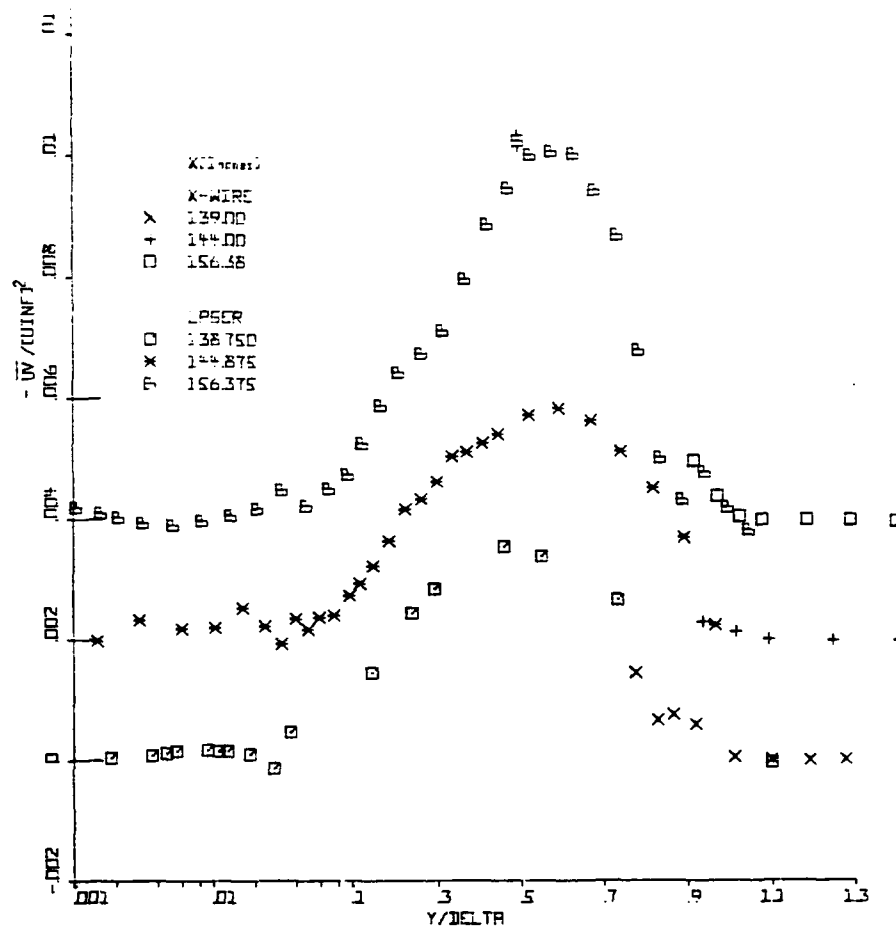


Figure 15(b). Reynolds shearing stress $-\overline{uv}/U_{\infty}^2$ vs. y/δ
 profiles: laser and cross hot-wire anemometer
 results. Note displaced ordinates.

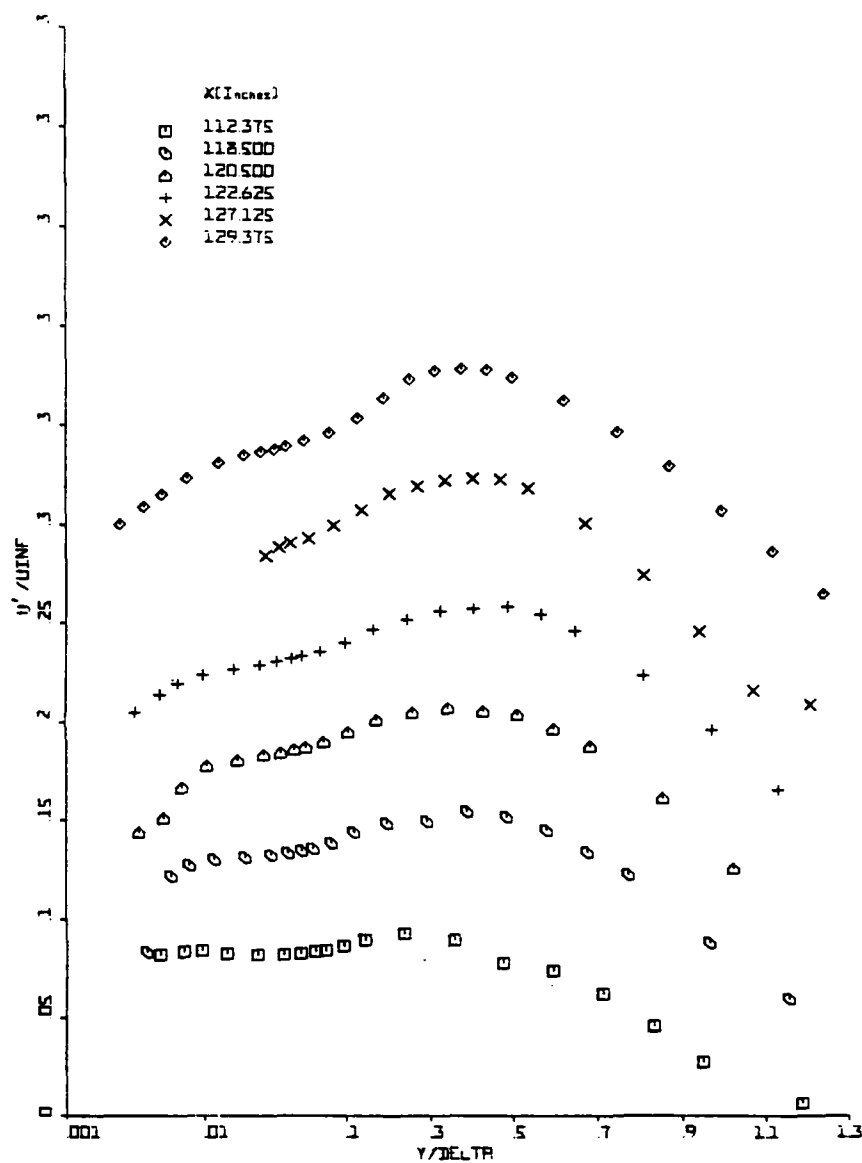


Figure 16(a). Smoothed u'/U vs. y/δ results from hot-wire and laser anemometers. Note displaced ordinates.

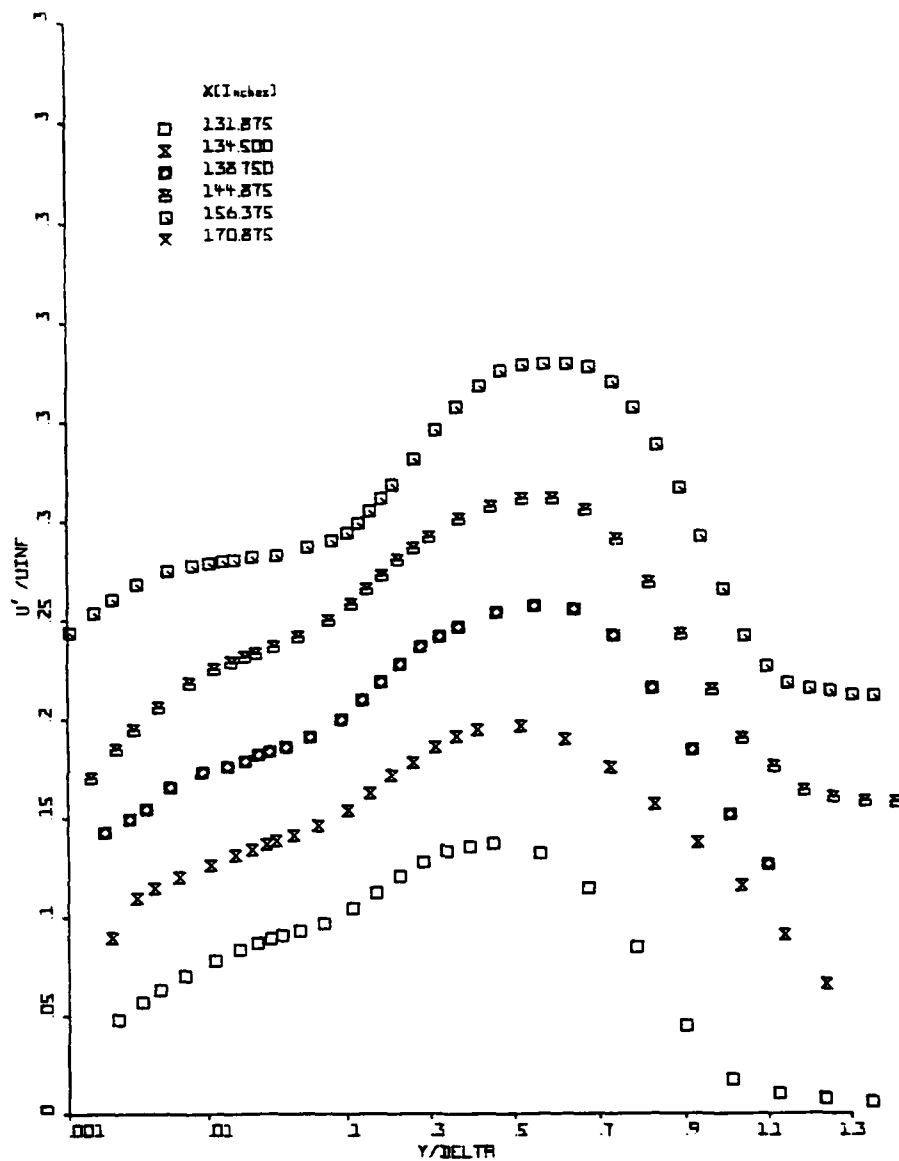
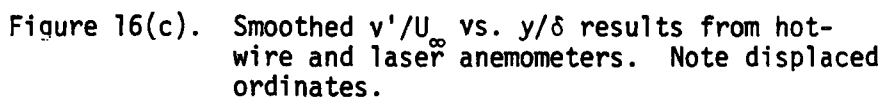


Figure 16(b). Smoothed u'/U_{∞} vs. y/δ results from hot-wire and laser anemometers. Note displaced ordinates.



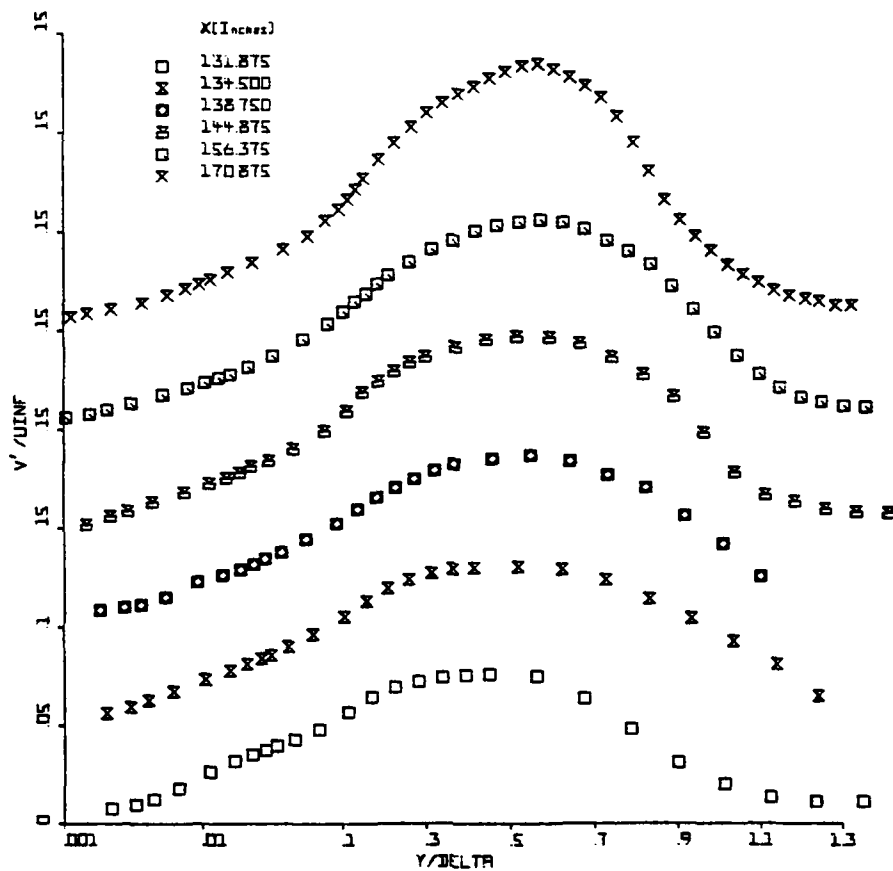


Figure 16(d). Smoothed v'/U_{∞} vs. y/δ results from hot-wire and laser anemometers. Note displaced ordinates.

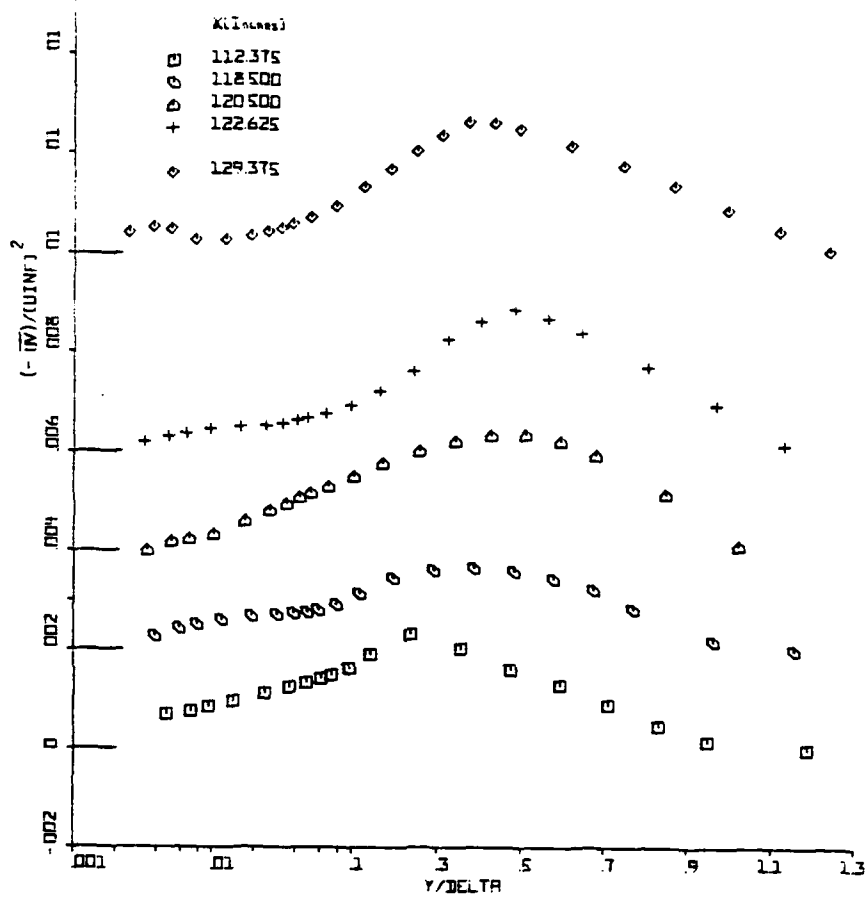


Figure 16(e). Smoothed Reynolds shearing stress $-\overline{uv}/U_{\infty}^2$ vs. y/δ results from laser and hot-wire anemometers. Note displaced ordinates.

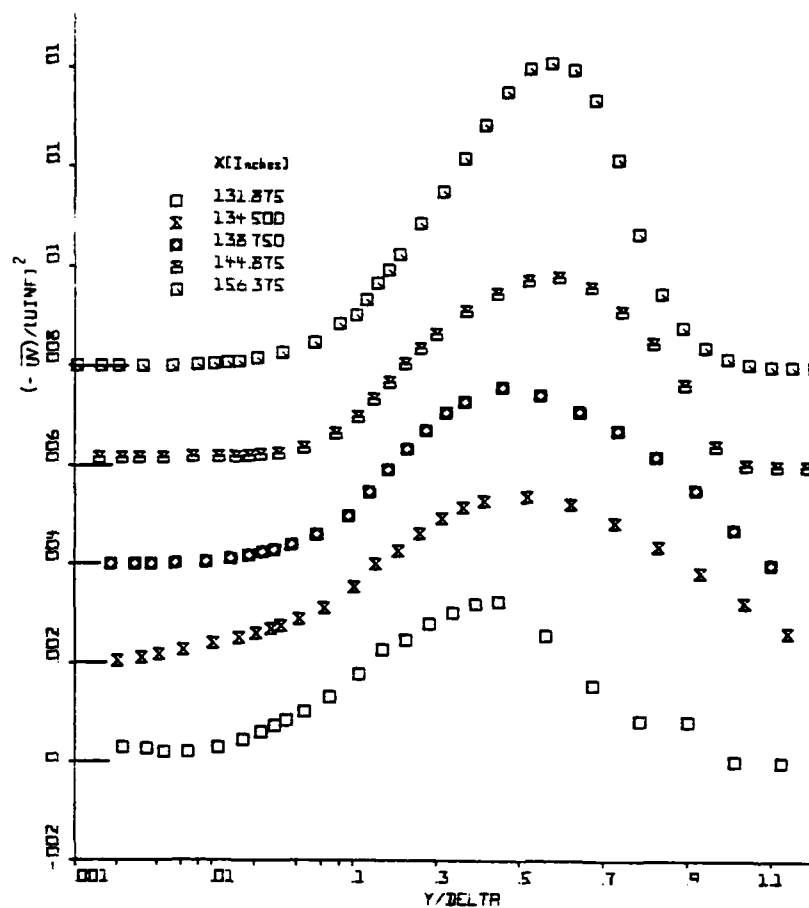


Figure 16(f). Smoothed Reynolds shearing stress $-\overline{uv}/U_{\infty}^2$ vs. y/δ results from laser and hot-wire anemometers. Note displaced ordinates.

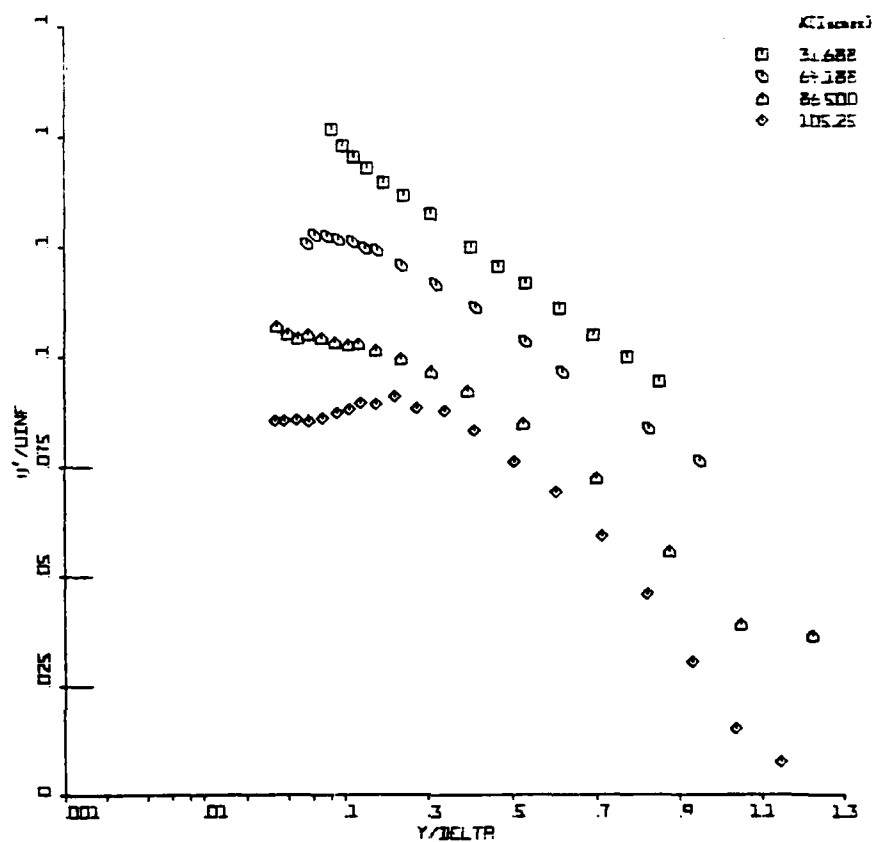


Figure 17(a). Cross hot-wire anemometer results well upstream of separation: u'/U_{∞} .

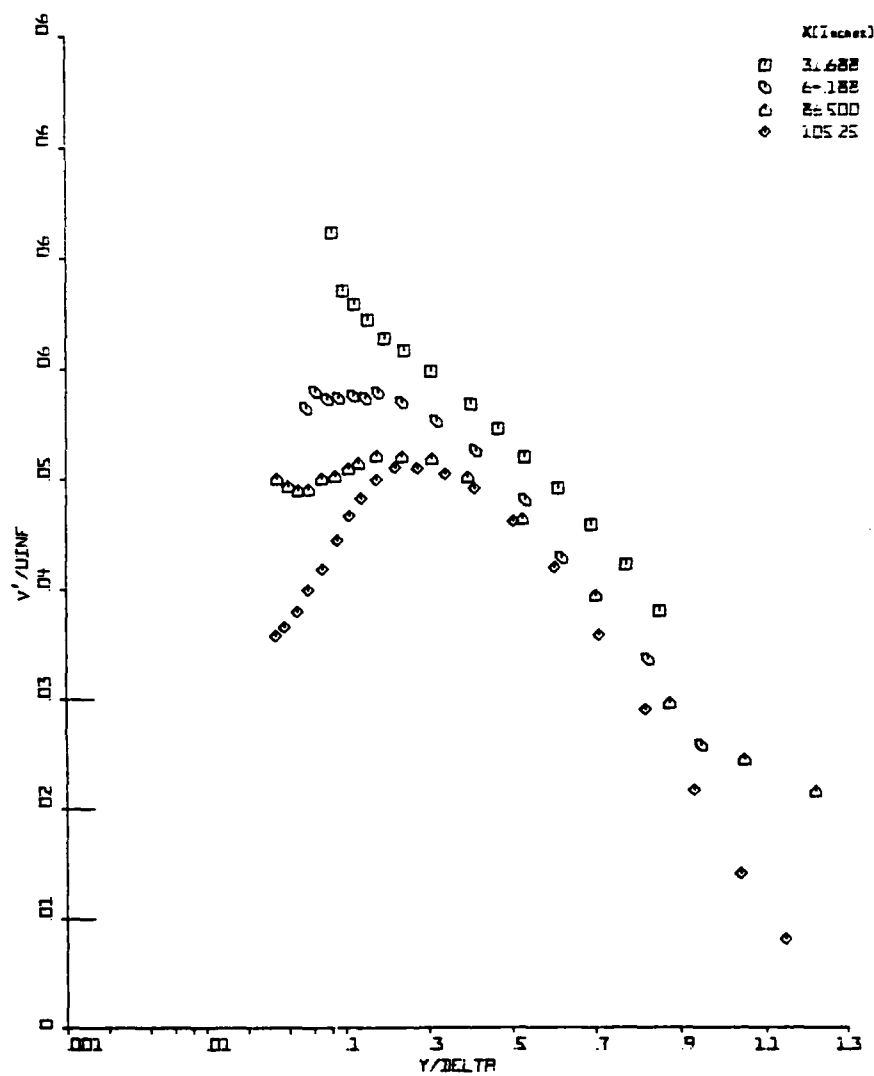


Figure 17(b). Cross hot-wire anemometer results well upstream of separation: v'/U_{∞} .

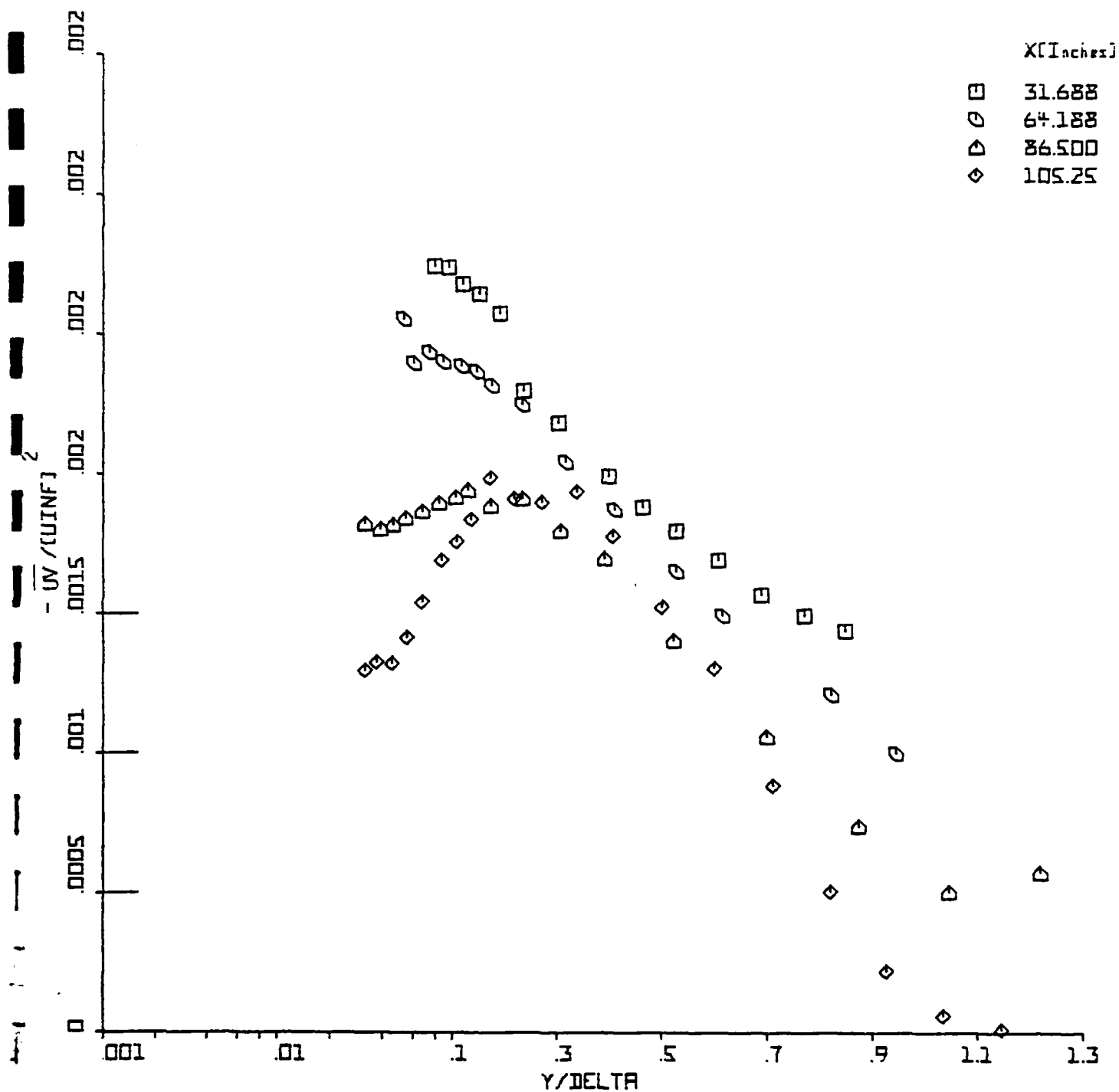


FIGURE 17(c). CROSS HOT-WIRE ANEMOMETER RESULTS WELL UPSTREAM OF SEPARATION:
 $-\overline{UV}/U_{\infty}^2$.

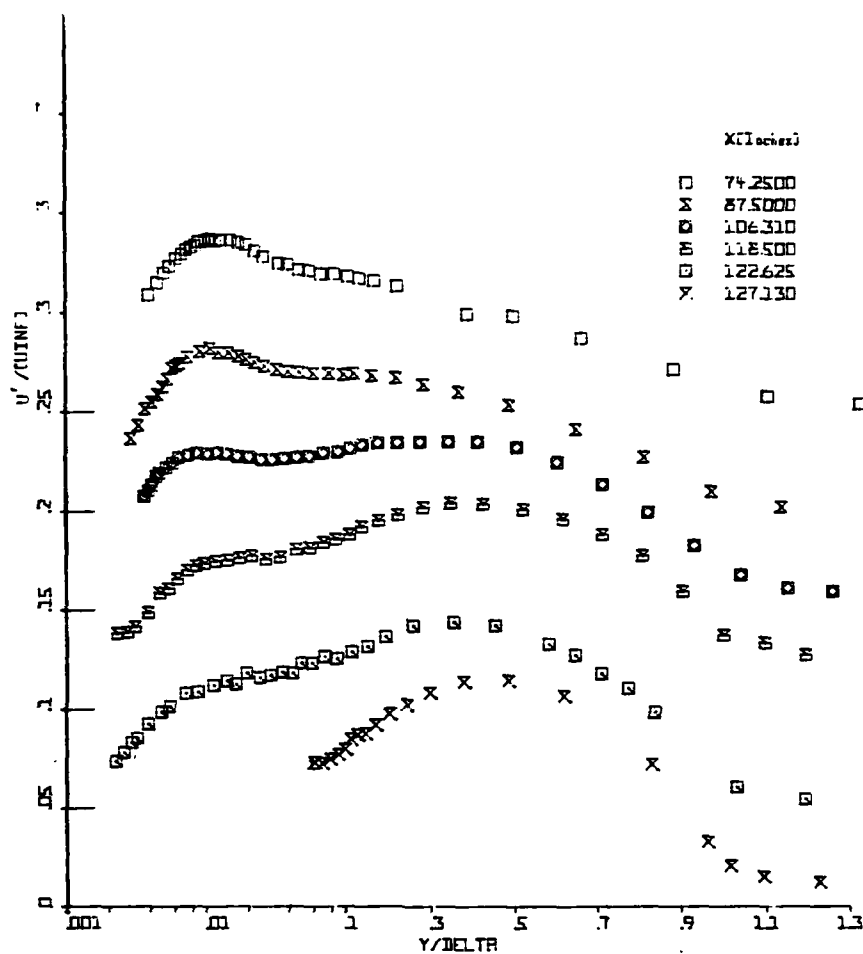


Figure 18(a). u'/U vs. y/δ , single hot-wire anemometer results.

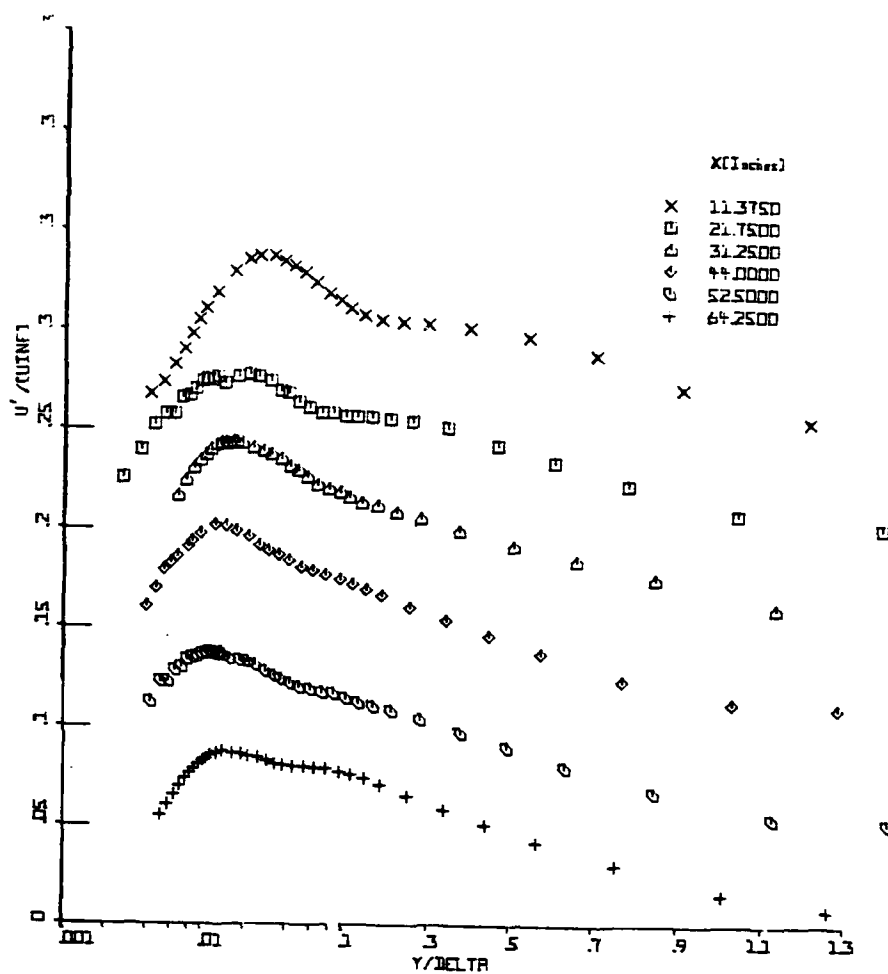


Figure 18(b). u'/U_{∞} vs. y/δ single hot-wire anemometer results.

Figure 19 shows the distributions of the intermittency across the boundary layer for the region approaching separation and downstream of it. The reverse flow first starts appearing at 122.6 inches but becomes clearly observable beyond 127 inches. Further downstream, the backflow intensifies and also spreads outwards from the wall. γ_{pu} reaches the lowest value of approximately 0.05 at the last station of measurement in the separated region, where backflow extends up to about 60% of the boundary layer thickness. The distributions in the separated region are trough-shaped near the wall showing that the maximum amount of reverse flow occurs slightly away from the wall. This is consistent with the velocity profile shape that shows that the highest velocity for the backflow is reached at a point slightly away from the wall. However, as shown in Table 1, the uncertainty in γ_{pu} becomes large as the mean velocity approaches zero, so one cannot place too much emphasis on this coincidence. Figure 20 shows the decay of γ_{pu} near the wall, γ_{puo} , as a function of the streamwise co-ordinate. As mentioned earlier the reverse flow is first measured at 122.6 inches and thereafter its persistence increases continuously, until it reaches a level where it exists 90% of the time after which its rate of increase diminishes.

IV. 4 Higher-order Turbulence Correlations

To investigate the effect of separation on higher order structure functions, the third and fourth moments given by equation (7) were calculated from the U and V LDV histograms. Simpson and Chew (1979) showed that the skewness factors, $S_u = (\overline{u^3})/(\overline{u^2})^{3/2}$ and $S_v = (\overline{v^3})/(\overline{v^2})^{3/2}$, and flatness factors, $F_u = (\overline{u^4})/(\overline{u^2})^2$ and $F_v = (\overline{v^4})/(\overline{v^2})^2$, were about ± 0.1 and ± 0.2 uncertain. Data obtained on different days were in close agreement, with the

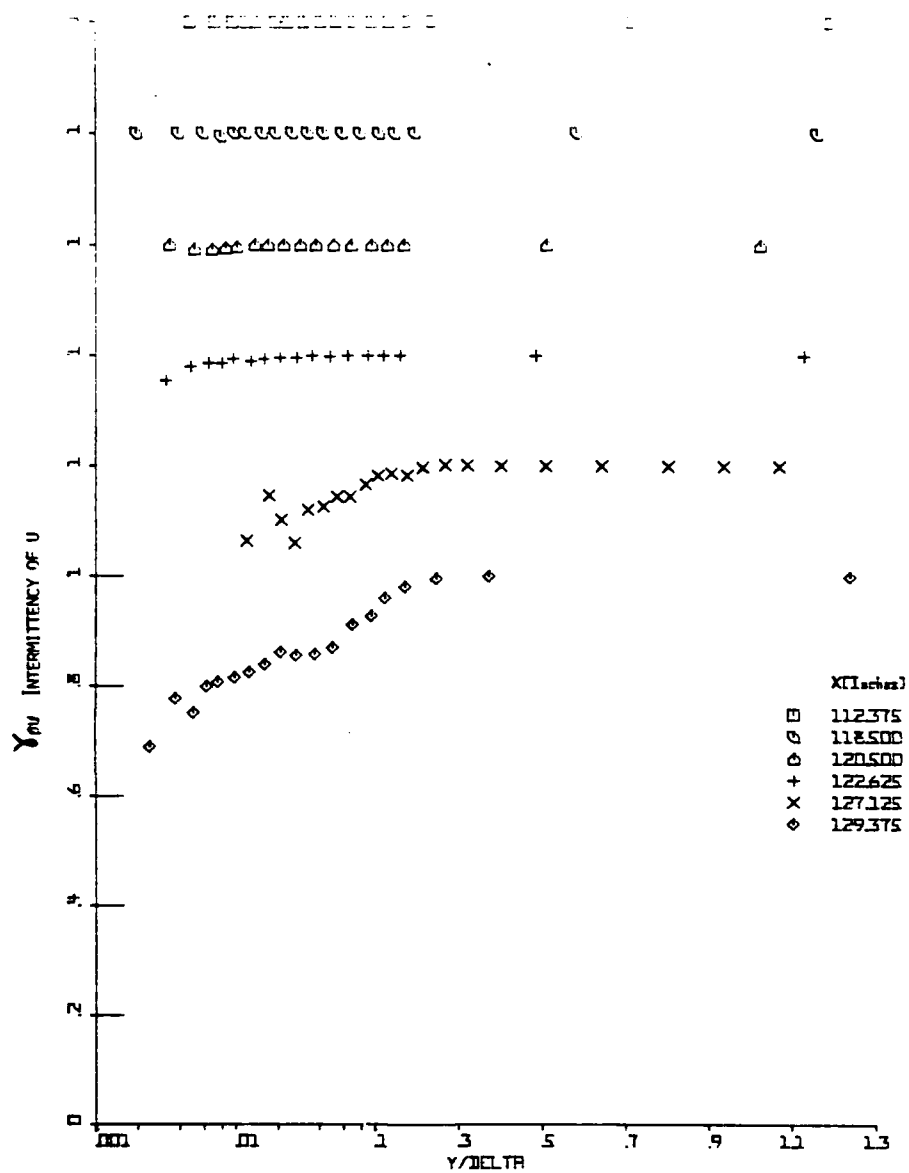


Figure 19(a). Streamwise fraction of time flow moves downstream, γ_{pu} vs. y/δ .

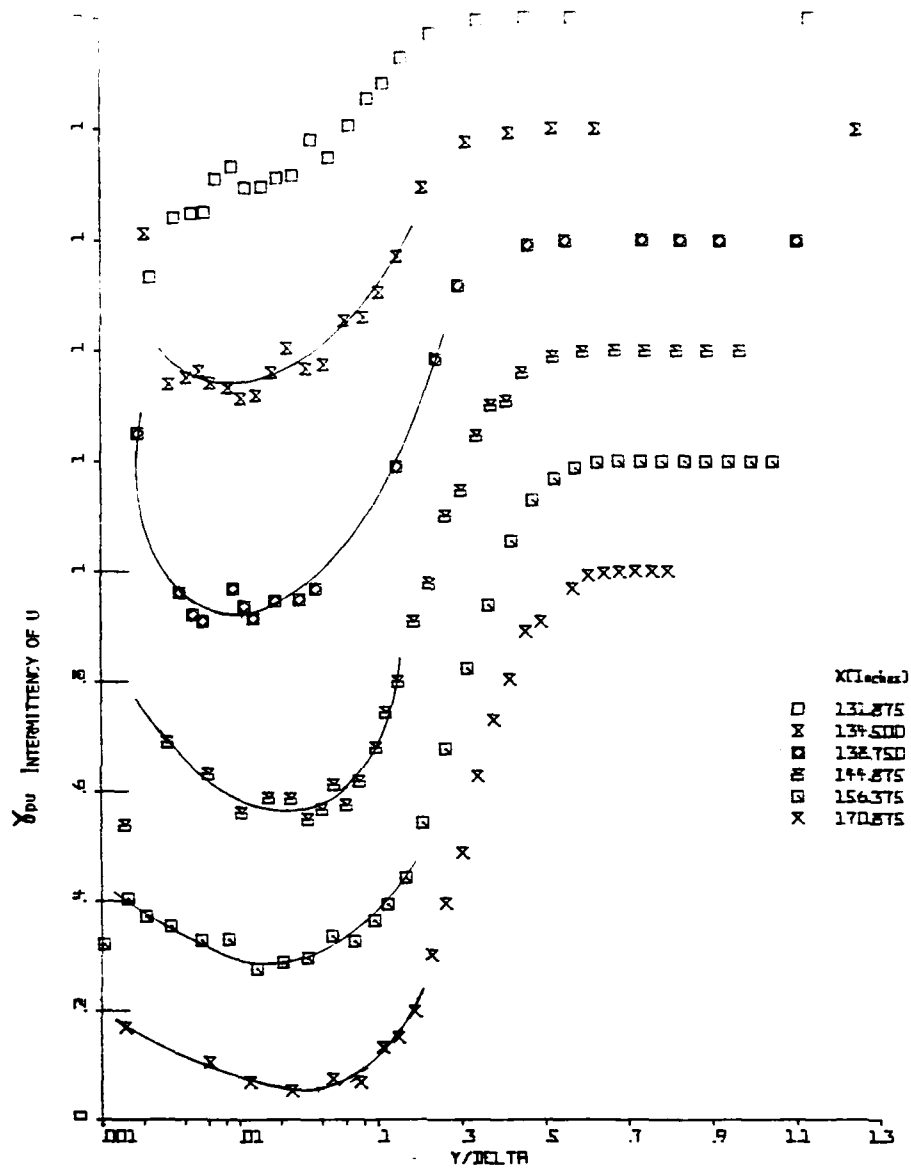


Figure 19(b). Streamwise fraction of time flow moves downstream, γ_{pu} vs. y/δ .

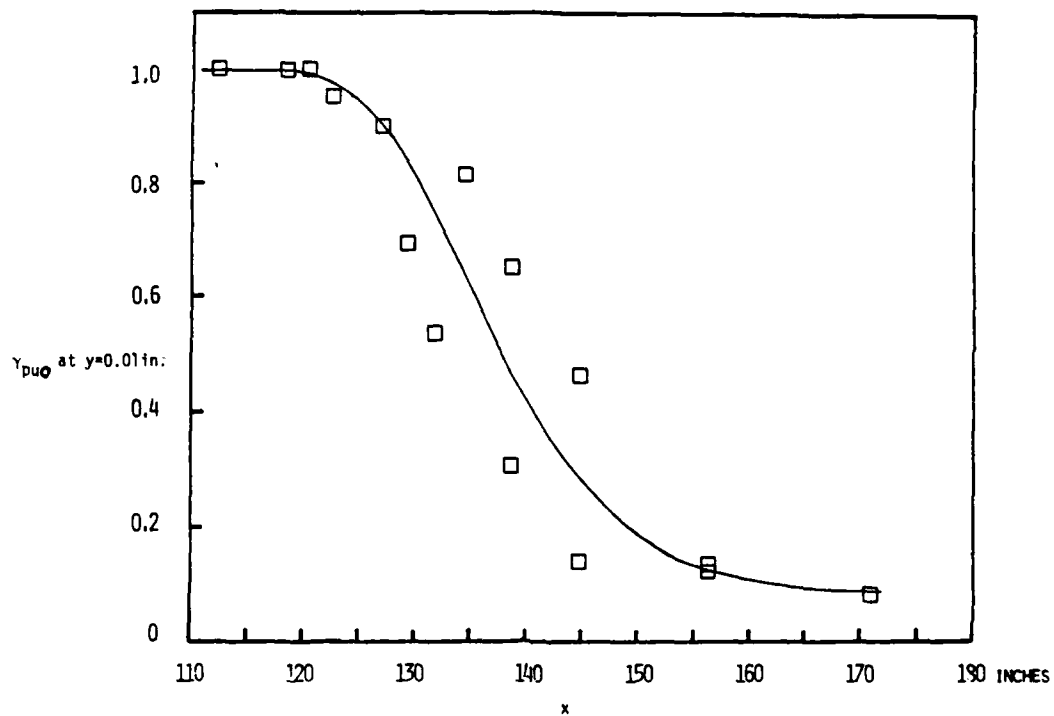


Figure 20. γ_{pu} at 0.01 inches from wall vs. x : $\square$, experimental data; solid line for visual aid only.

scatter being within these uncertainty levels.

For purposes of comparison and for additional information, $\overline{u^2 v}$ and $\overline{v^3}$ triple correlation data were obtained from the cross-wire anemometer. The main source of uncertainty in these measurements is the drift of the mean voltage level in the multipliers. This was kept to a minimum by adjusting the offset voltage before, several times during, and after taking a set of data, so that a zero voltage input produced a zero voltage output. During data reduction a correction was applied for the offset voltage. Table 2 gives the maximum uncertainties for each streamwise location that data are presented. All data which were greater 25% uncertain are not presented here. This arbitrary uncertainty limit is not really very high, considering that third-order correlations are expected to have high uncertainties.

Figure 21 shows the skewness factor S_v results obtained by laser and cross-wire anemometers for several streamwise locations. The agreement between the two types of experimental results away from the wall at a given location is generally within the estimated uncertainties. In the separated zone the hot-wire measurements were confined to the outer region where the instantaneous flow direction differed less than 45° from the mean flow direction.

IV.5 Skin-friction Results

Three different ways of deducing the near wall shearly-stress distribution were used: the Ludwig-Tillman skin-friction correlation, a Preston tube, and the surface hot-wire gage described in section II.4 above. Figure 22 shows the results from these three methods, which are in agreement within the uncertainties given in Table 1. Table 3 gives the Ludwig-Tillman results.

Table 2: Uncertainties for the diffusion results, y/δ positions given in parentheses.

x Inches	value at the location where the uncertainty was computed		Maximum absolute value		Maximum value of the absolute uncertainty		
	$\overline{u^2 v}$ (ft/sec) ³	$\overline{v^3}$ (ft/sec) ³	$\overline{u^2 v}$ (ft/sec) ³	$\overline{v^3}$ (ft/sec) ³	$\overline{u^2 v}$ (ft/sec) ³	$\overline{v^3}$ (ft/sec) ³	U_∞ (ft/sec)
31.688	0.58 (0.401)	3.93 (0.465)	4.78	6.43	0.2	0.15	62.36
86.5	1.07 (1.221)	1.03 (1.396)	14.53	10.09	0.91	1.0	66.73
117.625	3.09 (0.27)	3.02 (0.407)	11.49	3.5	1.7	0.25	51.86
126.75	12.72 (0.623)	4.83 (0.837)	16.6	8.59	1.02	0.33	48.94
131.0	13.38 (0.714)	3.44 (0.88)	13.86	4.69	1.37	0.5	47.97
144.0	9.67 (0.895)	4.13 (0.933)	11.24	6.2	1.03	0.39	47.06
156.375	6.97 (0.966)	1.53 (1.073)	14.27	9.74	1.57	0.88	45.33

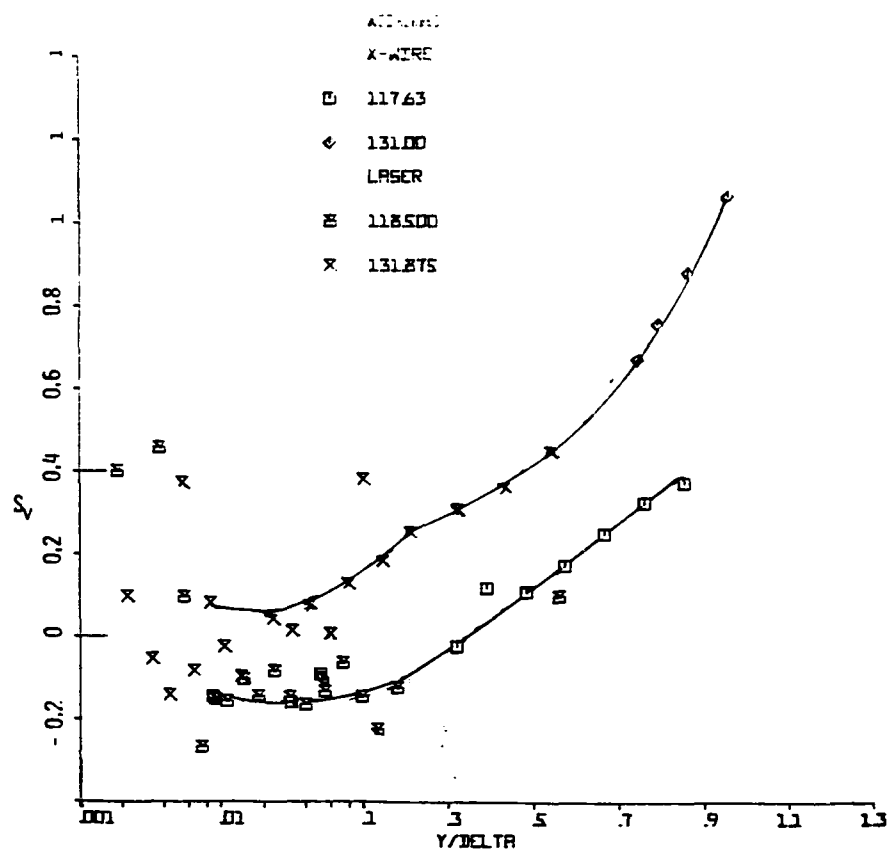


Figure 21. Comparison of skewness factor S_v for v from laser and hot-wire anemometers. v Solid lines for visual aid only. Note displaced ordinates.

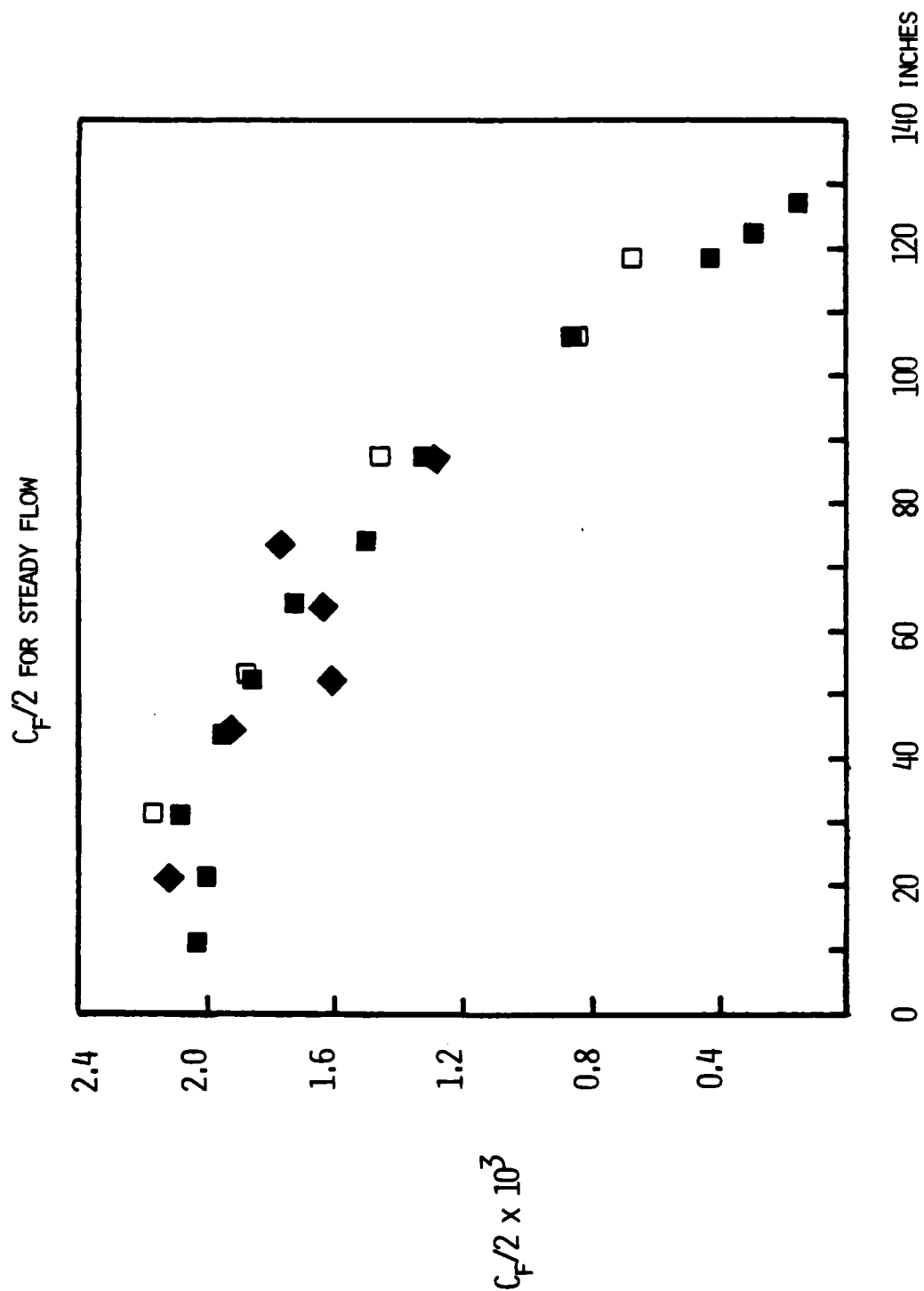


FIGURE 22. FRICTION FACTOR $C_f/2$ VS. x FROM THE SEVERAL EXPERIMENTAL METHODS: ■, LUDWIG-TILLMAN LAW; □, SURFACE HOT-WIRE GAGE; ♦, PRESTON TUBE.

X (INS.)	UINF (FT./SEC.)	DUINF/DX (1/SEC.)	δ_{99} (INS.)	$\delta_{99.5}$ (INS.)	δ_1 (INS.)	R_{δ_2}	H_{12}	$10^3 X C_f / 2$
11.375	52.600	5.38	.492	.517	.0699	1381.2	1.378	2.0350
21.750	57.800	6.48	.574	.615	.0728	1570.2	1.367	2.0010
31.250	63.200	6.30	.531	.563	.0707	1677.0	1.339	2.0810
44.000	69.700	4.38	.776	.907	.0898	2345.9	1.323	1.9530
52.500	71.500	2.40	.712	.761	.0901	2490.9	1.343	1.8620
64.250	71.600	-1.32	.792	.842	.1103	2900.6	1.357	1.7240
74.250	70.000	-2.36	.909	.959	.1481	3669.3	1.413	1.5030
87.500	66.800	-3.54	1.235	1.290	.2182	5201.9	1.418	1.3300
106.310	59.300	-6.31	1.828	1.891	.4612	8616.7	1.625	.8590
112.375	55.900	-5.68	2.338	2.388	.6302	9888.3	1.733	.6982
118.500	53.100	-4.72	2.799	2.842	.9122	11754.7	1.989	.4469
120.500	52.150	-4.45	2.946	2.973	1.0392	12924.8	2.010	.4219
122.625	51.300	-4.11	3.280	3.322	1.2101	13684.7	2.212	.3030
127.125	49.500	-3.49	3.804	3.844	1.6444	14747.9	2.696	.1418
129.375	48.750	-3.16	4.878	4.922	2.0658	19088.9	2.533	.1680
131.875	48.100	-2.86	4.610	4.676	2.0649	16138.2	2.973	.0884
134.500	47.400	-2.55	5.829	5.895	2.6497	19736.1	3.139	.0646
138.750	46.450	-2.05	5.779	5.834	3.1099	17185.9	4.118	.0145
144.875	45.500	-1.64	6.708	6.768	4.0101	16297.7	5.404	.0020
156.375	44.600	-1.28	9.346	10.066	6.2550	18024.4	7.689	.0001
170.875	43.700	-1.21	12.518	12.841	8.3127	18664.8	9.453	.0000

Table 3: Parameters of the mean flow development

The Preston tube and Ludwig-Tillman methods require the existence of a universal logarithmic law-of-the-wall velocity profile. The data obtained using the surface hot-wire gage are not dependent on the requirement of a logarithmic wall region. This suggests that the law of the wall is valid until the location where γ_{pu} is first less than one near the wall. These results are in agreement with results of Simpson et al., (1977).

IV.6. Data Tabulation

These data are tabulated in Table 3 and in the Appendix. These data are recorded on magnetic tape in the format required for the 1980-81 AFOSR-HTTM-Stanford Conferences on Complex Turbulent Flows, a copy of which is on file in the Thermosciences Division of the Stanford University Department of Mechanical Engineering.

V. DISCUSSION

V.1 Mean Velocity Distribution

Figure 23 shows the mean streamline pattern for the flow in the vicinity of separation. Note that in the backflow region the turbulence level is very high compared to the mean flow, so these mean streamlines do not represent the average pathlines for elements of fluid. As discussed in section VI below, it appears that the fluid in the backflow does not come from far downstream as the streamlines may suggest, but is supplied fairly locally.

Figures 24 (a) and (b) show that the U^+ vs y^+ law-of-the-wall velocity profile holds all along the flow channel when the Ludwig-Tillman skin friction values are used. Although no wall proximity corrections to the hot-wire data were applied in the viscous sublayer, the $U^+ = y^+$ relationship is obeyed rather well. Oka and Kostić (1972) noted that hot-wire measurements are only influenced by flow interference and conduction to the test wall for $y^+ < 4$, which

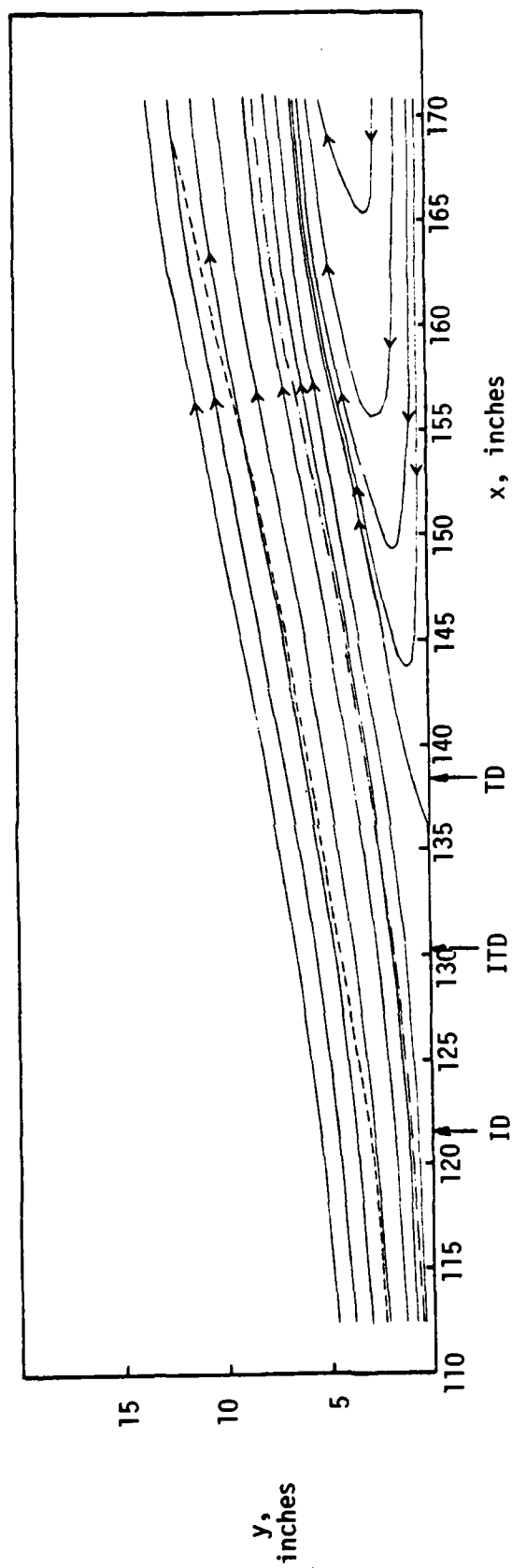


Figure 23. Mean streamline flow pattern in the vicinity of separation. — streamlines, --- displacement thickness distribution, - · - boundary layer edge, — • — displacement thickness distribution.

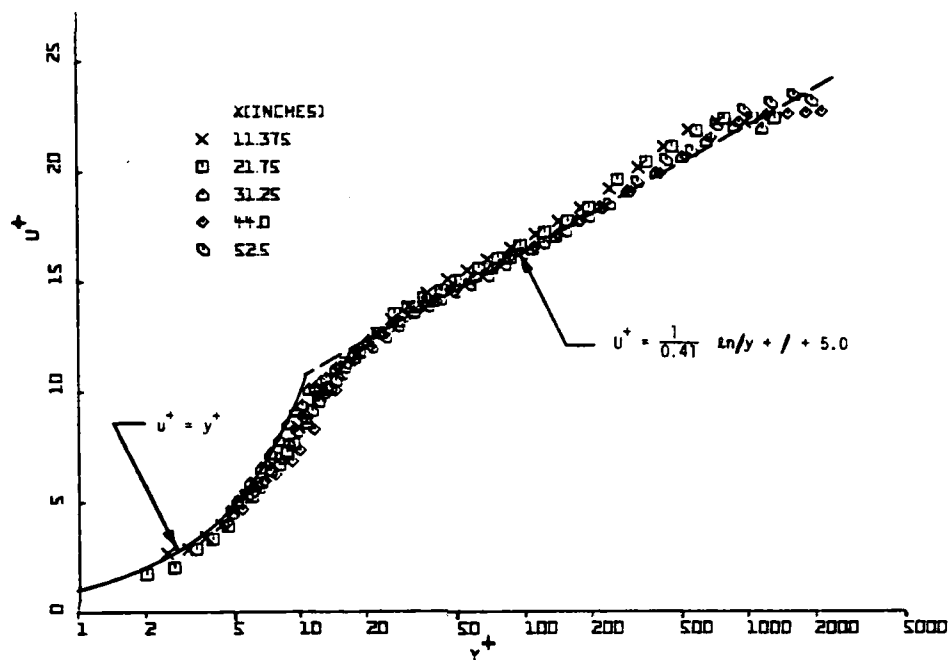


Figure 24(a). Law-of-the-wall velocity profiles, U^+ vs. y^+ , upstream of separation.

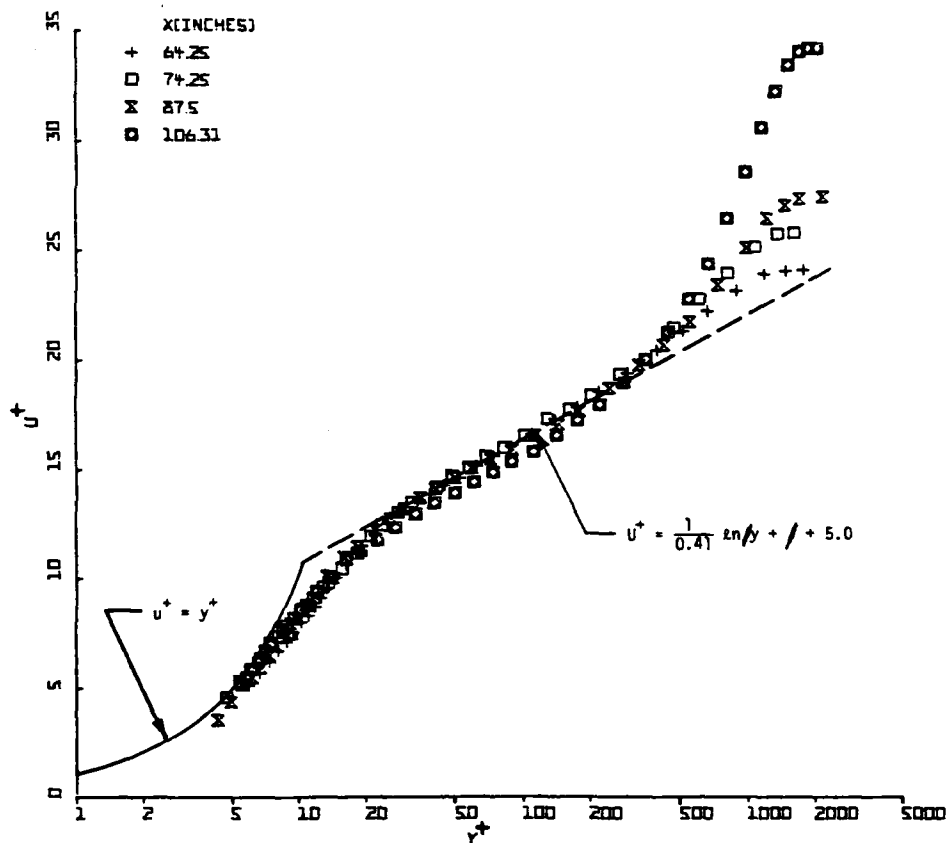


Figure 24(b). Law-of-the-wall velocity profiles, U^+ vs. y^+ , upstream of separation.

explains why the present data for $y^+ > 4$ obey the viscous sublayer equation so well. Upstream of the vicinity of separation, the usual logarithmic form for $y^+ > 30$ holds

$$U^+ = \frac{1}{0.41} \ln|y^+| + 5.0 \quad (9)$$

as shown in Figures 24.

Perry and Schofield (1973) proposed universal empirical correlations for the inner and outer regions of adverse pressure gradient boundary layers near separation. Their correlations apply to all types of adverse pressure gradient boundary layers irrespective of whether they are in equilibrium or not, but with the restriction that the ratio $(-\overline{uv})_{\max}/U_\tau^2$ must exceed 1.5. They proposed the defect law for the outer flow as

$$\frac{U_\infty - U}{U_s} = f_2(\eta_2), \text{ where } \eta_2 = y/\Delta \quad (10)$$

and

$$\Delta = \frac{U_\infty}{U_s} \frac{\delta_1}{C} \quad (11)$$

C is a universal constant given by $C = \int_0^\infty f_2(\eta_2) d\eta_2$ and found empirically to be equal to 2.86. The inner law was defined as

$$\frac{U}{U_\tau} - h = f_1(\eta_1), \quad \eta_1 = \frac{y}{e}, \quad e = \frac{Lu_\tau^2}{U_{MP}^2} \quad (12)$$

where h is a constant and U_{MP}^2 and L are described later.

The condition for the overlap between the inner and the outer region lead to the following relations

$$\frac{U}{U_\infty} = 0.47 \left(\frac{U_s}{U_\infty} \right)^{3/2} \left(\frac{y}{\delta_1} \right)^{1/2} - \left(\frac{U_s}{U_\infty} \right) + 1 \quad (13)$$

$$f_1(\eta_1) = 6.4 \eta_1^{1/2} \quad (14)$$

and

$$\frac{U_s}{U_{MP}} = 8 \left(\frac{\Delta}{L} \right)^{1/2} \quad (15)$$

Equation (13) was used to obtain the values of the velocity scale factor U_s by drawing a Clauser-type chart for $\frac{U}{U_\infty}$ and $\left(\frac{y}{\delta_1} \right)^{1/2}$ with U_s as the parameter. All the parameters obtained for Perry's correlations are given in Table 4.

The condition $(-\overline{uv})_{\max}/U_\tau^2 > 1.5$ was satisfied by the data for the region downstream of $x = 105$ inches. Hence, Perry and Schofield's correlations were tried for the locations downstream of 105 inches where the profiles of mean velocity as well as those of normal and shear stresses were available. The data for the normal stresses are also required since Perry and Schofield neglected the normal stresses term in the momentum equation while computing the shear stress profiles from the mean velocity profiles. It was shown later by Simpson (1975) that the normal stresses term plays a significant part in both the momentum and the turbulence energy equations for flows approaching separation. The normal stresses effects have been considered in a way as discussed by Simpson et al. (1977) and in accordance the pseudo-shear stress U_{MP}^2 is defined as

$$U_{MP}^2 = \left[-\overline{uv} + \int_y^\infty \frac{\partial(\overline{u^2} - \overline{v^2})}{\partial x} dy \right]_{\max} \quad (16)$$

and L is defined as the distance from the wall to the maximum in the pseudo-shear stress profile.

Figures 25 and 26 show the velocity profiles plotted in the inner and outer layer co-ordinates. The inner law correlation given by eqns. (12) and (14)

Table 4. Experimental values for the parameters used in the Perry and Schofield correlation.

x in inches	U_s/U_∞	U_s/U_M	U_s/U_{Mp}	y_c/Δ	$\Delta/\delta_{.99}$	$L/\delta_{.99}$
106.31	0.67	15.86	15.89	0.0889	1.077	0.340
111.125	0.78	16.80	16.64	0.0421	1.103	0.284
118.5	0.86	21.33	18.21	0.0392	1.183	0.423
126.75	1.02	22.47	18.66	0.0151	1.212	0.617

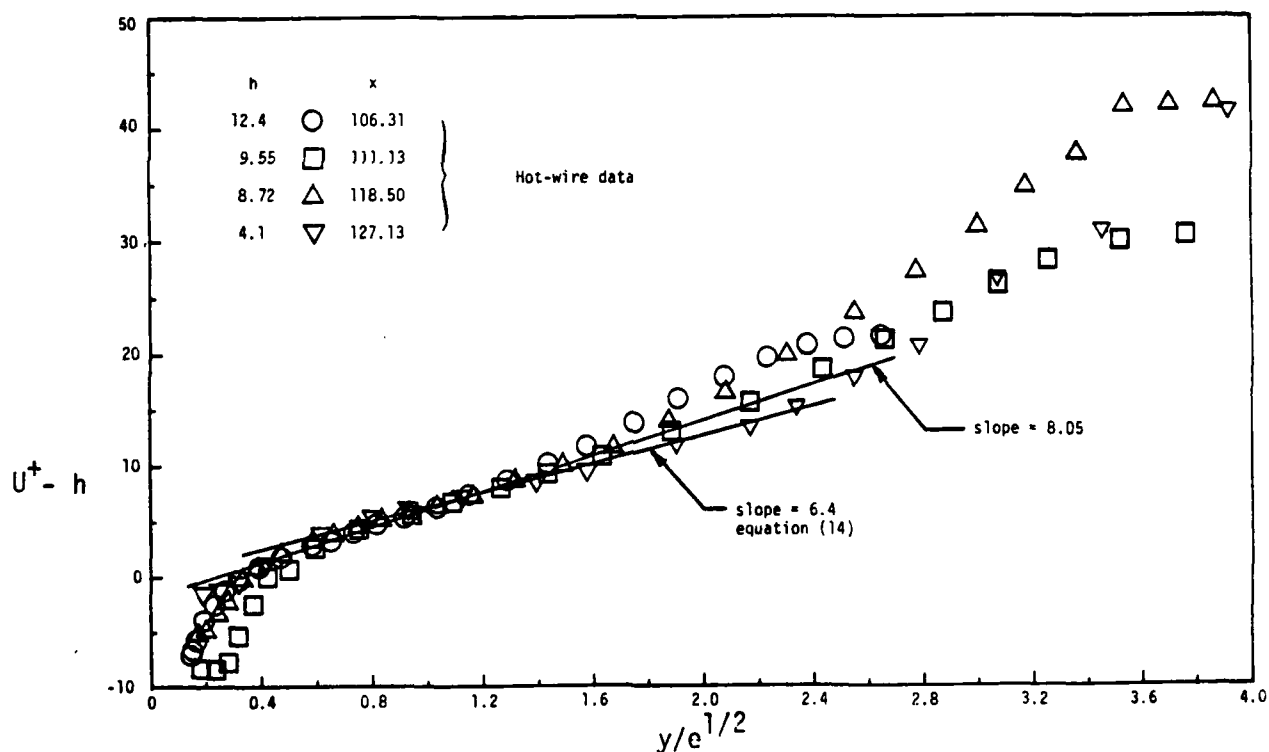


Figure 25. Perry and Schofield inner region correlation for the present data near separation, $U^+ - h$ vs. $(y/e)^{1/2}$, equations (12) and (14) given by solid lines for 6.4 and 8.05 slopes.

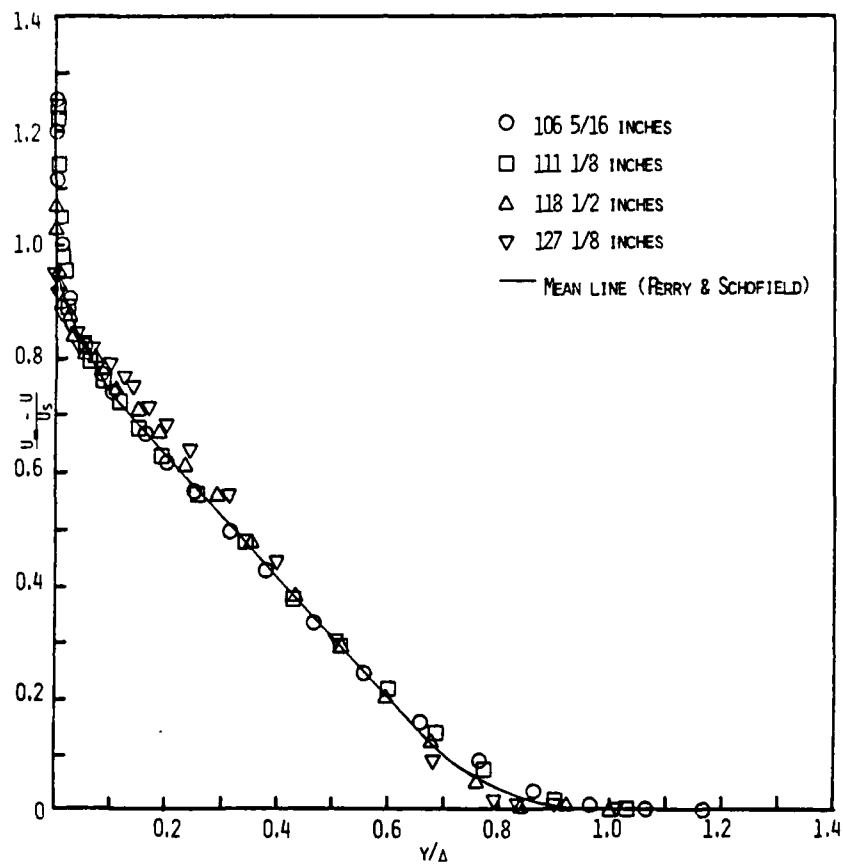


Figure 26. Perry and Schofield outer region correlation for the present data near separation, $(U_\infty - U)/U_s$ vs. y/Δ , eqn.(10); solid line is mean line from Perry and Schofield (1973).

seem to be satisfied reasonably well, although the higher slope of 8.05 satisfies the upstream most profiles better (Simpson et al., 1977). In the region near the wall, eqn. (12) takes the usual logarithmic form of eqn. (9). By matching the logarithmic and the half power regions, Perry and Schofield obtained the expression for the point of tangency as $y_c = 0.58e$. As shown in Table 4 the predicted point of tangency moves toward the wall as one proceeds downstream, indicating that the extent of the logarithmic region gradually decreases, which can also be seen in Figure 11c. The present data satisfy the other matching condition given by eqn. (15) to a reasonable extent. The present data upstream of intermittent backflow lie within the band represented by the scatter in the data plotted by Perry and Schofield.

Following Strickland and Simpson (1973), the velocity profiles in the separated region were normalized to see whether the profiles in the outer region show any resemblance to those observed in mixing layers. For this purpose $\frac{U-U_0}{U_\infty-U_0}$ was plotted as a function of $\frac{\sigma' y'}{x_0}$ as shown in Figure 27 for a few stations downstream of 127 inches. In the case of the mixing layer, y' represents the distance from the center of the mixing layer and here the location where the Reynolds Shear Stress $-\overline{uv}$ reaches a maximum was considered as the center of the shear layer. x_0 is the streamwise distance from a reference point and in the present studies $x = 88''$ was taken as the reference point. U_0 is equal to twice the velocity at the center of the shear layer minus the free-stream velocity and σ' is a constant. Also shown is the curve obtained by Halleen (1964) for a mixing layer. An error function type of distribution represented by

$$\frac{U - U_0}{U_\infty - U_0} = \frac{1}{2} \left\{ 1 + \operatorname{erf} \left(\frac{\sigma' y'}{x_0} \right) \right\} \quad (17)$$

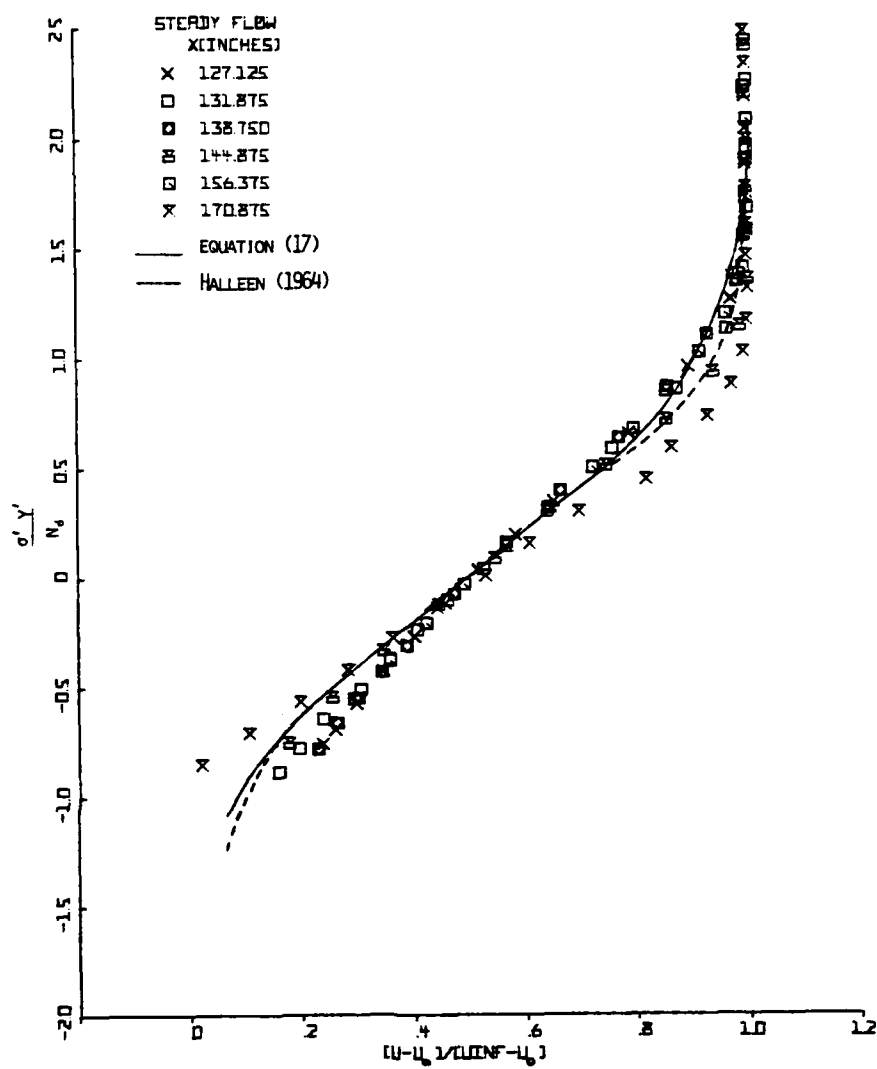


Figure 27. Present data in mixing-layer-type co-ordinates; solid line, eqn.(17) with $\sigma' = 24$ and $X_0 = 88"$; dashed line, Halleen's (1964) mixing layer correlation.

is also plotted for comparison. There is good agreement of the data with these distributions, confirming the analogy with mixing layers. However, σ' is about 24 while Halleen obtained a value of about 17.5.

As one can see in Figure 11d, there is some profile shape similarity for the backflow mean velocity downstream of 138 inches. Figure 28 shows a good correlation when normalized on the maximum negative mean velocity U_N and its distance from the wall N . A slightly poorer correlation results when δ is used instead of N . The U^+ vs. y^+ law-of-the-wall velocity profile is not consistent with this correlation since both U_N and N increase with streamwise distance, while the law-of-the-wall length scale ν/U_τ varies inversely with its velocity scale U_τ . The data of Simpson et al. (1977) for the one available location are also shown to be in fair agreement with this correlation.

An attempt was made to see if the mean velocity profiles downstream of separation could be composed of the "law-of-the-wake" (Coles and Hirst, 1969)

$$\omega(y/\delta) = 2 \sin^2\left(\frac{\pi y}{2\delta}\right) \quad (18)$$

and a similarity distribution for the remaining wall flow, Figure 29, which is a plot of $U/U_\infty - \sin^2(\pi y/2\delta)$ vs. y/δ , shows the remainder for the wall flow. There is no significant profile similarity.

Another attempt was made to scale the wake function by using the maximum backflow velocity and the free-stream velocity before subtracting it from the velocity profile. This was done as follows:

$$\frac{U}{U_\infty} = \left[\frac{U_\infty + |U_N|}{U_\infty} \right] \frac{1}{2} \omega(y/\delta) - \frac{|U_N|}{U_\infty} + R(y/\delta) \quad (19)$$

where $R(y/\delta)$ can be called a "backflow" function. Furthermore, another function

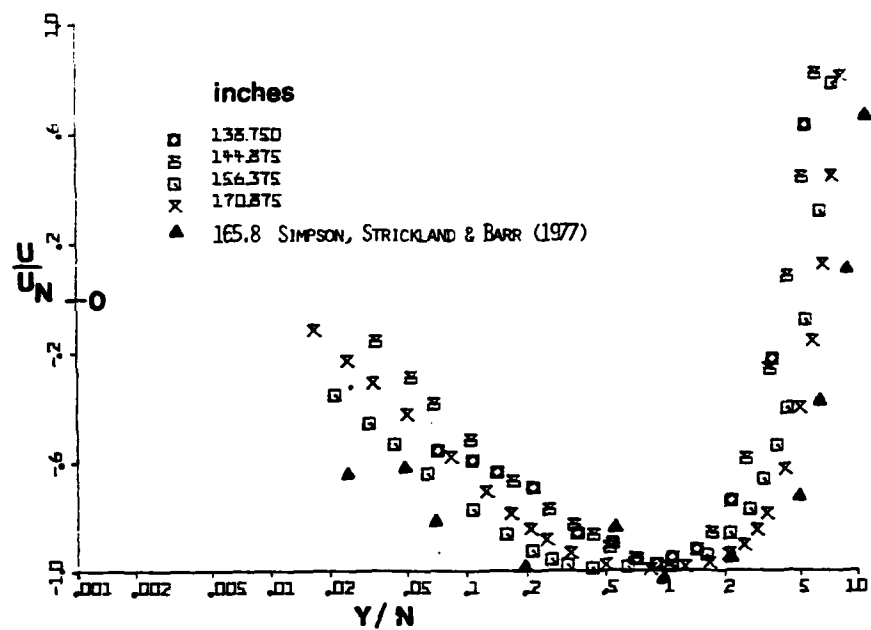


Figure 28. Normalized mean backflow velocity profiles:
 u_N and N , maximum mean backflow velocity and
its distance from the wall, respectively.

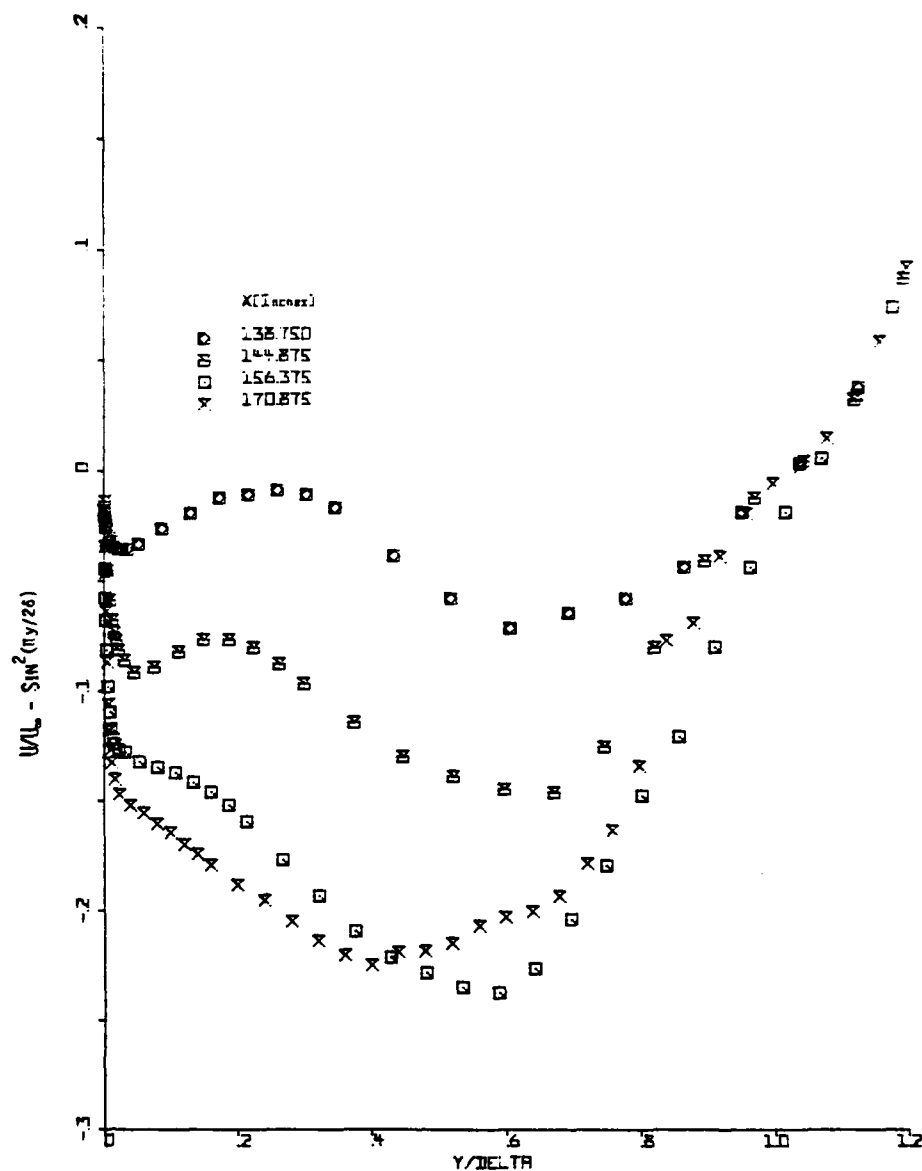


Figure 29. Difference between present mean velocity data and Coles' wake velocity profile vs. y/δ .

$B(y/\delta) = R(y/\delta) \frac{U_\infty}{|U_N|}$ was formed so that $B(y/\delta)$ has definite limits of 1 and 0 at $y/\delta = 0$ and 1, respectively. The plots of these function $R(y/\delta)$ and $B(y/\delta)$ are shown in Figures 30 and 31. They neither show any similarity nor small values in the outer region. This leads one to conclude that it is not possible to describe the velocity profile in the outer region for a separated flow by the universal wake function. No universal backflow function appears to exist.

V.2 Flow Detachment and Upstream-Downstream Intermittency

It is well established that separation of a turbulent boundary layer does not occur at a single streamwise location but is spread over a streamwise region and involves a spectrum of states. Sandborn and Kline (1961) and Sandborn and Liu (1968) defined the limiting points of the region as the "intermittent" and the "fully-developed" separation points. The former indicates the onset of separation by the appearance of intermittent backflow and the latter signifies the vanishing of the mean wall shear stress.

Sandborn and Liu (1968) gave correlations between H_{12} and $\delta_1/\delta_{.995}$ to demarcate the regions of intermittent and fully-developed separation. Figure 32 gives their correlations and the present experimental data points. According to their correlations, the present data show intermittent separation to occur at 130 inches. The value of γ_{puo} at that point is 0.81 which very nearly coincides with the value obtained by Simpson et al. (1977) and is also in reasonable agreement with the value obtained by Sandborn and Liu. By interpolation the fully-developed separation point occurred at 140 inches.

At the recent Project SQUID Colloquium on Flow Separation (Simpson, 1979), it was pointed out that the term "separation" must mean the entire process of

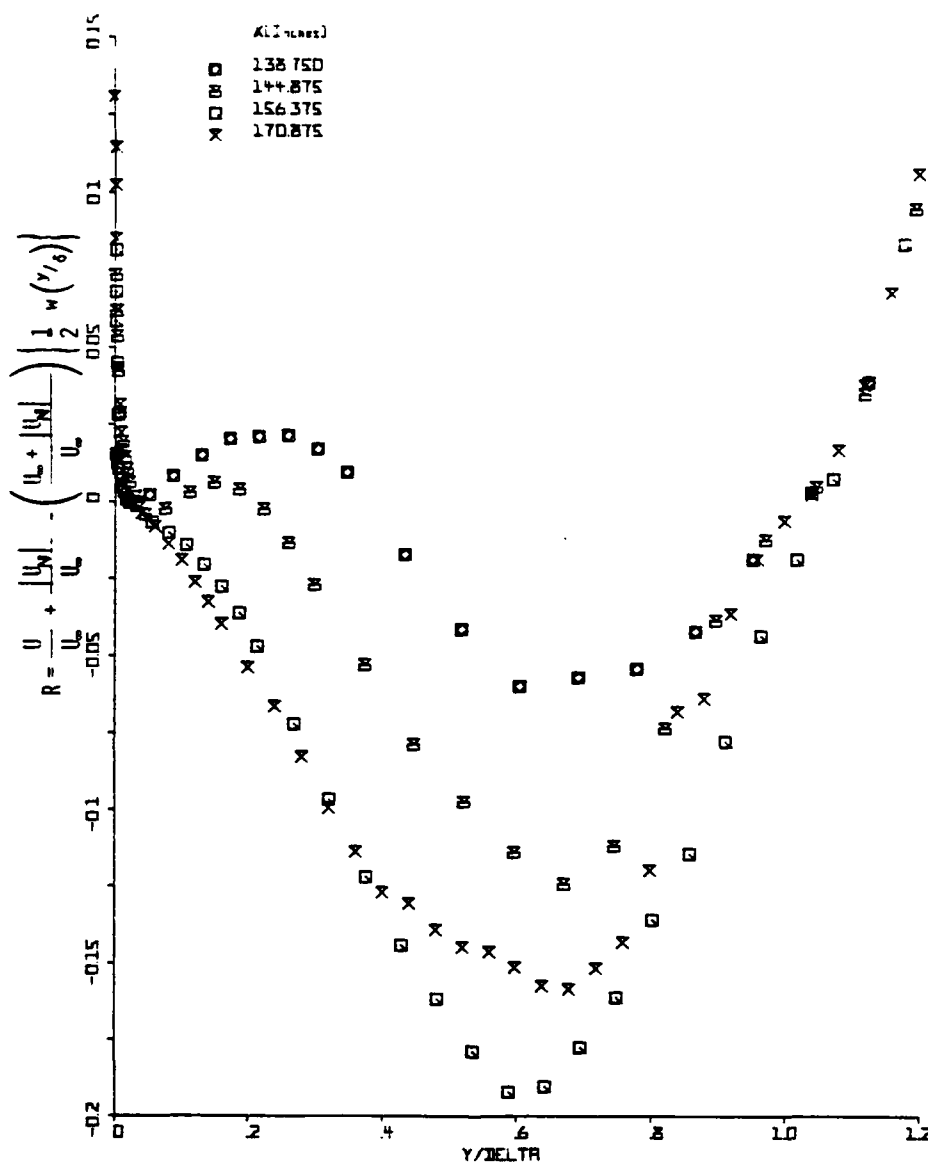


Figure 30. "Backflow" function defined in eqn.(19).

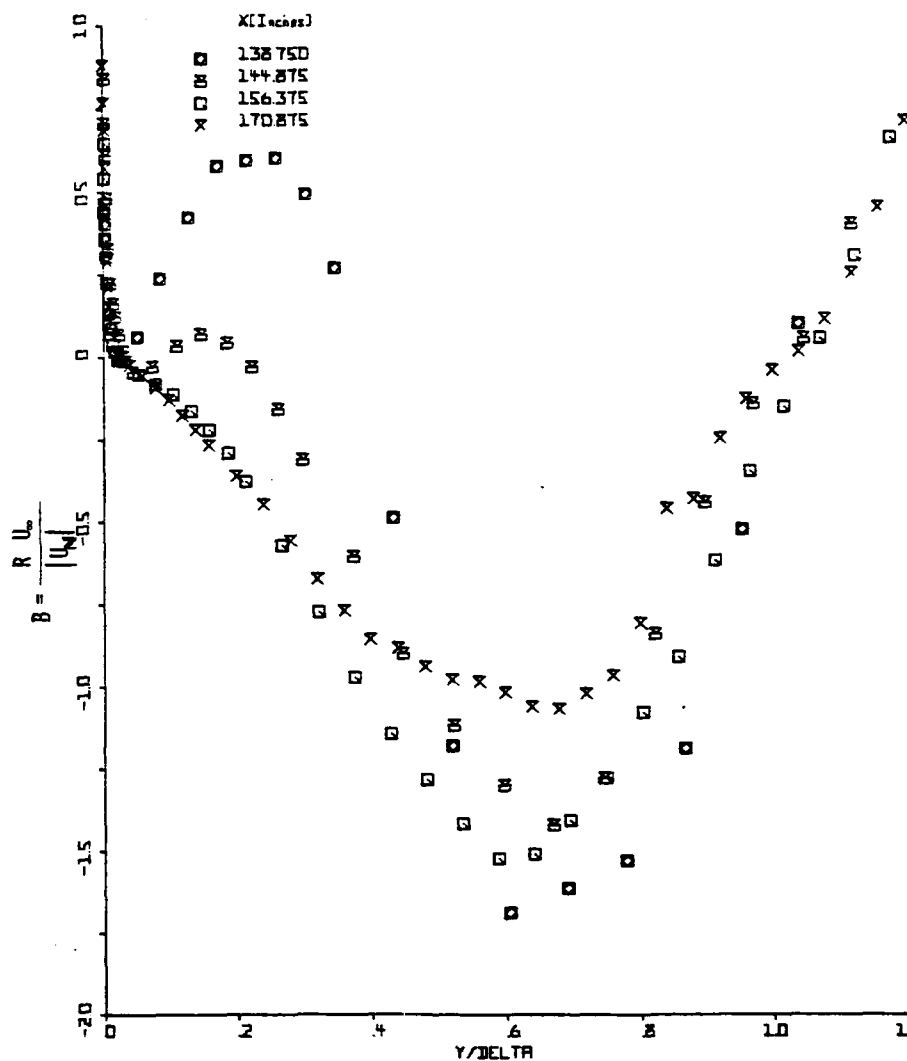


Figure 31. Normalized "backflow" function.

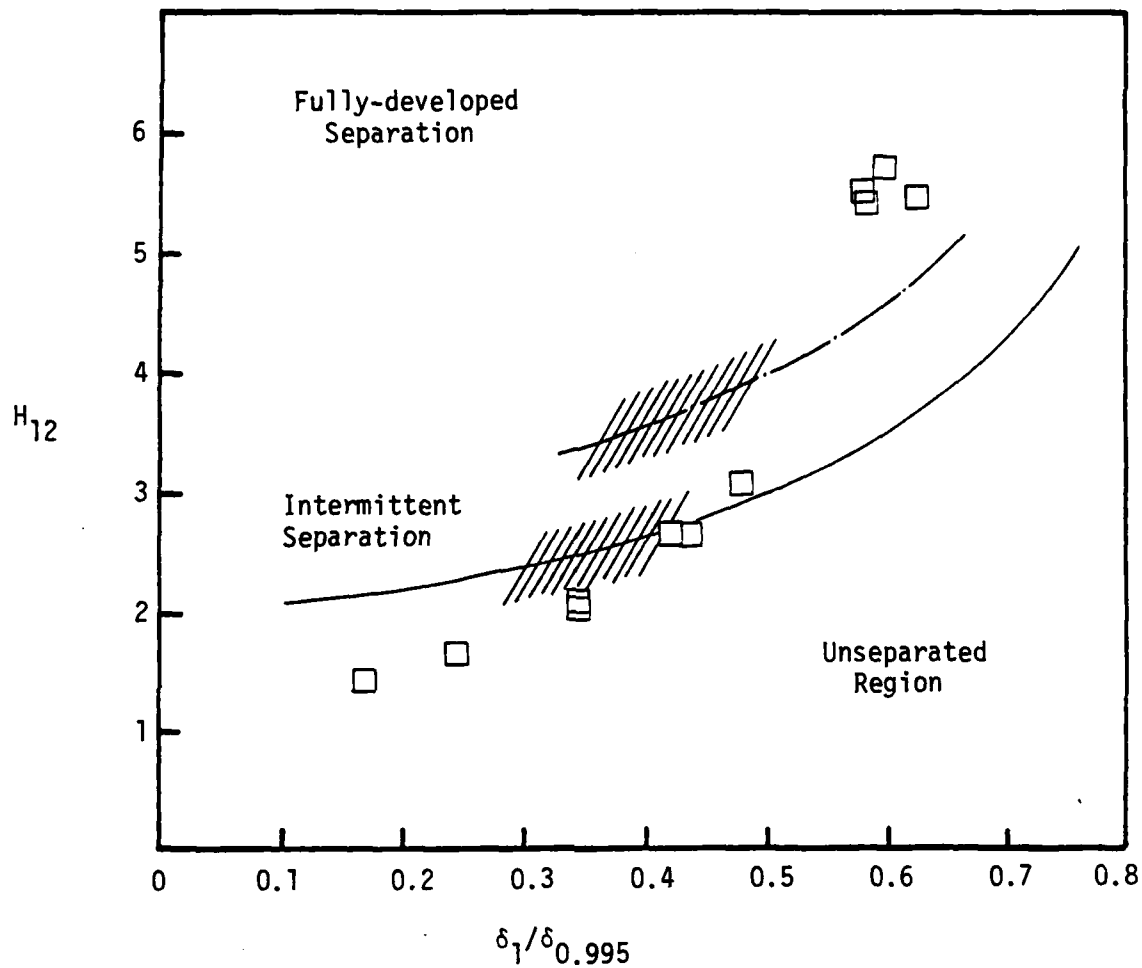


Figure 32. Sandborn's H_{12} vs. $\delta_1/\delta_{0.995}$ separation correlation: symbols, present data; solid line, intermittent separation; broken line, fully-developed separation.

"departure" or "breakaway" or the breakdown of boundary-layer flow. An abrupt thickening of the rotational flow region next to a wall and significant values of the normal-to-wall velocity component must accompany breakaway, else this region will not have any significant interaction with the freestream flow. A set of quantitative definitions were proposed and are shown on Figure 33 along with old definitions. Figure 23 shows the locations of incipient detachment, intermittent transitory detachment, and transitory detachment for the present flow obtained from Figure 20. In describing a quantitative amount of backflow, the word "detachment" was preferred over "separation" since the latter term refers to the entire phenomenon. Here we will continue to use the time-honored terminology, but mention the new terminology for the sake of completeness.

Downstream of intermittent separation, Simpson et al. (1977) showed the existence of similarity in γ_{pu} distributions by normalizing and plotting $\frac{(\gamma_{pu} - \gamma_{pu_0})}{(1 - \gamma_{pu_0})}$ vs. y/M where γ_{pu_0} was taken as the value near the wall as obtained from a figure similar to Figure 20 and M was the distance of the peak in the u' distribution from the wall. The present data also exhibit similarity, particularly in the region $0.1 \leq y/M \leq 1.0$, with it improving as one moves downstream. In fact the last two stations at 156.4 inches and 170.9 inches show the similarity to exist all across the boundary layer, including the backflow region. The similarity in the backflow region improves when the minimum value of γ_{pu} is used instead of γ_{pu_0} as shown in Figure 34. This is due to the relatively large uncertainty in γ_{pu_0} . Simpson et al. (1977) curve-fitted their data and gave an

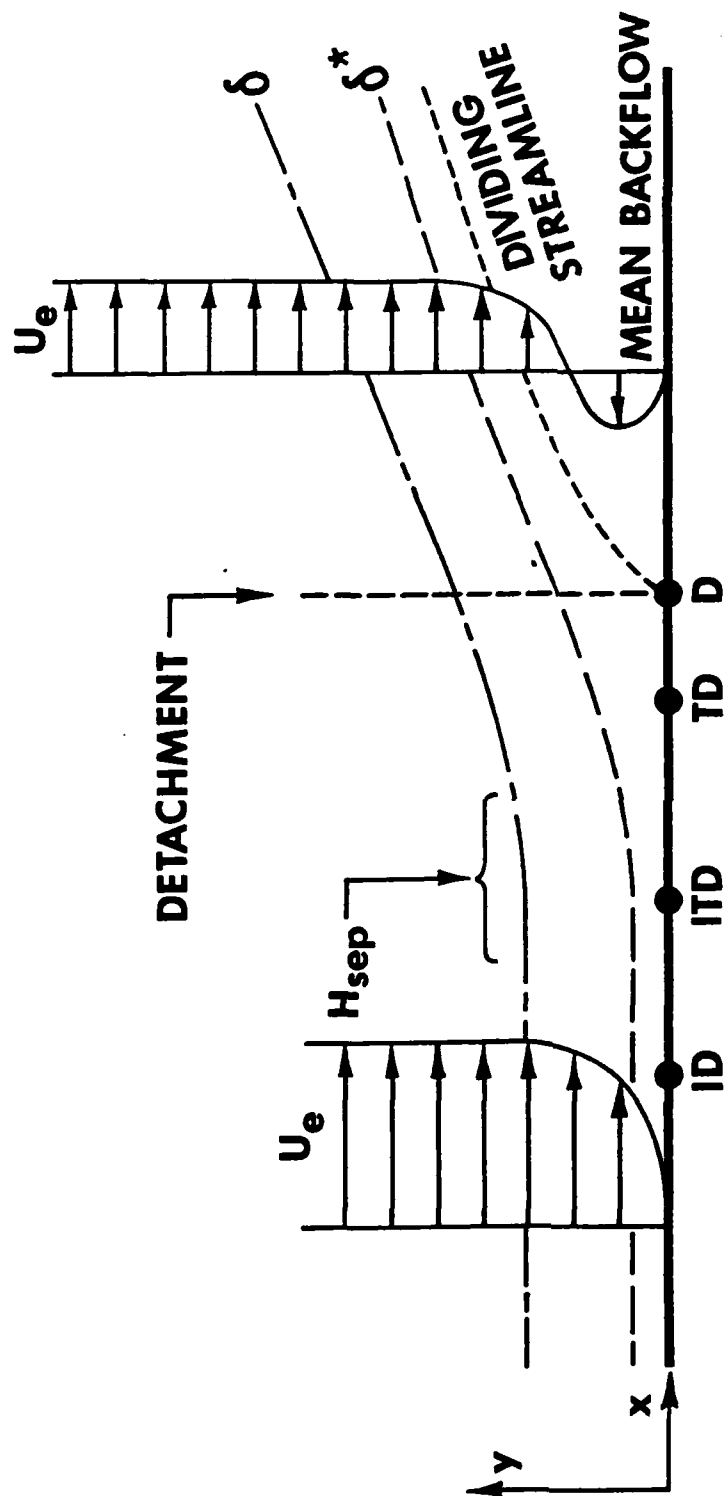


Figure 33. Definitions of two-dimensional turbulent detachment states. Distances not to scale. "% Instantaneous Backflow" means along a spanwise line at a given time, or percent of time at a point.

OLD TERM	SYMBOL	NEW TERM	CONDITION
none	ID	Incipient Detachment	1% Instantaneous Backflow
Intermittent Separation (Sandborn and Kline, 1961)	ITD	Intermittent Transitory Detachment	20% Instantaneous Backflow
none	TD	Transitory Detachment	50% Instantaneous Backflow
Steady or Fully-Developed Separation (Sandborn and Kline, 1961)	D	Detachment	$\frac{\tau_w}{\tau_w} = 0$

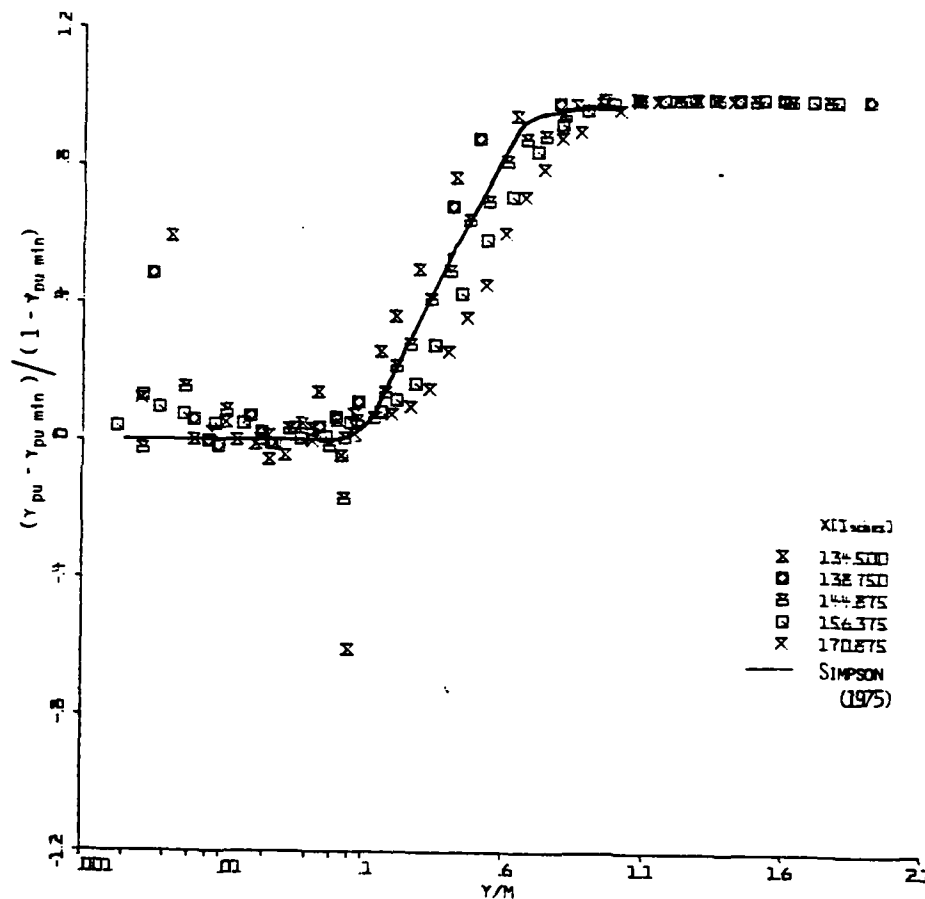


Figure 34. $(\gamma_{pu} - \gamma_{pu_{min}}) / (1 - \gamma_{pu_{min}})$ vs. y/M ; $\gamma_{pu_{min}}$ obtained from Figure 19; M is distance from wall to u'_{max} ; solid line, distribution from data of Simpson et al. (1977).

equation for the distribution in the region $0.1 \leq y/M \leq 1.0$. Figure 34 shows that the present data approximately satisfy the equation. Similar plots drawn with M being taken as the distance from the wall to the location where peaks were observed in the v' and $-\overline{uv}$ distributions show as good or better similarity, such as in Figure 35.

Figures 36 (a) and (b) show results for γ_{pv} or the fraction of time that the flow is away from the wall. Because the uncertainties in γ_{pv} are relatively large near the wall, $\gamma_{pv_{min}}$ was used in the normalized results shown in Figure 37 for the region downstream of intermittent separation. Near the outer edge of the boundary layer the intermittency is everywhere approximately equal to one, indicating that the flow is always directed outwards. Near the wall, the intermittency γ_{pv} obtained in the region downstream of intermittent separation is higher than the values attained upstream of it, which can be attributed to the flow leaving the wall as a consequence of intermittent separation. As in the case of γ_{pu} , the distributions near the wall are trough-shaped in the region downstream of intermittent separation and show some similarity.

V.3 Turbulence Correlations

A. Reynolds Stresses Correlations

Figures 38 show distributions of the shear stress correlation coefficient $-\overline{uv}/u'v'$, which is a measure of the extent of correlation between u and v fluctuations. Table 5 gives typical uncertainty values for the correlation coefficients presented here for the central portion of the boundary layer. Near the outer edge the values are larger since $-\overline{uv}$, u' and v' approach zero. Figure 38 (a) also shows distributions for the Schubauer and Klebanoff (1951)

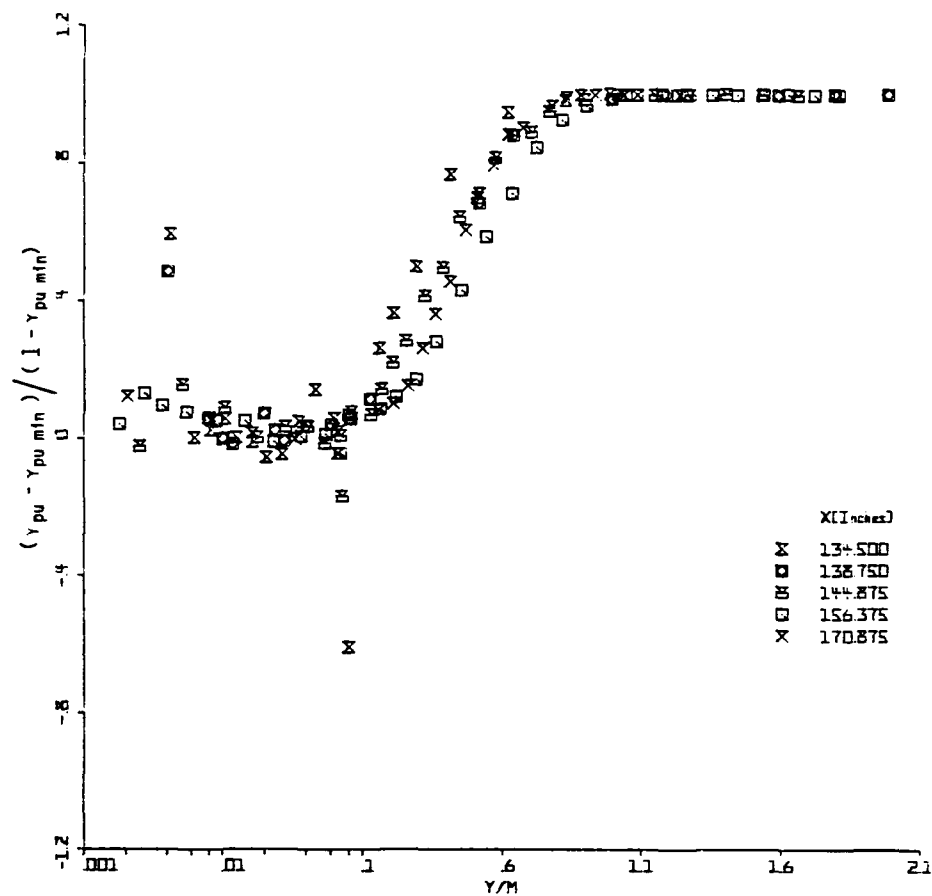


Figure 35. $(\gamma_{pu} - \gamma_{pu_{min}}) / (1 - \gamma_{pu_{min}})$ vs. y/M ; $\gamma_{pu_{min}}$ obtained from Figure 19; M is distance from wall to $-uv_{max}$.

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PURDUE UNIV LAFAYETTE IN PROJECT SQUID HEADQUARTERS
MEASUREMENTS OF A SEPARATING TURBULENT BOUNDARY LAYER. (U)

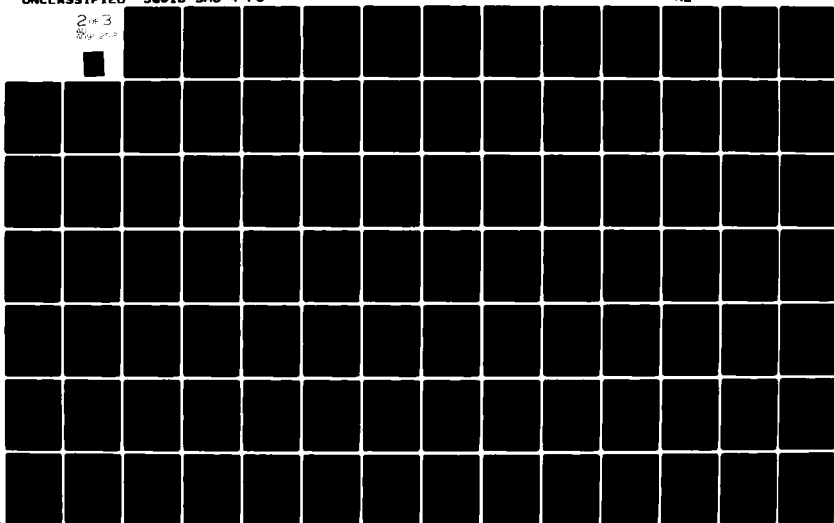
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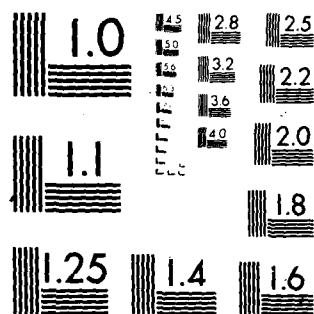
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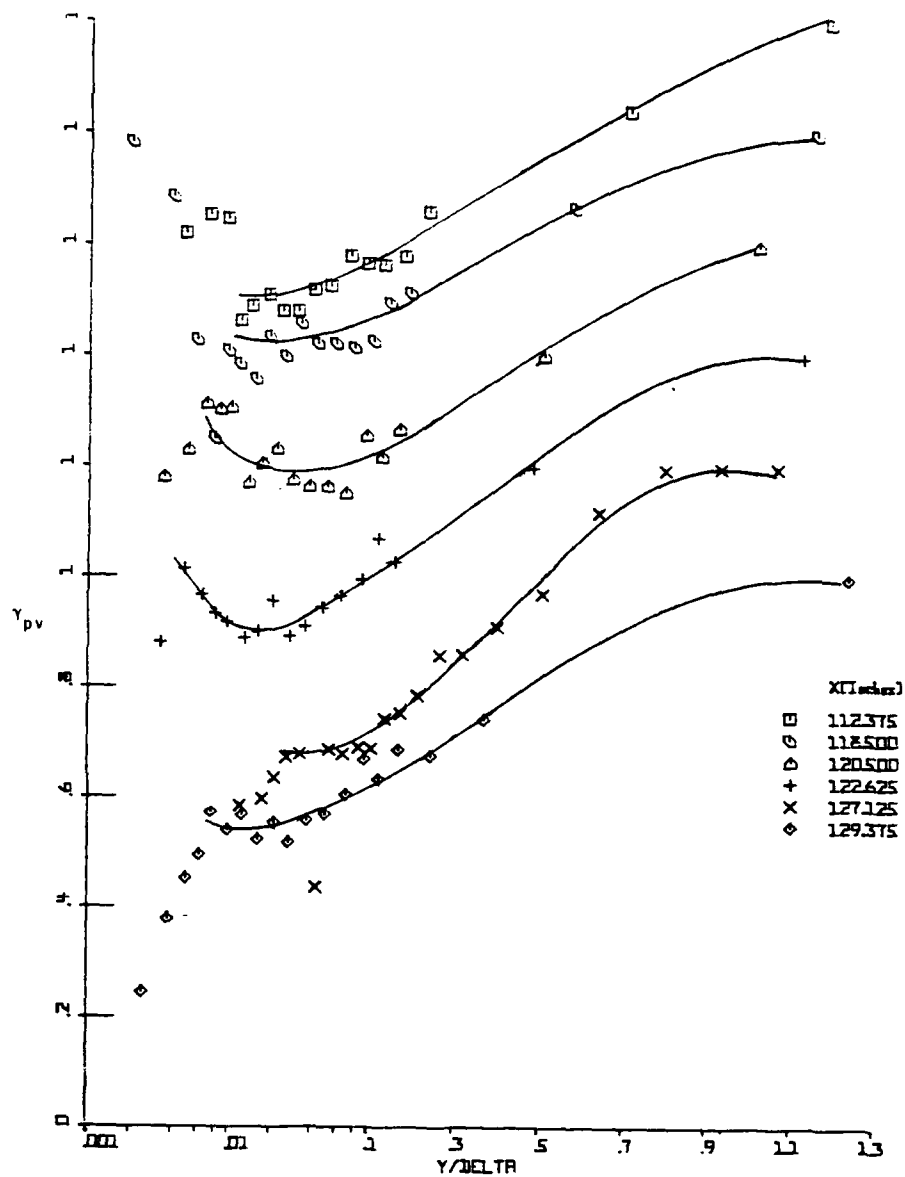


Figure 36(a). Fraction of time that the flow moves away from the wall, γ_{pv} vs. y/δ . Lines for visual aid only. Note displaced ordinates.

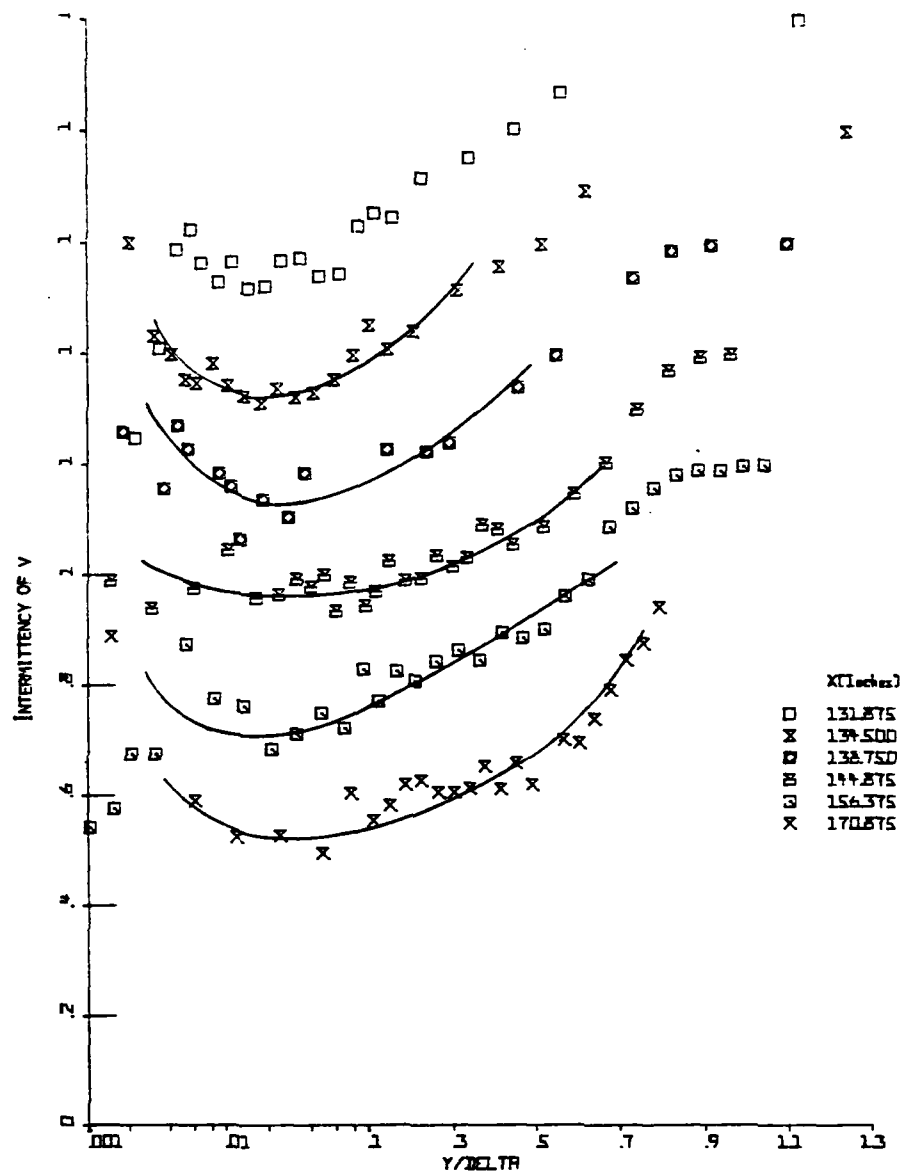


Figure 36(b). Fraction of time that the flow moves away from the wall, y_v vs. y/δ . Lines for visual aid only. Note displaced ordinates.

$$\ell = 0.4 y \left(1 - \exp(-y/A) \right), \quad A = \frac{26\nu}{U_{\tau} N}, \quad N = (1 - 11.8 p^+)^{\frac{1}{2}},$$

$$p^+ = \frac{\nu U_{\infty}}{U_{\tau}^3} \frac{dU_{\infty}}{dx} \quad (22)$$

for the 86.5 inches location. As recommended by Cebeci and Bradshaw (1977), a constant value of 0.08 is used for ℓ/δ in the outer region. The present data at 86.5 inches are in reasonable agreement with these results.

Although the downstream stations exhibit similarity in the inner layer, they show a continuously decreasing mixing length in the outer layer as one moves downstream. Further downstream in the intermittent separation region, the inner layer similarity gradually disappears and the mixing length in the outer layer continues to decrease with no region of constant mixing length. In the separated region, Prandtl's mixing length cannot be defined in the backflow region where $\frac{\partial U}{\partial y}$ is negative. The distributions for the forward flow region are shown in Figure 41 (d). They indicate large values of the mixing length closest to the wall where it can be defined, decreasing continuously as one moves farther away from the wall. There is also some indication of the profiles achieving similarity.

Figure 42 show the eddy viscosity profiles in the various regions. As in the case of the mixing length, a few sets of data from earlier investigations are also plotted for comparison. In general, the same comments made about the mixing length profiles are applicable to these profiles also. The present data in Figure 42 (a) show good agreement with Klebanoff's (1955) data in the zero pressure gradient region. The data in Figure 42 (b) show good agreement with Bradshaw's data in the adverse pressure gradient region in the inner layer. A prediction using Cebeci and Smith's model in the relation

$$\nu_e = \ell^2 \frac{\partial U}{\partial y} \quad (23)$$

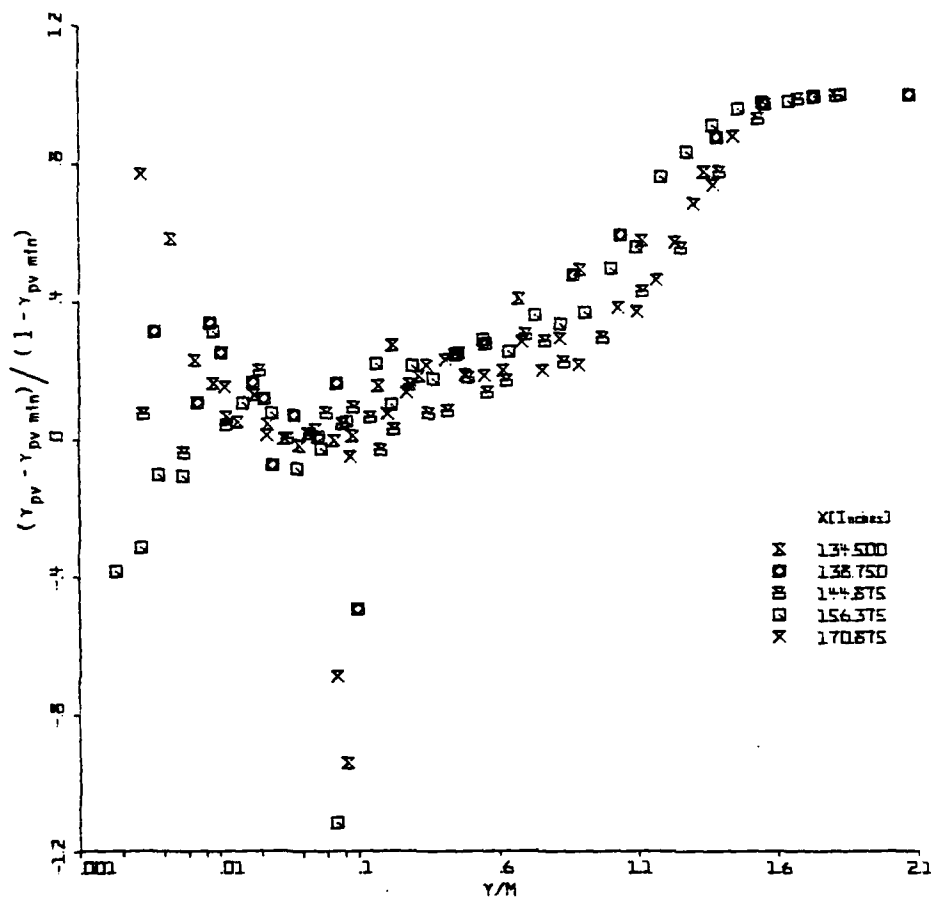


Figure 37. $(\gamma_{pv} - \gamma_{pv \min}) / (1 - \gamma_{pv \min})$ vs. y/M ; $\gamma_{pv \min}$ obtained from smoothed γ_{pv} data in Figure 36; $M = y$ at $v'_{\max}$.

TABLE 6: Typical Uncertainties for turbulence correlations

Location		Quantity	Type of Data	Absolute Value	Absolute Value of the uncertainty at the particular x-y location	Estimate of percentage uncertainty for the complete data set
X inches	Y inches					
112.375	0.5	$\frac{-\overline{uv}}{\overline{u'v'}}$	L.D.V.	0.462	0.031	6.6
111.25	0.6		x-wire	0.399	0.076	19
112.375	0.5	$\frac{-\overline{uv}}{(\overline{u'^2} + \overline{v'^2})}$	L.D.V.	0.204	0.014	6.8
111.25	0.6		x-wire	0.174	0.034	19.5
112.375	0.5	$\tan^{-1} \left(\frac{-2\overline{uv}}{\overline{u'^2} - \overline{v'^2}} \right)$	L.D.V.	40.9°	1.8°	4.4
111.25	0.6		x-wire	35.4°	6.5°	18.4
131.875	1.0	$\frac{-(\overline{u'^2} - \overline{v'^2})}{\overline{uv}} \frac{\partial u}{\partial x}$	Smoothed x-wire & L.D.V.	0.389	0.132	35
118.5	2.0	$\frac{\partial(\overline{u'^2} - \overline{v'^2})}{\partial x}$	Smoothed x-wire & L.D.V.	-0.411	0.314	Varies widely
131.875	2.5	$\frac{\partial(-\overline{uv})}{\partial y}$		-0.742	0.041	
131.875	1.5	$\frac{L_m}{\delta}$	L.D.V.	0.052	0.0056	12
86.5	0.354		x-wire	0.064	0.013	20
131.875	1.5	$\frac{v_s}{U_\infty}$	L.D.V.	0.006184	0.00074	15
86.5	0.354	$\frac{U_\infty}{U_\delta}$	x-wire	0.0133	0.0027	20

Table 6: Flow conditions for the present and previous investigations.

Parameter	streamwise location (in inches) for the present data			Data of other investigators					
				streamwise location (in ft) for Klebanoff's data	Bradshaw		East & Sawyer, flow 4	East & Sawyer, flow 1	
	86.5	105	117.6	17.5	22.5	a=-0.15	a=-0.255		
θ (Inches)	0.153	0.284	0.458					0.338	0.129
R_θ	5205	8617	11988	18750	41850	22900	38800		
H_{12}	1.418	1.625	2.024	1.35	1.6	1.4	1.54	1.344	1.31
$C_{f/2} \times 10^3$	1.33	0.859	0.422	1.73	0.935			1.1	0.0014
$E_p = - \left(\frac{H_{12}}{H_{12}^*} \right)^2 \left(\frac{\delta_1}{U_\infty} \frac{dU_\infty}{dx} \right)$	0.0109	0.0269	0.0271					0.0804	-0.0064
$B = \frac{\delta_1}{\tau_w} \frac{dP_w}{dx}$	-0.71	-4.64	-16.45	0	-4.57	-0.9	-5.57		

strong adverse gradient boundary layer. These two sets of measurements compare reasonably well, considering the fact that the adverse pressure gradient distributions are different. Table 6 shows a comparison of some parameters for the two flows.

Figure 38 (b) shows distributions in the vicinity of the beginning of intermittent backflow. Unlike the distributions far upstream shown in Figure 38 (a) or those observed in zero pressure gradient boundary layers, the distributions in this region do not exhibit a constant value over a large part of the outer layer. However, the distributions for some of the stations do indicate a small region with a nearly constant value as low as 0.2 to 0.3. As one moves downstream, the peaks for the distributions seem to gradually move towards the outer edge of the boundary layer. Similar features such as correlation coefficients as low as 0.3 with the peaks occurring near the outer edge of the boundary layer were observed by Spangenberg et al. (1967) in their experiments on an adverse pressure gradient flow approaching separation. Not much significance can be attached to the dips in the distributions observed near the wall except to hint that they might be a consequence of the peaks in the production curves occurring near the wall. Figure 38 (c) indicates that the profiles for the separated region seem to exhibit some similarity. These distributions compare fairly well in the outer region with the results of Wygnanski and Fielder (1970) for a mixing layer. Figure 39 gives the distributions of another type of correlation coefficient, $a_1 = \overline{-uv} / (u'^2 + v'^2)$, similar to the one used by Bradshaw et al. (1967) for converting the turbulent kinetic energy equation into an equation for shear stress. Using $w'^2 = \frac{1}{2} (u'^2 + v'^2)$, it is possible to relate a_1 to the more commonly used Bradshaw's constant 'a' defined as $a = \overline{-uv} / (u'^2 + v'^2 + w'^2)$ by the relation $a = 2/3a_1$.

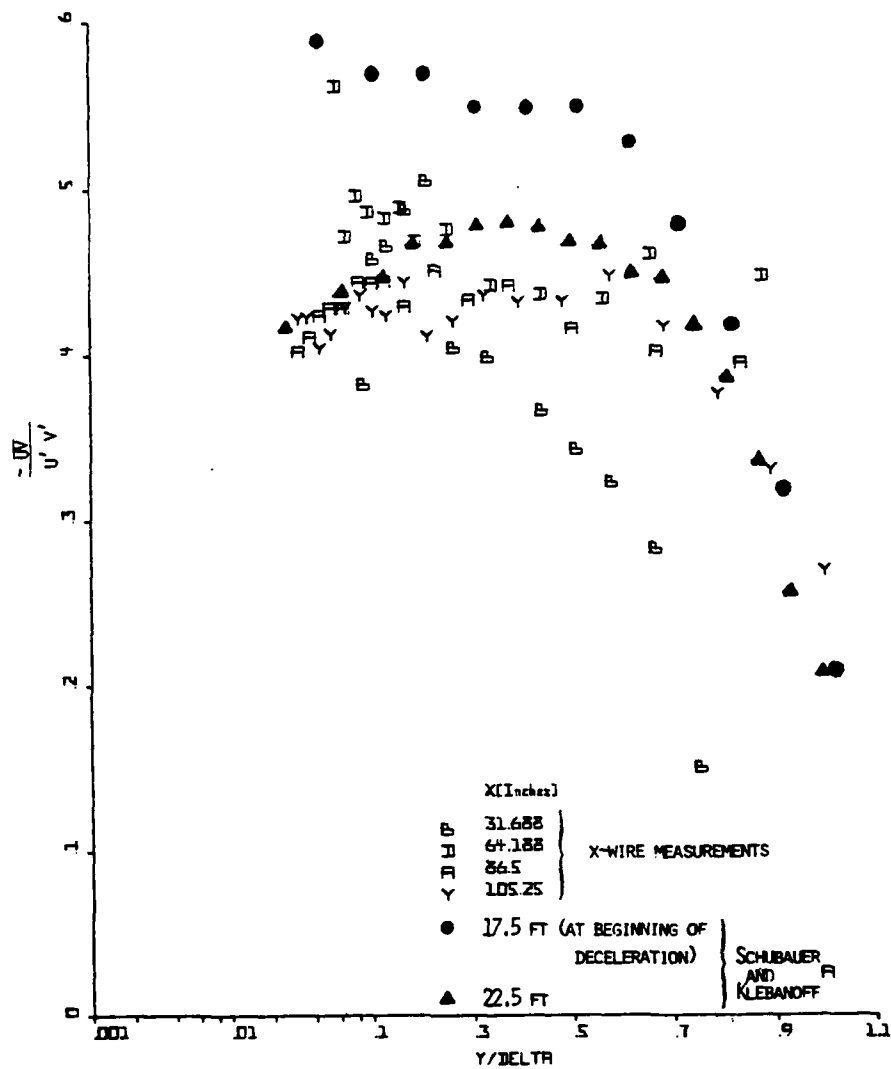


Figure 38(a). Shear stress correlation coefficient profiles from smoothed laser and hot-wire data, Figures 16, $-\frac{uv}{u'v'}$ vs. y/δ : upstream of separation.

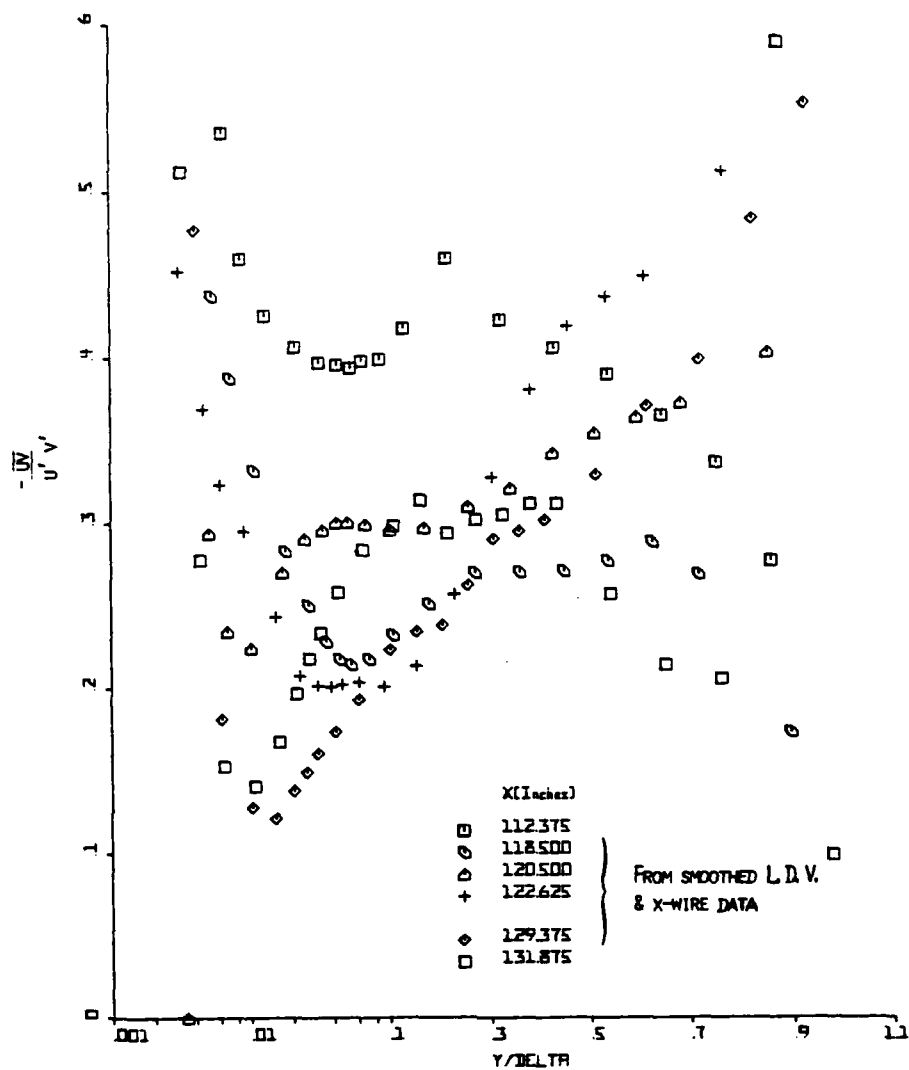


Figure 38(b). Shear stress correlation coefficient profiles from smoothed laser and hot-wire data, Figures 16, $-uv/u'v'$ vs. y/δ : in the vicinity of the beginning of intermittent backflow.

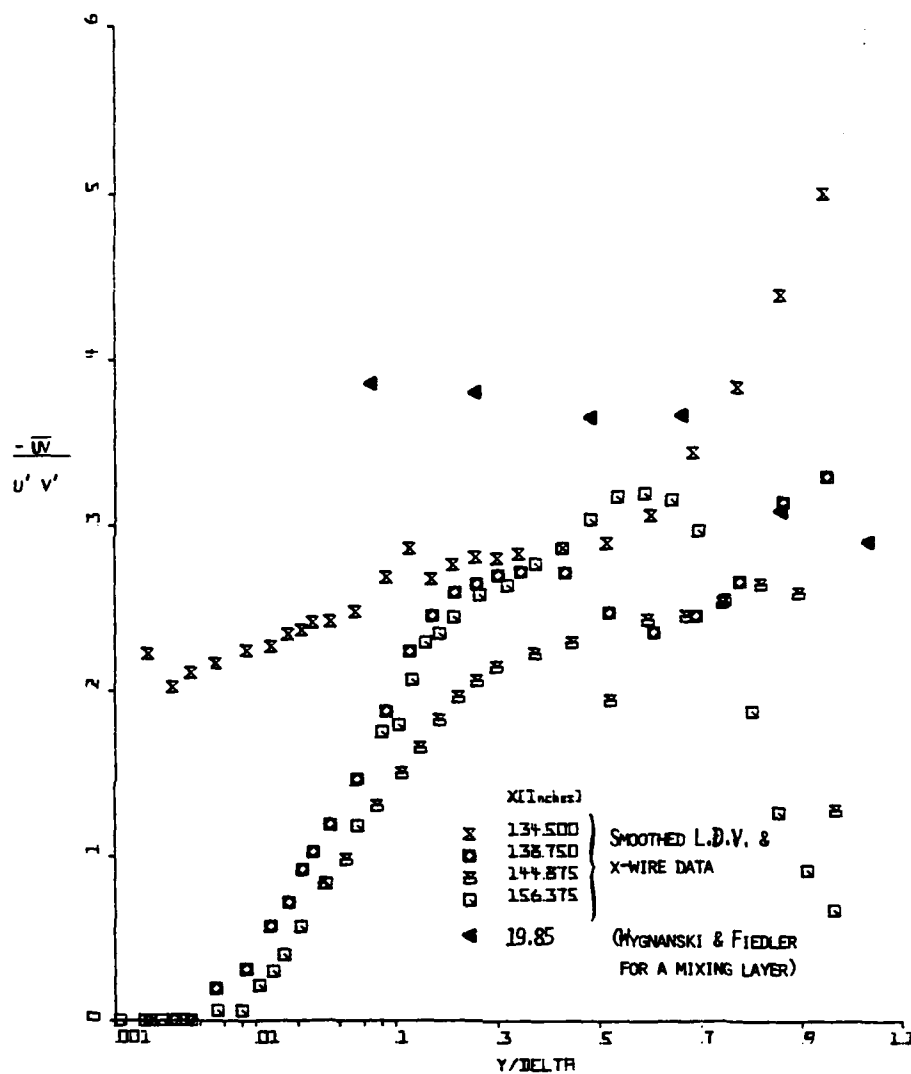


Figure 38(c). Shear stress correlation coefficient profiles from smoothed laser and hot-wire data, Figures 16, $-\overline{uv}/u'v'$ vs. y/δ : separated region.

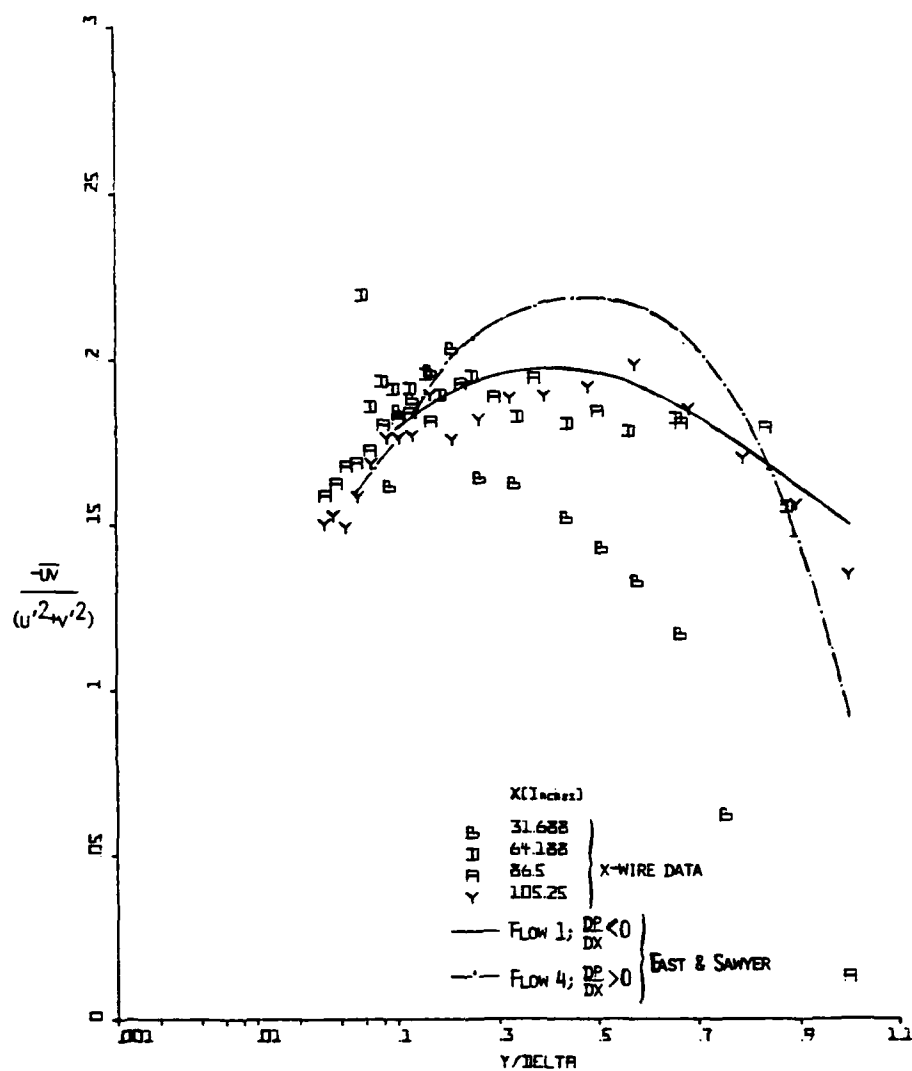


Figure 39(a). Shear stress correlation coefficient profiles from smoothed laser and hot-wire data, Figures 16, $-uv / (u'^2 + v'^2)$ vs. y/δ : upstream of separation.

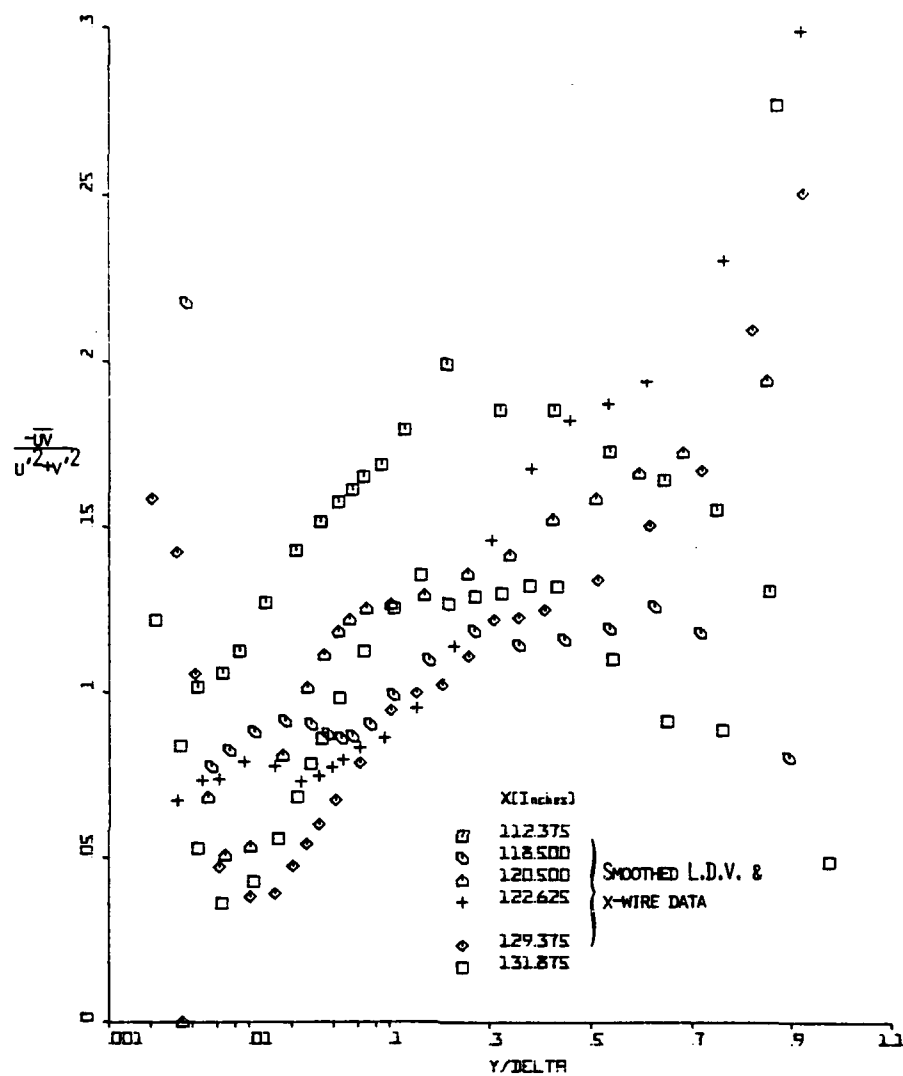
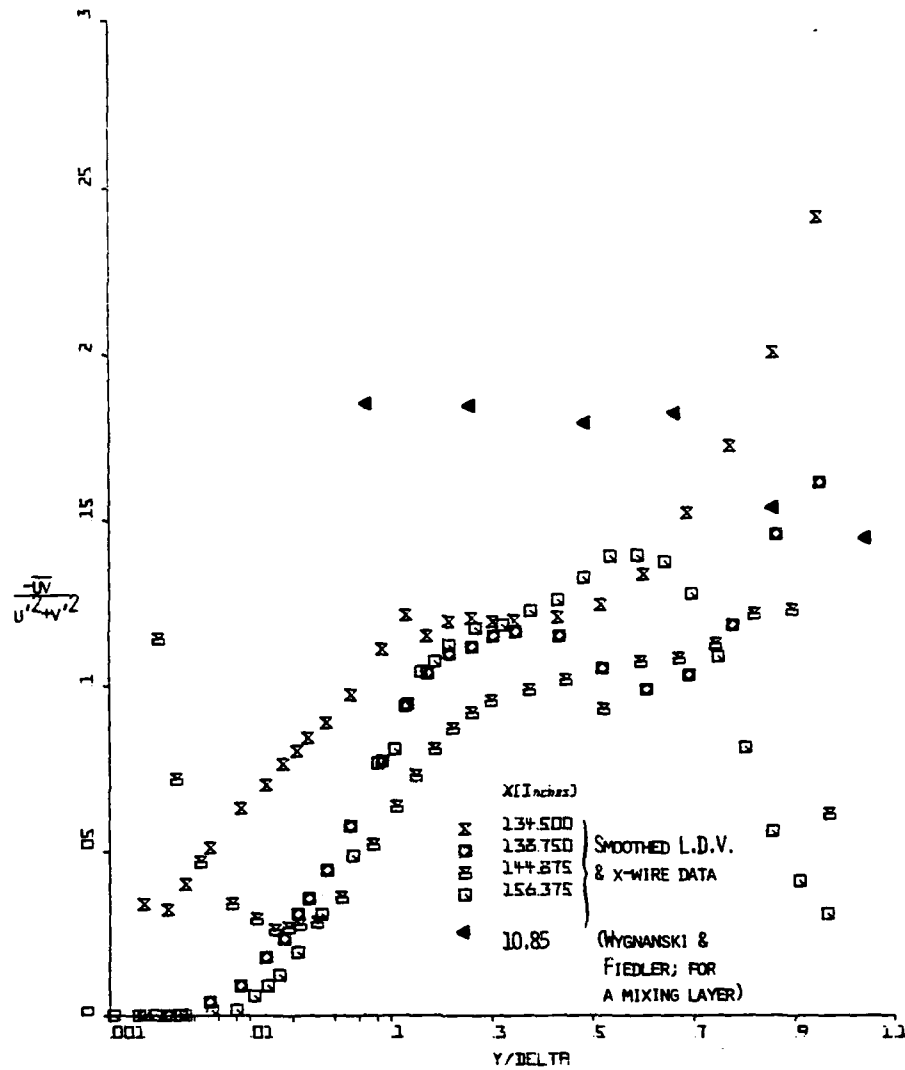


Figure 39(b). Shear stress correlation coefficient profiles from smoothed laser and hot-wire data, Figures 16, $-\overline{uv}/(u'^2 + v'^2)$ vs. y/δ : in the vicinity of the beginning of intermittent backflow.



Figures 39(c). Shear stress correlation coefficient profiles from smoothed laser and hot-wire data, Figures 16, $-\overline{uv}/(u'^2 + v'^2)$ vs. y/δ : separated region.

Figure 39 (a) also contains the data of East and Sawyer (1979) for favorable and adverse pressure gradient flows. The flow conditions for those cases are given in Table 6. Considering the wide variations in the flow conditions and the uncertainties in the measurements, the agreement seems to be reasonable, particularly for the adverse pressure gradient case. The variation in the behavior of the distributions as one moves downstream is similar to that for the shear correlation coefficient $-\overline{uv}/u'v'$, with an increasingly reduced flat region and a reduction in the value of a_1 to as low as 0.1 for the separated region.

Another quantity which can be derived from u' , v' and $-\overline{uv}$ is $\theta = \frac{1}{2} \tan^{-1} \left(\frac{-2\overline{uv}}{u'^2 - v'^2} \right)$, which gives the angle of inclination of the principal axis to the

flow direction. This has been plotted in Figures 40. Sandborn and Slogar (1955) observed that θ remains almost independent of x and y except for a small part of the inner layer. They also noticed that in the inner layer the angle θ decreases rapidly as the wall is approached, thus tending to align the axis of the principal stress with the flow direction. Considering the uncertainties in θ , particularly near the outer edge where all the quantities u' , v' and $-\overline{uv} \rightarrow 0$, the present data seem to indicate those same trends, at least for the stations downstream of 86.5 inches and up to the beginning of the intermittent separation. In the intermittent separation region, only some of the stations indicate a weak dependence with respect to y in the outer layer. In the fully-separated region there is an indication of the profiles tending to become similar. The angle in the flat region decreases from approximately 18° at 86.5 inches to 12° in the separated region.

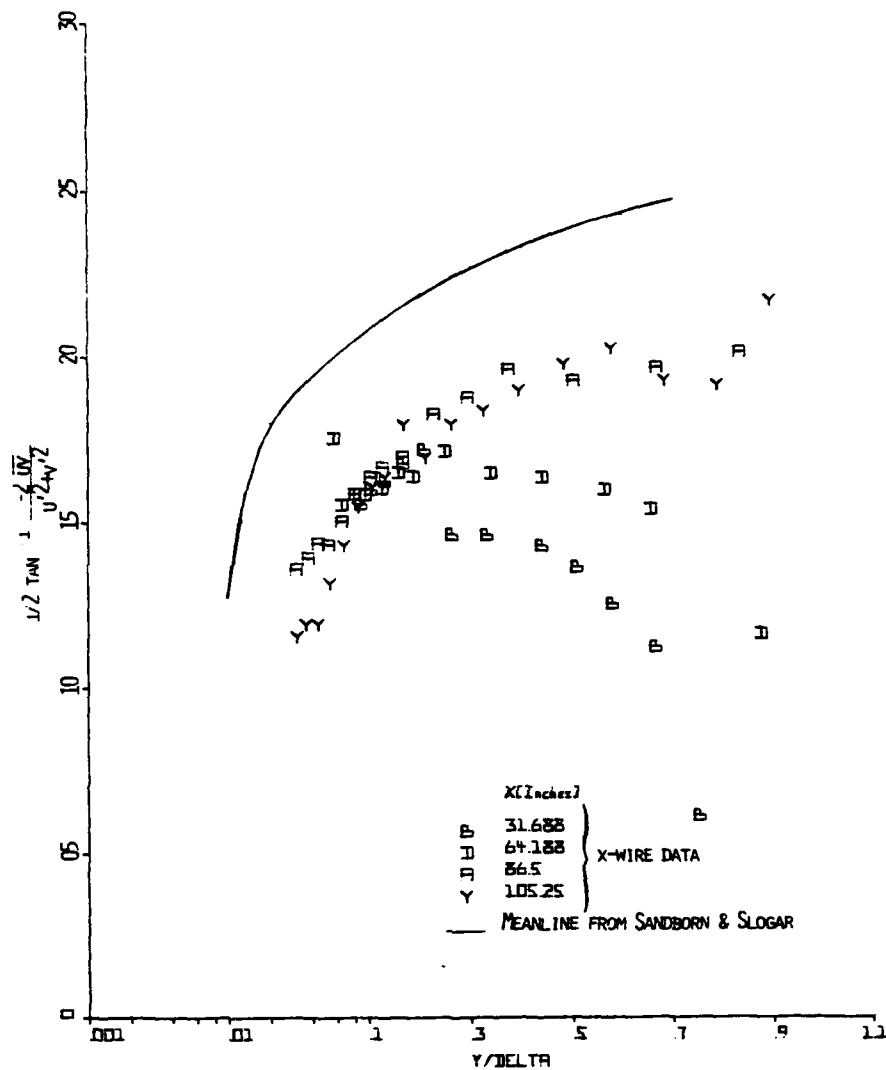


Figure 40(a). Angle of principal axis of stress to the flow direction, $\theta = 1/2 \tan^{-1}(-2\overline{uv}/(\overline{u'^2} - \overline{v'^2}))$ vs. y/δ . Solid line is mean line from Sandborn and Slogar (1955).

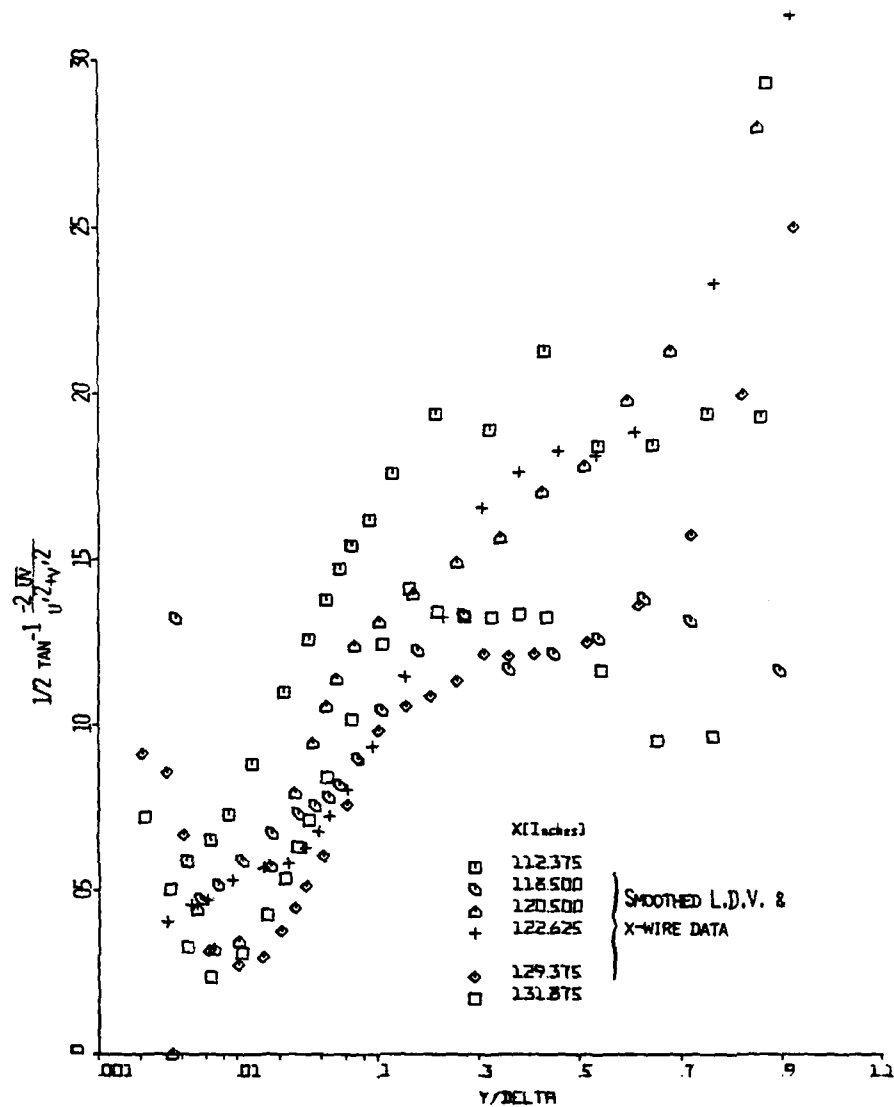


Figure 40(b). Angle of principal axis of stress to the flow direction, $\theta = \frac{1}{2} \tan^{-1} \left(\frac{-2\overline{uv}}{u'^2 - v'^2} \right)$ vs. y/δ . Solid line is mean line from Sandborn and Slogar (1955).

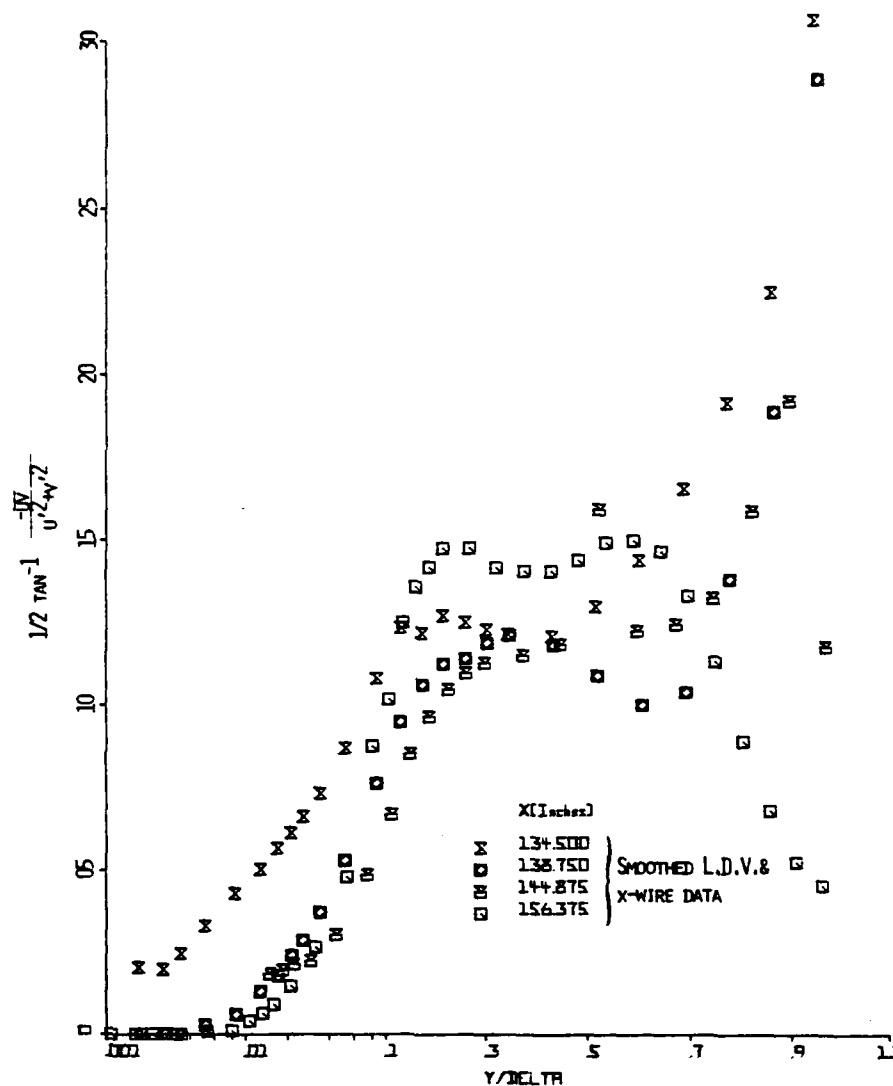


Figure 40(c). Angle of principal axis to the flow direction, $\theta = \frac{1}{2} \tan^{-1} \left(\frac{-2\overline{uv}}{u'^2 - v'^2} \right)$ vs. y/δ . Solid line is mean line from Sandborn and Slogar (1955).

B. Eddy viscosity and Prandtl mixing length distributions

The Prandtl mixing length

$$\frac{\ell}{\delta} = \frac{-\overline{uv}}{\delta} \left| \frac{\partial U}{\partial y} \right|^{-1} \left(\frac{\partial U}{\partial y} \right)^{-1} \quad (20)$$

and the eddy viscosity

$$\frac{\nu_e}{U_\infty \delta_1} = \frac{-\overline{uv}}{U_\infty \delta_1 \partial U / \partial y} \quad (21)$$

were calculated from measured Reynolds shearing stress and calculated velocity gradient distributions. Figure 41 (a) shows the mixing length results for the region up to the throat of the test section where the pressure gradient is either favorable or approximately zero. The data of Klebanoff (1955) for a zero pressure gradient boundary layer and that of East and Sawyer (1979) for zero and favorable pressure gradient boundary layers are also presented for comparison. The present data at 64.2 inches show good agreement within the limits of uncertainty with the zero pressure gradient data of the earlier investigators. The data at 31.25 inches show agreement only in the inner layer with the favorable pressure gradient data of East and Sawyer. One possible reason for this might be the close proximity of that station to the entrance region of the test section.

Figure 41 (b) covers the adverse pressure gradient region of the flow up to the start of the intermittent separation. The data of Bradshaw (1967) for adverse pressure gradient equilibrium boundary layers and East and Sawyer (1979) are presented for comparison. Also shown is Cebeci and Smith's (1974) extension of van Driest's mixing length model for the inner layer

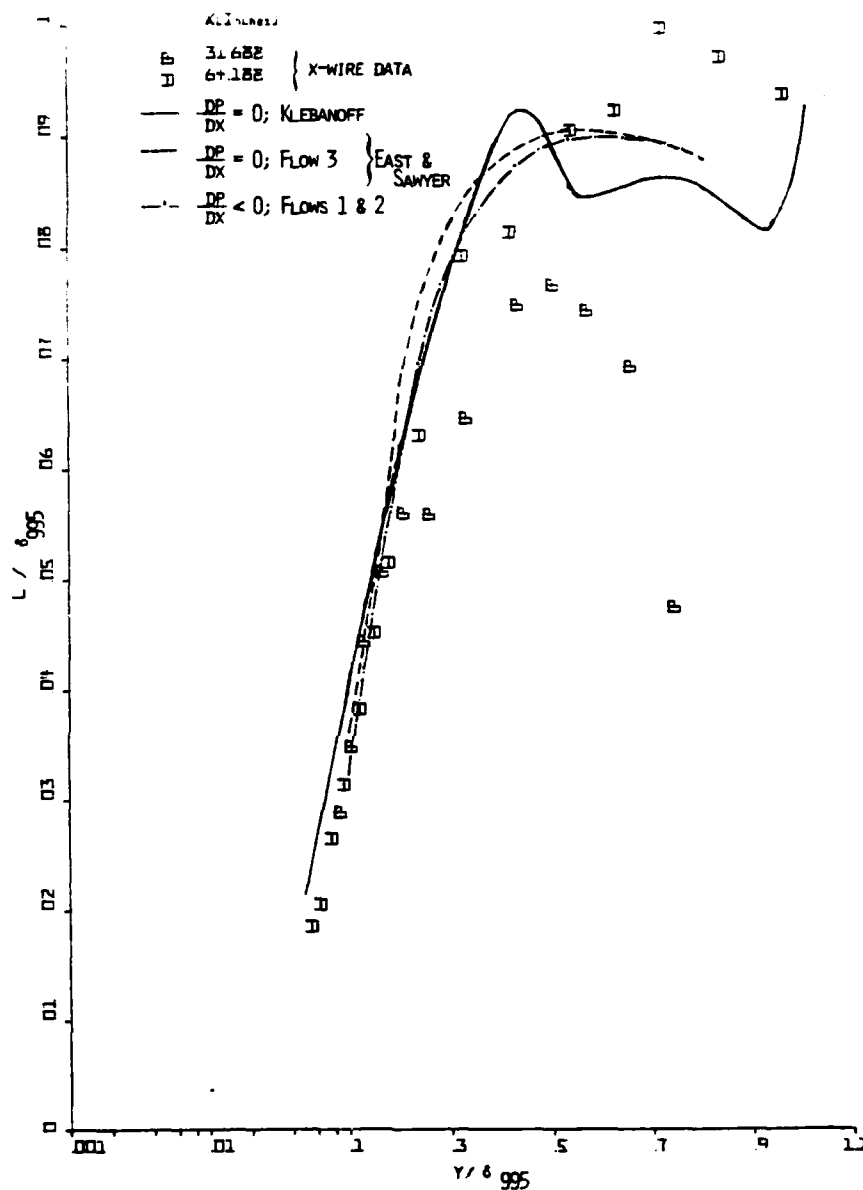
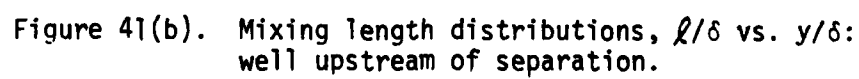


Figure 41(a). Mixing length distributions, l/δ vs. y/δ : well upstream of separation.



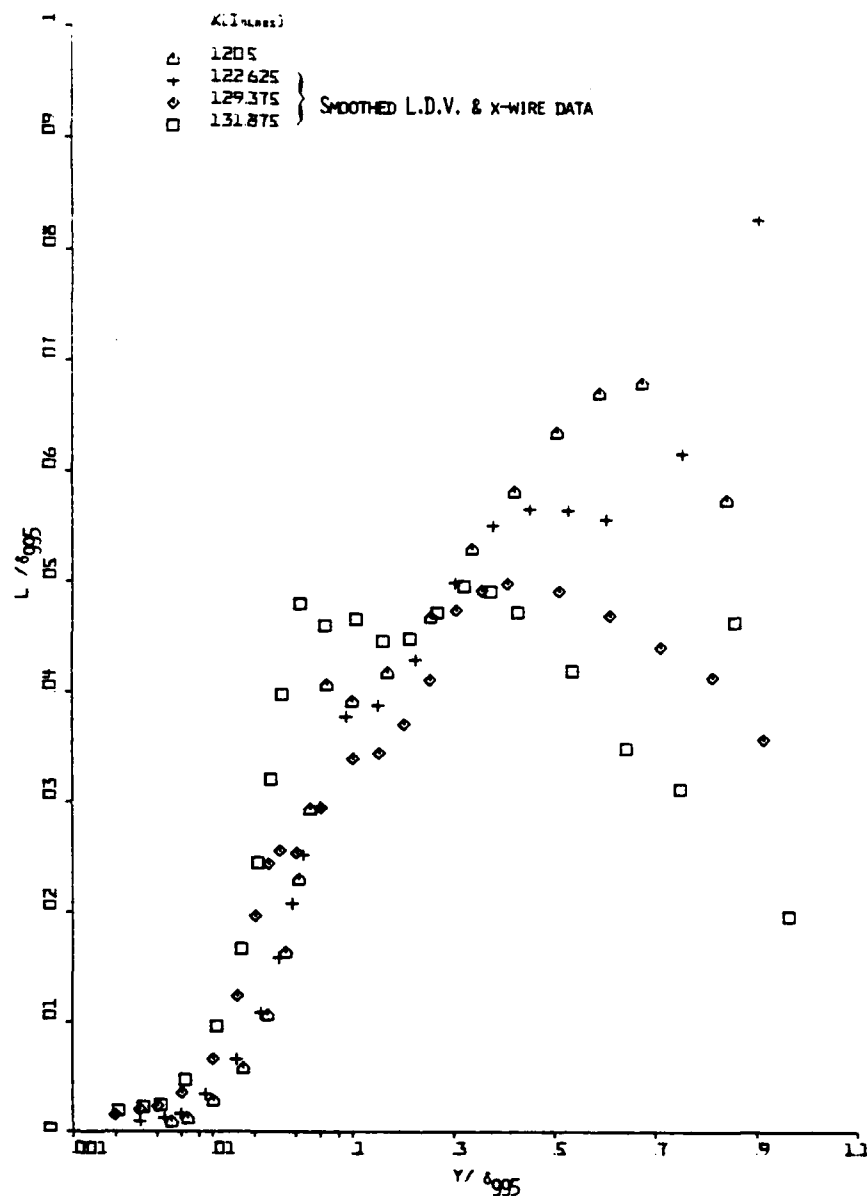


Figure 41(c). Mixing length distributions, L/δ vs. y/δ : in the vicinity of separation.

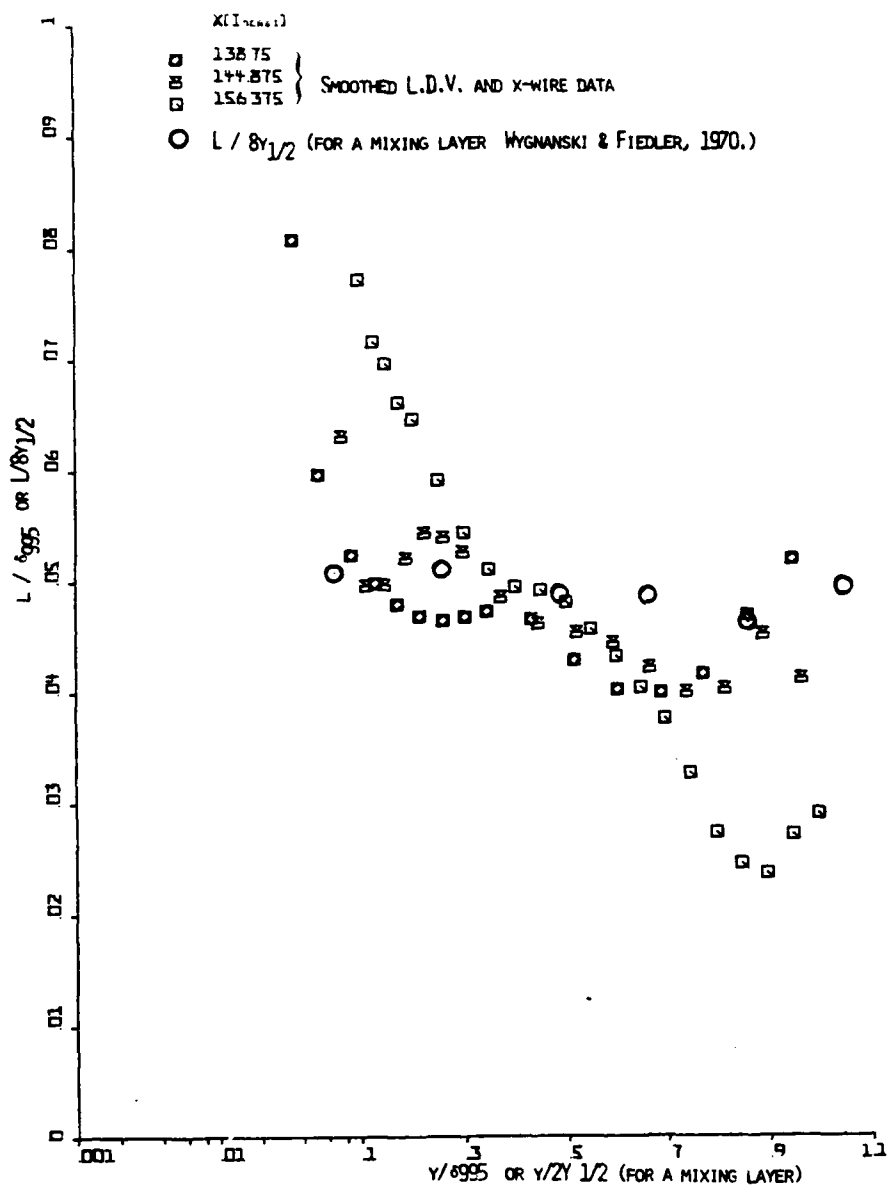


Figure 41(d). Mixing length distributions, l/δ vs. y/δ : downstream of separation.

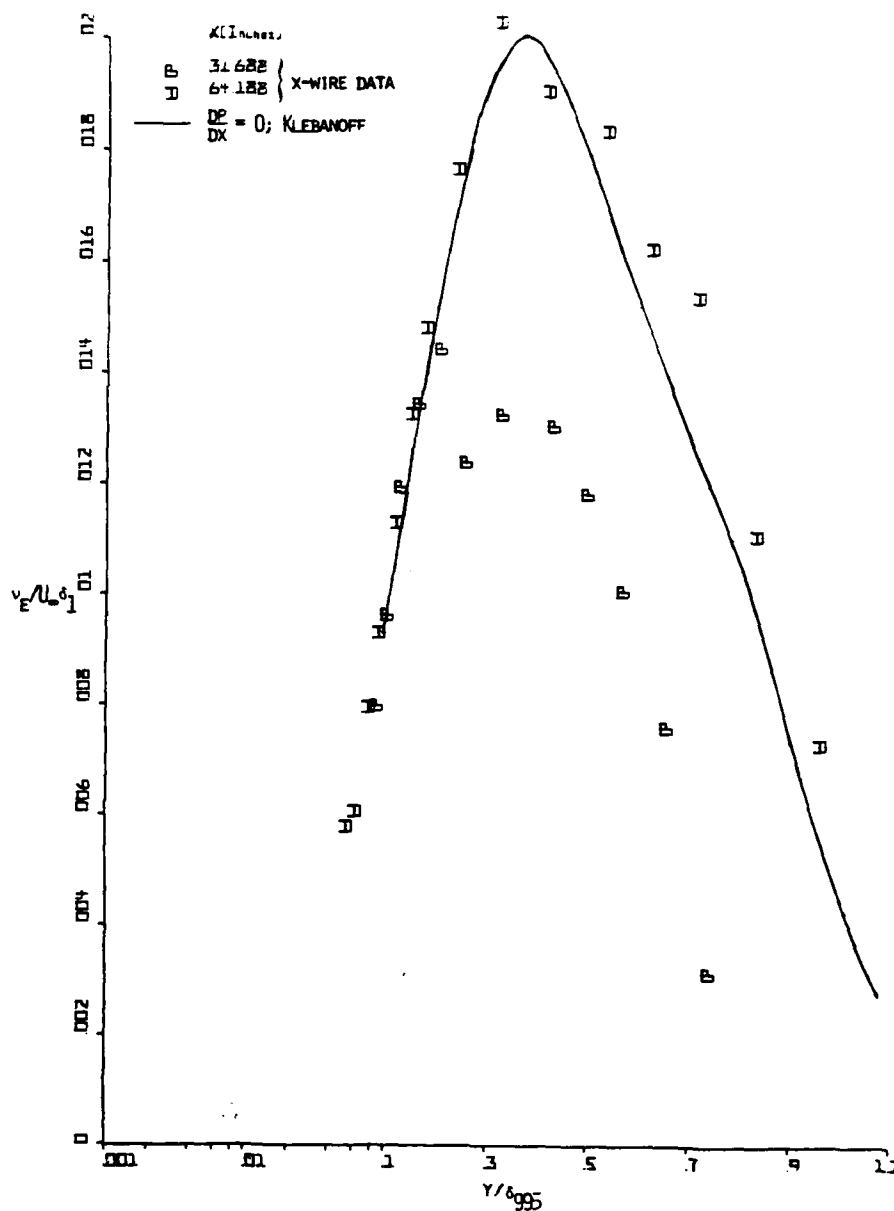


Figure 42(a). Eddy viscosity distributions, $v_e / U_\infty \delta_1$ vs. y / δ : well upstream of separation.

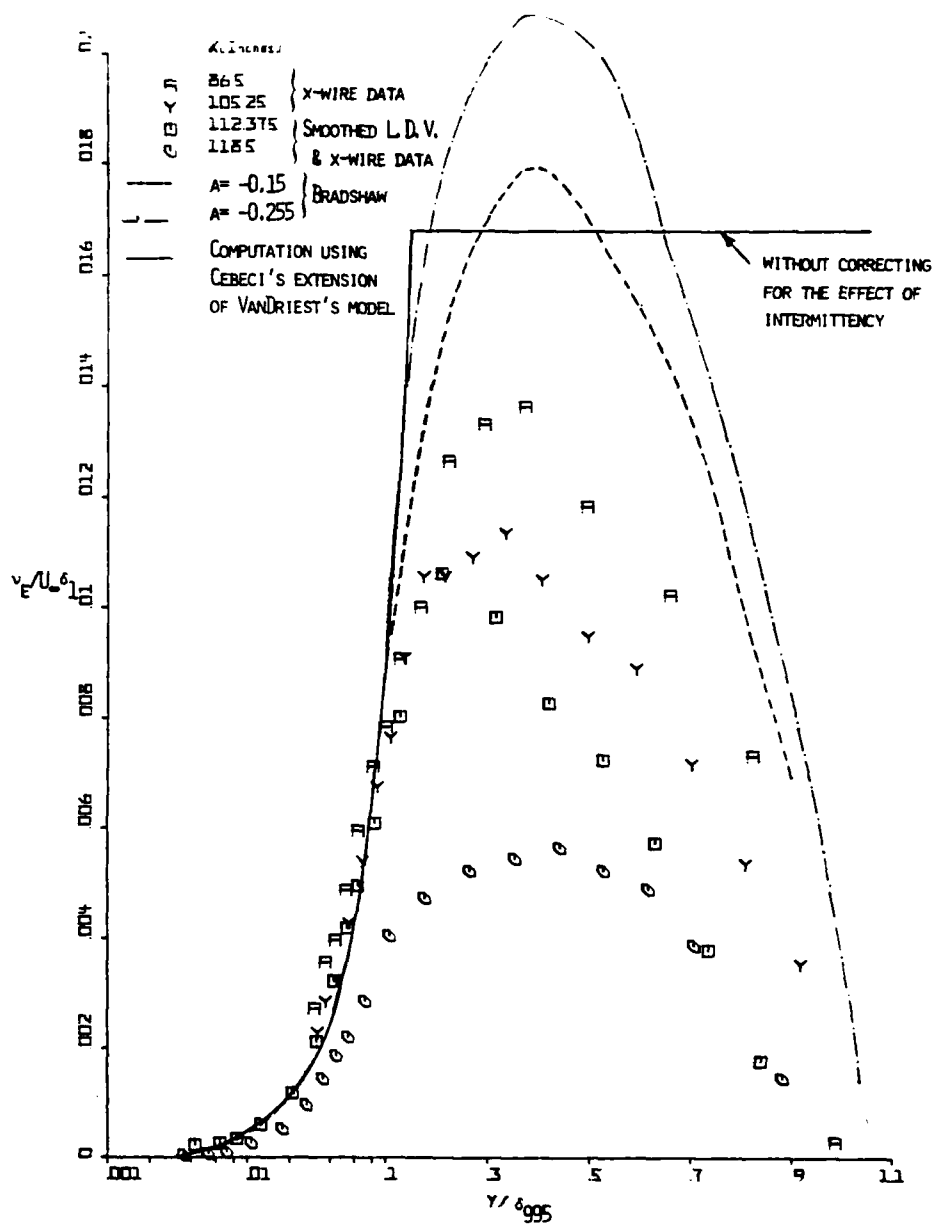


Figure 42(b). Eddy viscosity distributions, $v_e / U_\infty \delta_1$: well upstream of separation.

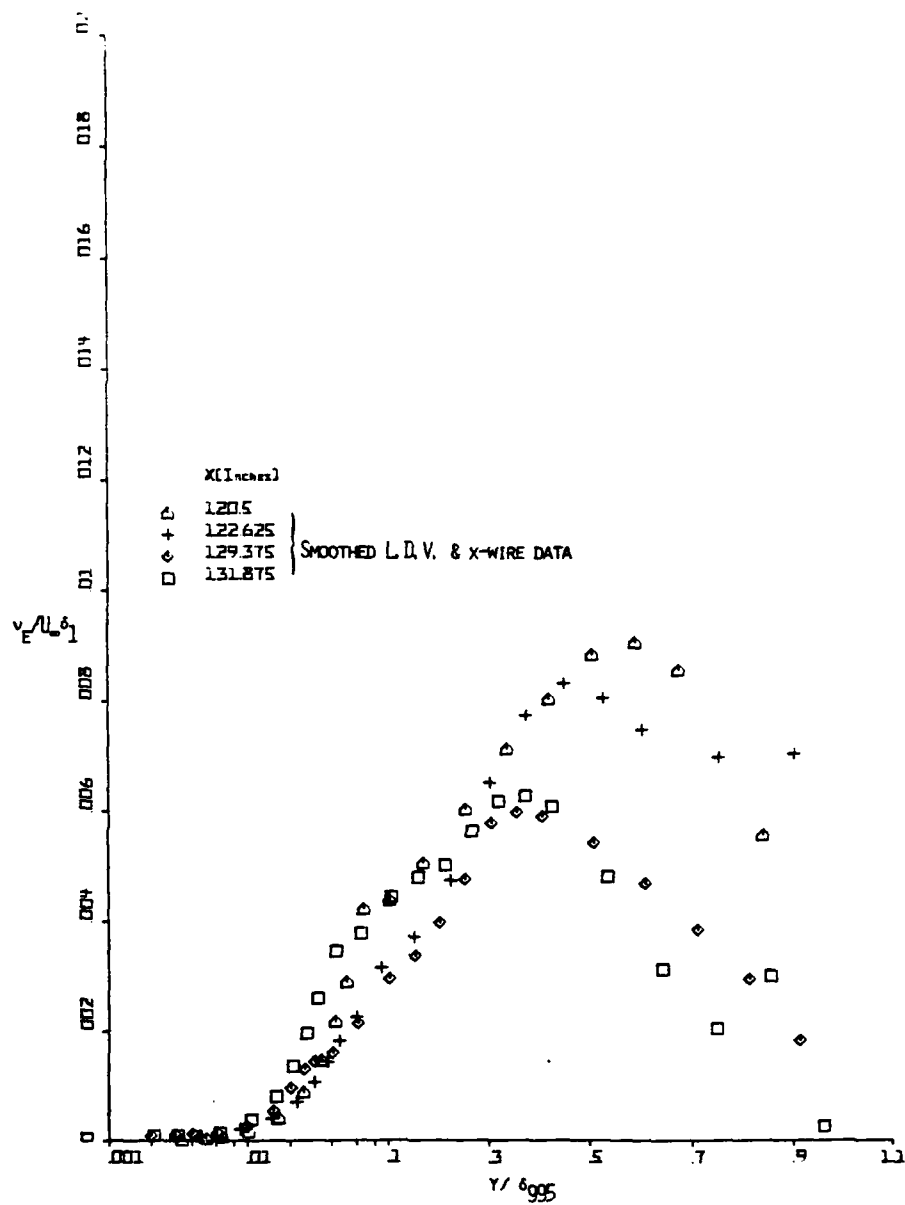


Figure 42(c). Eddy viscosity distributions, $\nu_e / U_\infty \delta_1$ vs. y / δ : in the vicinity of separation.

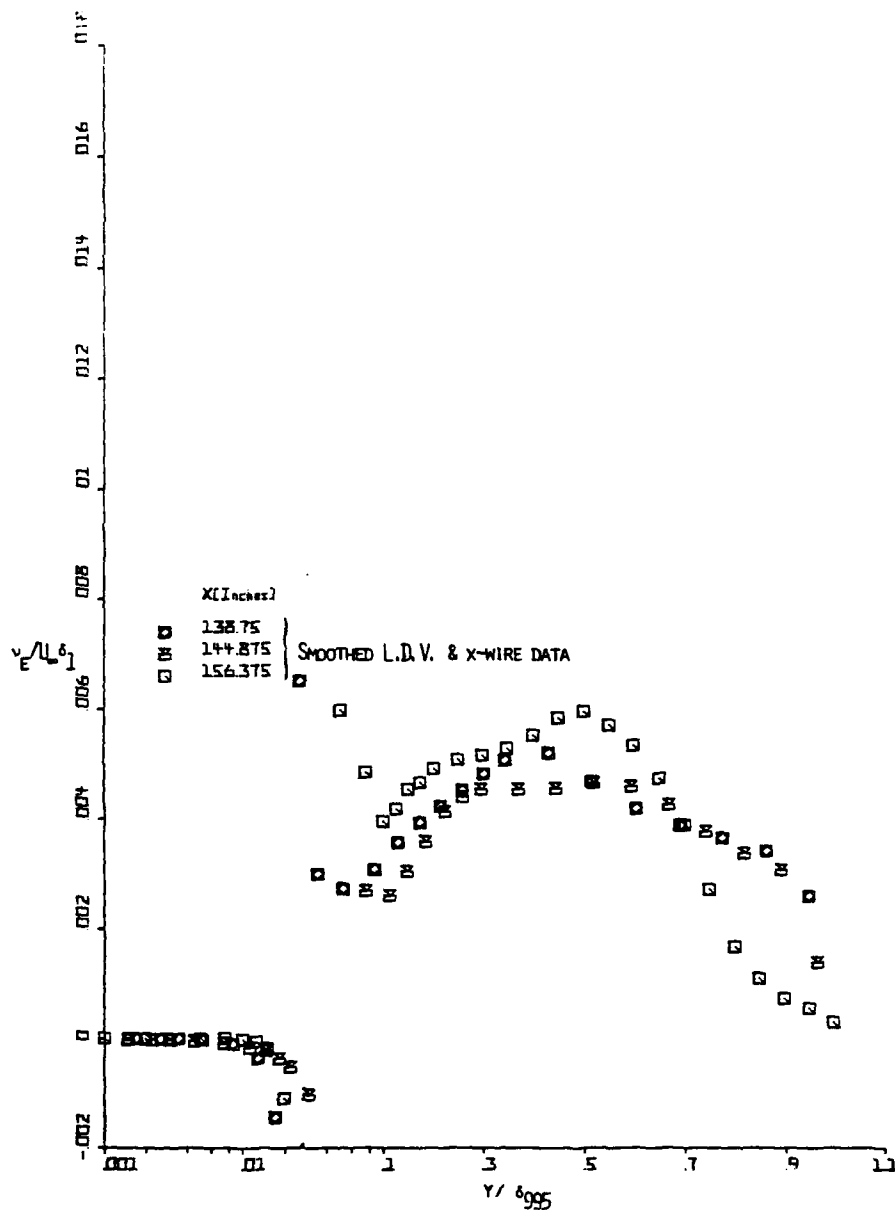


Figure 42(d). Eddy viscosity distributions, $\nu_e / U_\infty \delta_1$ vs. y / δ : downstream of separation.

Table 7: The ratio of $U_{\tau} \delta_{99}$ for successive locations

Streamwise location in inches	$U_{\tau} \delta_{99}$ ft. ² /sec.	Ratio of $U_{\tau} \delta_{99}$ for successive stations
86.5	0.255	1.066 1.058 0.909
105.3	0.272	
112.4	0.288	
118.5	0.262	

is in reasonable agreement with the inner layer data at 86.5 inches.

At first it is a little surprising that there is similarity in the inner layer mixing length distributions and similarity in the inner layer eddy viscosity distributions near separation when δ is used for scaling y . However, as shown in Table 7 the ratio of $U_\tau \delta$ at successive stations is near unity in this region, so $y^+/(y/\delta)$ is the same for successive stations and the profiles near the wall are similar with respect to y^+ as well. In the intermittent separation region, the inner layer similarity disappears and the eddy viscosity decreases with respect to x in the outer layer. In the separated region, v_e can be defined everywhere except where $\partial U/\partial y = 0$. Eddy viscosity profiles also show some similarity in the outer layer as well as near the wall in the separated region.

For both mixing length and eddy viscosity, the data in the vicinity of separation indicate much lower values in the outer region than for attached boundary layers. As shown below in section V.5, normal stresses effects can be used to explain this behavior.

c. Skewness and flatness factor distributions

Some measurements of skewness and flatness factors of the u and v fluctuations have been done in zero pressure gradient boundary layers and in channel flows by Dumas (1966), Zaric (1972), Kreplin (1973), Antonia (1973) and Ueda and Hinze (1975). Only Sandborn (1959) is known to have made measurements of the flatness factor in an adverse pressure gradient boundary layer flow in the vicinity of separation.

Figures 43 (a) and 44 (a) show a comparison of the present laser anemometer data for F_u and F_v with the zero pressure gradient boundary layer data of Antonia (1973). The good agreement observed between the two sets of data in the logarithmic

- SANDBORN; TURBULENT BOUNDARY LAYER IN THE VICINITY OF SEPARATION; $R_{\delta_2} = 5687$
- ▲ ANTONIA; TURBULENT BOUNDARY LAYER; $R_{\delta_2} = 31000$
- ▼ DUMAS; TURBULENT BOUNDARY LAYER; $R_{\delta_2} = 32500$

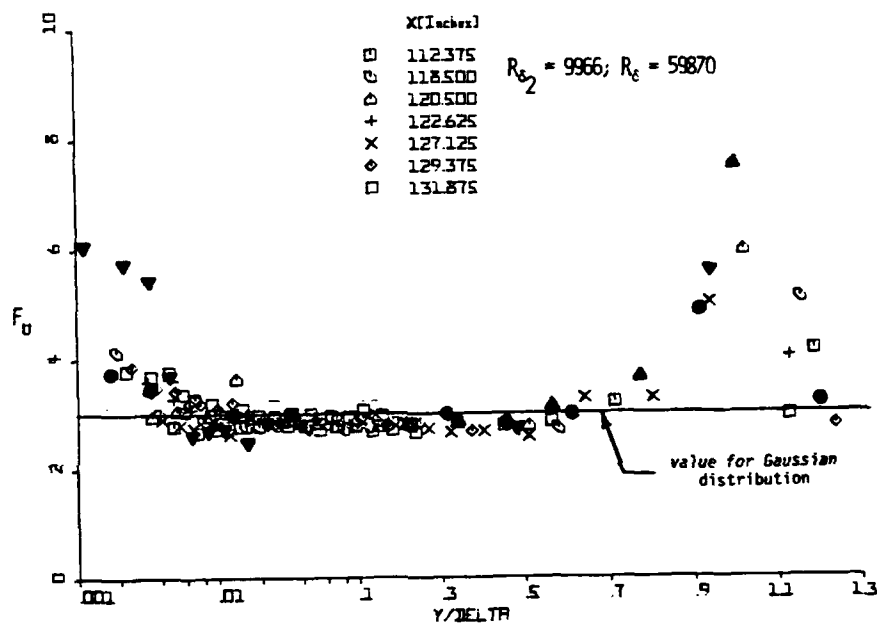


Figure 43(a). Flatness factor F_u profiles: upstream results.

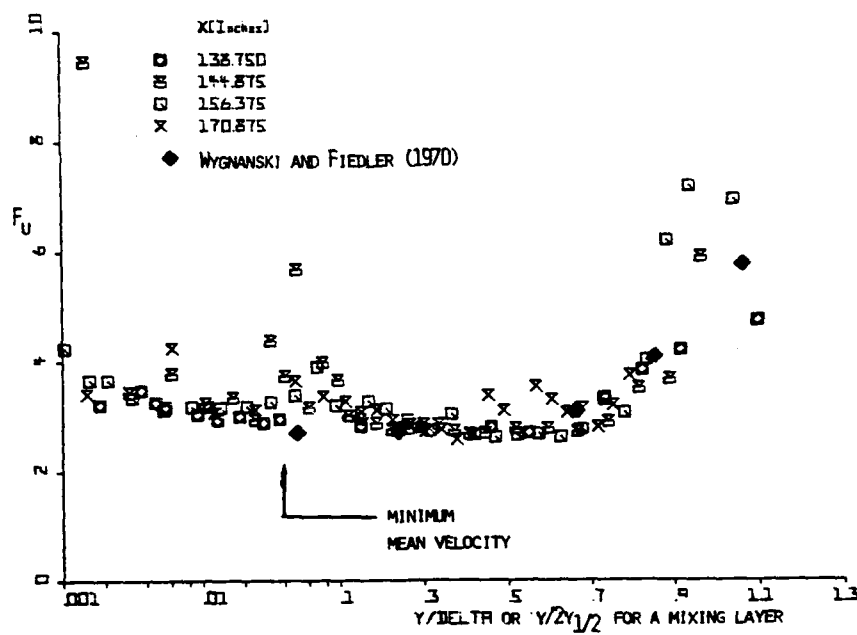


Figure 43(b). Flatness factor F_u profiles: downstream of separation.

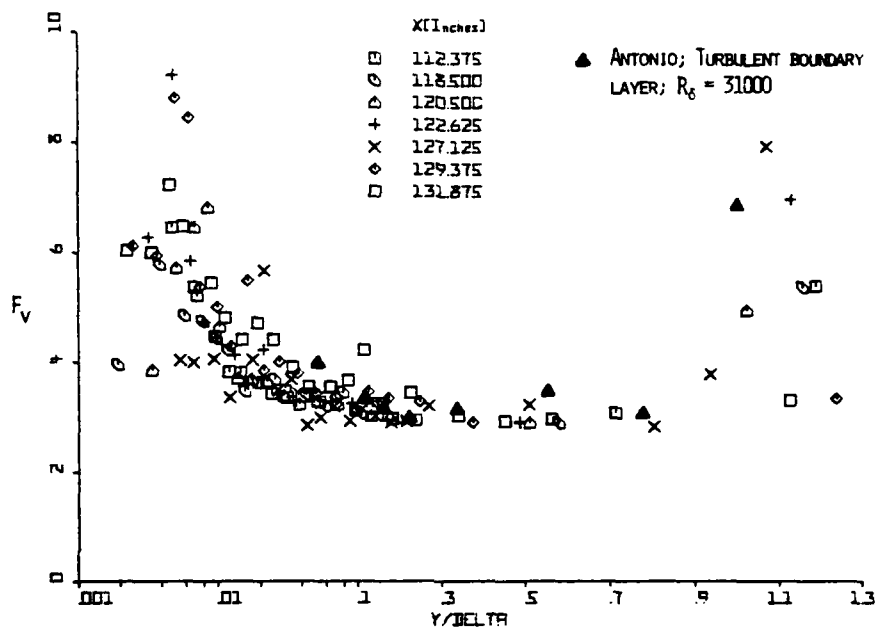


Figure 44(a). Flatness factor F_v profiles: upstream results.

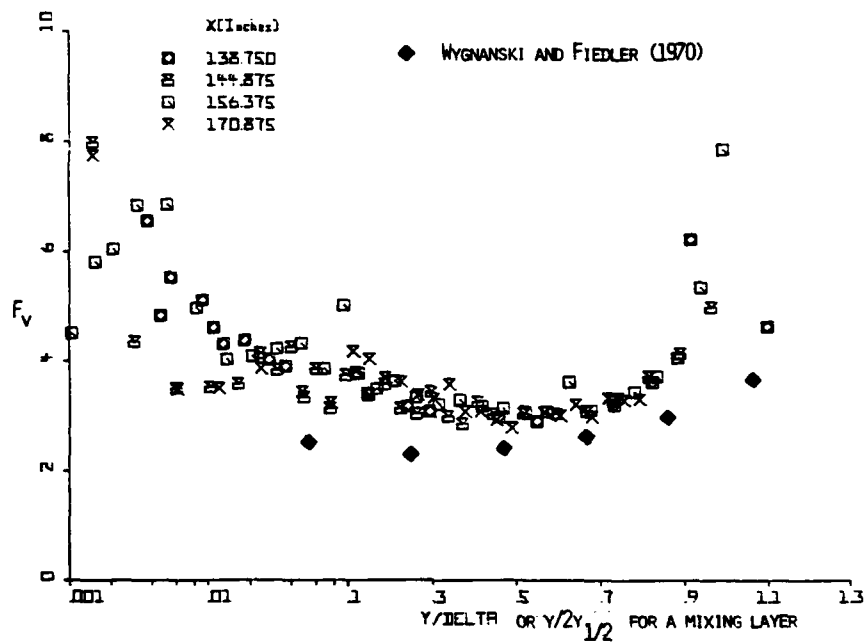


Figure 44(b). Flatness factor F_v profiles: downstream of separation.

region and the outer region indicates that the pressure gradient does not have much effect on F_u and F_v in those regions. Comparison with Figures 43 (b) and 44 (b) for the flow downstream of separation indicates that separation also does not have much effect on F_u and F_v over the shear layer.

However, when plotted against y^+ in Figure 45, the data for F_u upstream of separation indicate an apparent effect of pressure gradient in the region close to the wall, mainly in the buffer layer. In the viscous sublayer for both zero and adverse pressure gradient flows, the flatness factor attains values much higher than the value for a gaussian probability distribution, which is equal to 3. This is possible because the inrush phase of the bursting cycle which brings in high velocity fluid from the outer region results in large amplitude positive u fluctuations and consequently produces a large skirt in the velocity probability distribution. Similarly, near the outer edge of the boundary layer, intermittent large amplitude negative u fluctuations occur as a result of the large eddies driving the fluid from the low velocity regions outwards, which tends to increase the flatness factor. In the buffer layer near a y^+ of 13, the zero pressure gradient flows of Ueda and Hinze, Zaric, and Kreplin all show a dip in the F_u flatness factor distributions and a change in sign in the skewness factor S_u distributions for u as shown in Figure 46. Ueda and Hinze have remarked that this location is where u' attains the maximum value. The present data neither show any such predominant dip in F_u nor sign change of S_u in the buffer layer. Sandborn's (1959) data for F_u in an adverse pressure gradient boundary layer flow show a behavior similar to the present data. The present data for F_u and S_u also show reasonable agreement with those of Dumas (1966), but the significance of this is clouded since the pressure-gradient-flow conditions were not mentioned in his paper.

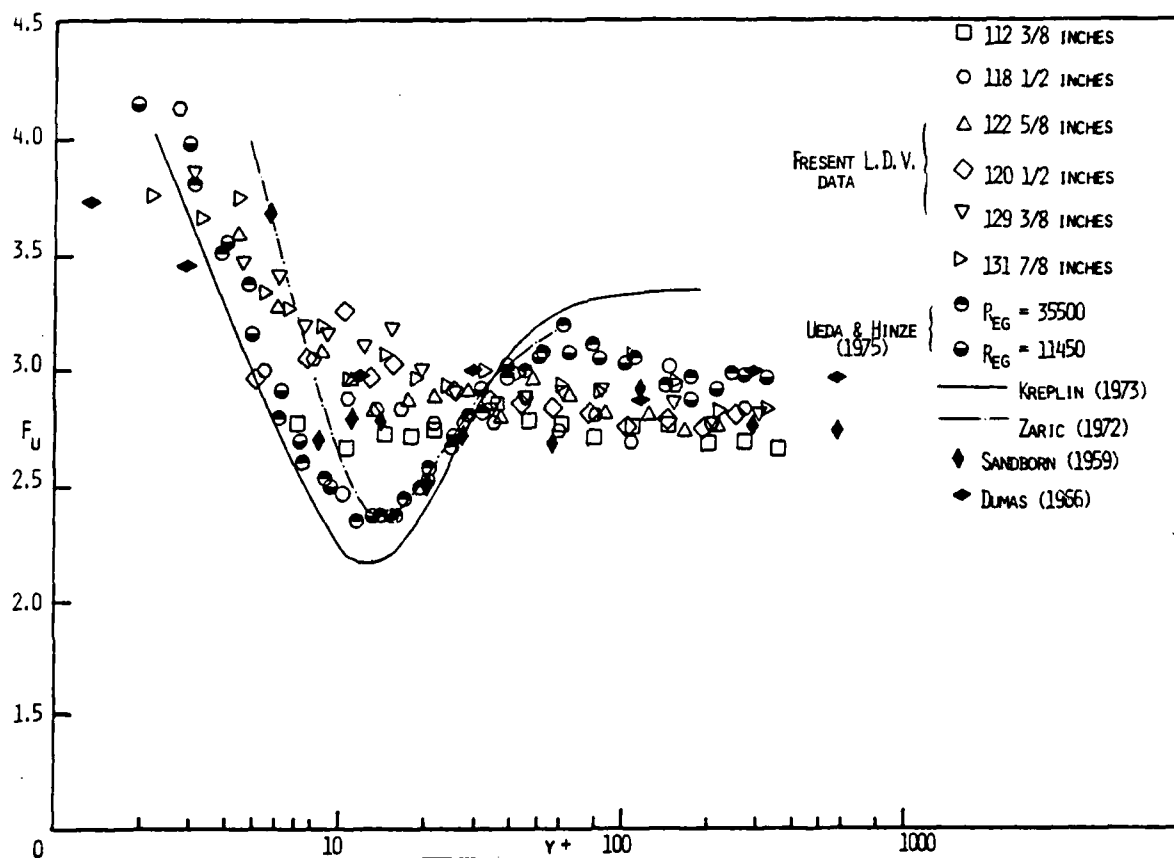


FIGURE 45. F_u vs. y^+ UPSTREAM OF SEPARATION.

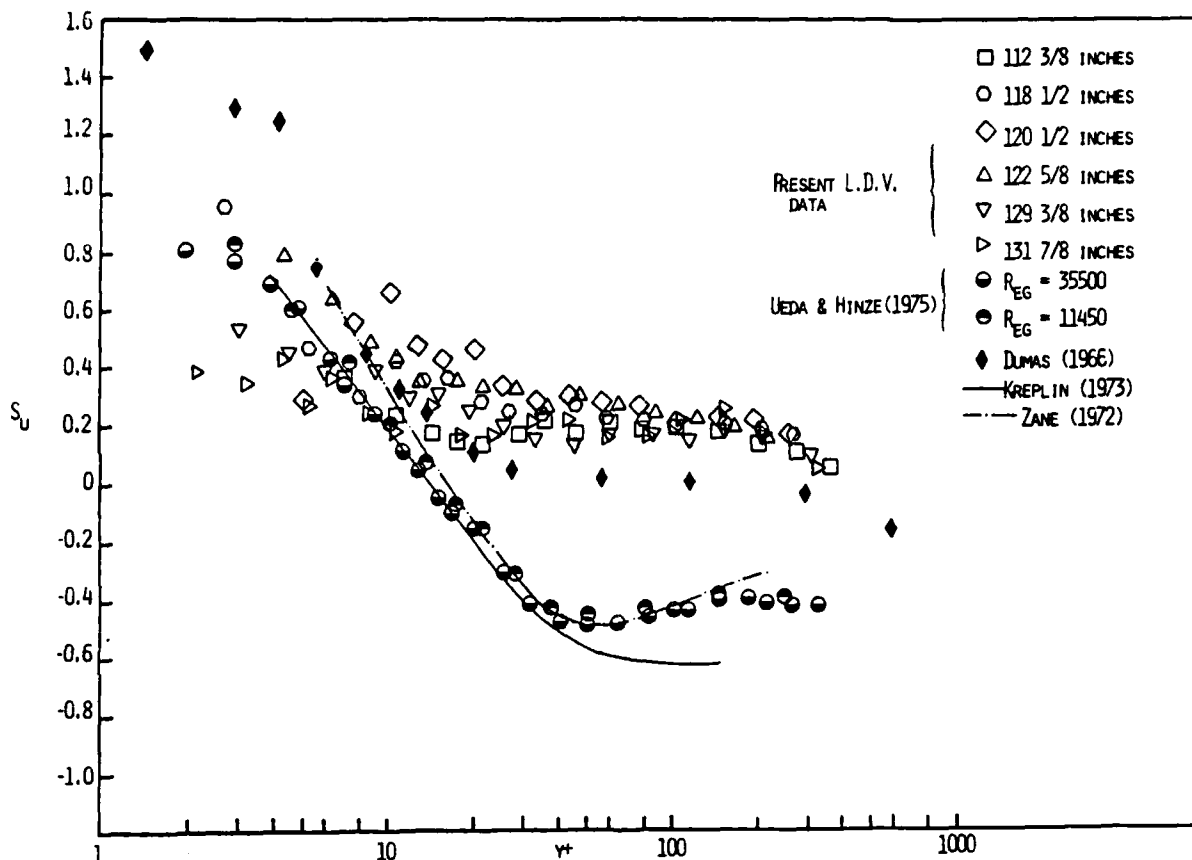


FIGURE 46. SKINNESS FACTOR S_u VS. y^+ UPSTREAM OF SEPARATION.

The present data for S_u as shown in Figure 47 (a) indicate a change in sign at a location farther away from the wall ($y/\delta \approx 0.4$). This location corresponds to the region where the Reynolds shear stress and the turbulent intensities reach their maximum values. The intense momentum exchange in this region results in the lack of occasionally very high or very low fluctuations and as a consequence the probability distribution does not have much skewness. As one moves closer to the wall, the intermittent large amplitude positive u fluctuations tend to make the probability distributions more positively skewed (Eckelmann, 1974) and vice-versa when one moves away from the wall.

The location corresponding to zero skewness for u occurs very close to the wall in zero-pressure-gradient flows because the Reynolds shear stress attains a maximum value in that region. Furthermore, the intense mixing in that region suppresses large amplitude u fluctuations, thus removing the skirt in the positively skewed velocity probability distribution and changing it to a more nearly top-hat shape with a low flatness factor. The same does not happen in adverse pressure gradient flows in the region of maximum shear because the probability distribution in that region is more nearly gaussian with only a slight skewness and with no significant large amplitude fluctuations to be suppressed.

Downstream of separation the skewness S_u is reduced to negative values in the backflow region as shown in Figure 47 (b). A maximum is observed in the vicinity of the minimum mean velocity. As shown in Figure 43 (b), F_u also has a local maximum near this location. The second zero-skewness point is slightly closer to the wall than the location of the maximum shear stress.

The flatness factor distributions for v in Figures 44 (a) and (b) show a

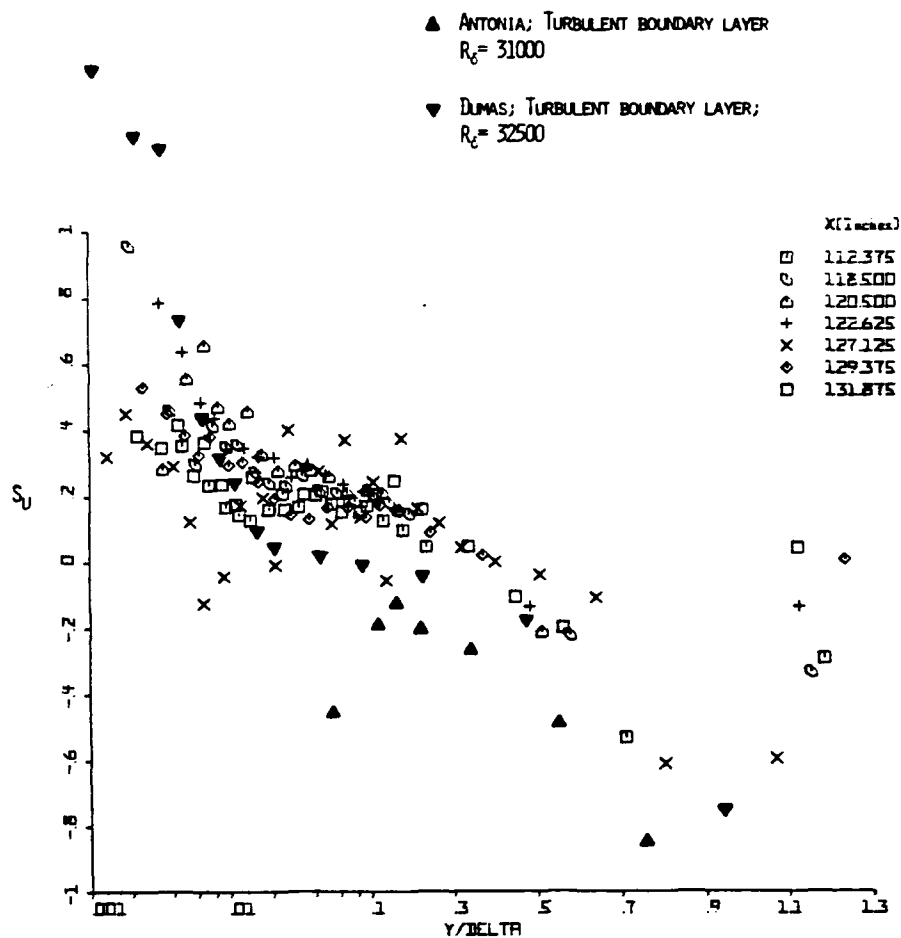


Figure 47(a). Skewness factor S_u vs. y/δ profiles, laser anemometer data: u_{upstream} results.

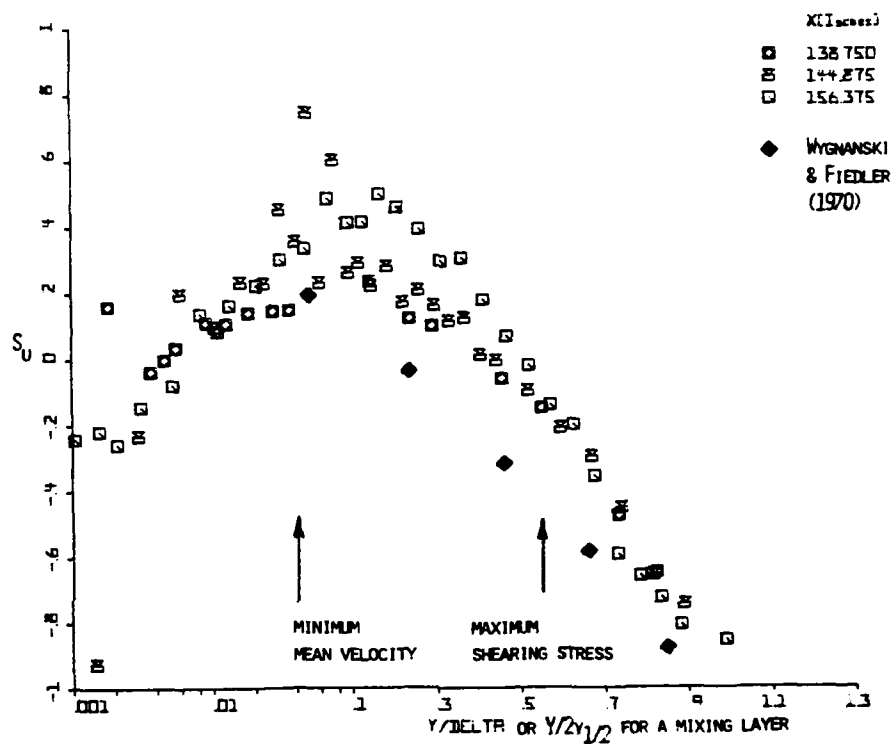


Figure 47(b). Skewness factor S_u vs. y/δ profiles laser anemometer data: u results downstream of separation.

trend similar to that of u , the only difference being the reduced width of the flat region. Figures 48 and 49 show that there is a significant variation of S_v along the flow. Only downstream of 112 inches is there profile similarity in the outer region. S_v shown in Figure 49 exhibit a shape approximately opposite in sign to that of S_u , with a large positive skewness factor near the outer edge of the boundary layer, gradually decreasing to negative values towards the wall. This results in the appearance of two zero-skewness points in the distributions of S_v both upstream and downstream of separation. The zero-skewness point which is farther from the wall occurs in the region of maximum shear both upstream and downstream of separation, which indicates that the backflow has no influence on the location of this point as in the case of S_u . Downstream of separation the flatness and skewness factors away from the wall are in qualitative agreement with those of Wygnanski and Fiedler (1970) for a plane mixing layer. This is not surprising since the mean velocity profiles resemble those in mixing layers.

D. Diffusion of turbulence kinetic energy

The diffusion term $\partial/\partial y (\overline{pv}/\rho + 1/2 \overline{q^2 v})$ of the turbulence kinetic energy equation is known to become more important as a turbulent boundary layer approaches separation (Bradshaw, 1967b; Simpson and Collins, 1978). The term $\overline{pv}/\rho$ which represents the diffusion flux due to pressure forces cannot be measured directly using available techniques. Normally, it is estimated by the difference of other measureable terms in the turbulence kinetic energy equation, although experimental uncertainties make the results quite uncertain. Here the turbulence kinetic energy diffusion flux

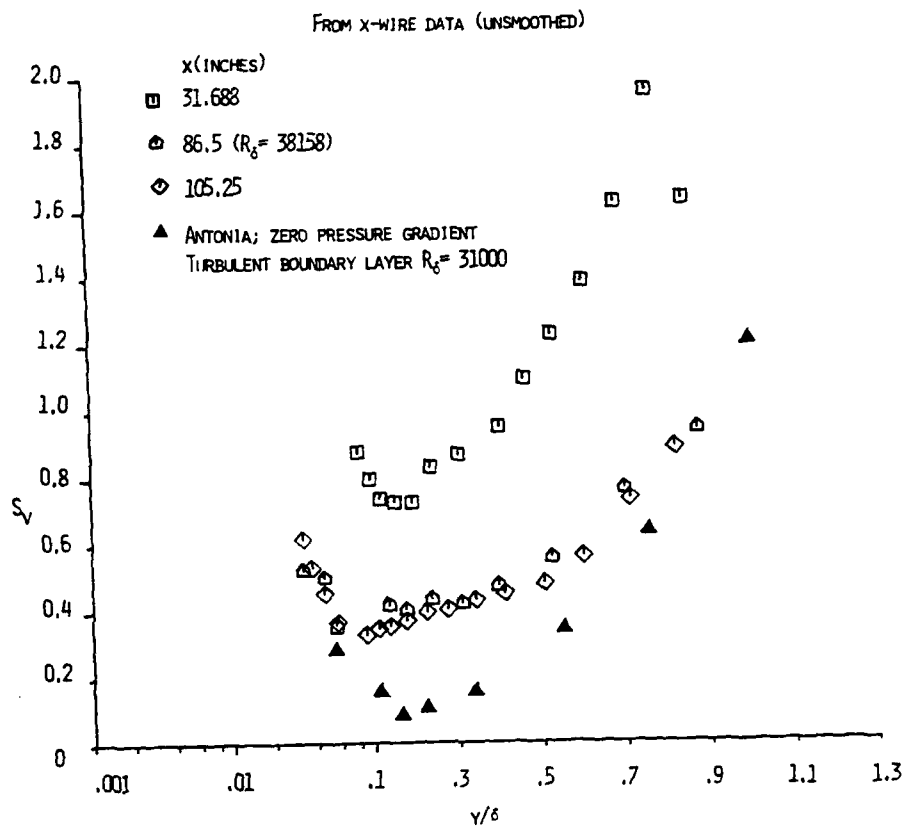


FIGURE 48. SKEWNESS FACTOR S_v VS. y/δ PROFILES FROM CROSS HOT-WIRE ANEMOMETER DATA.

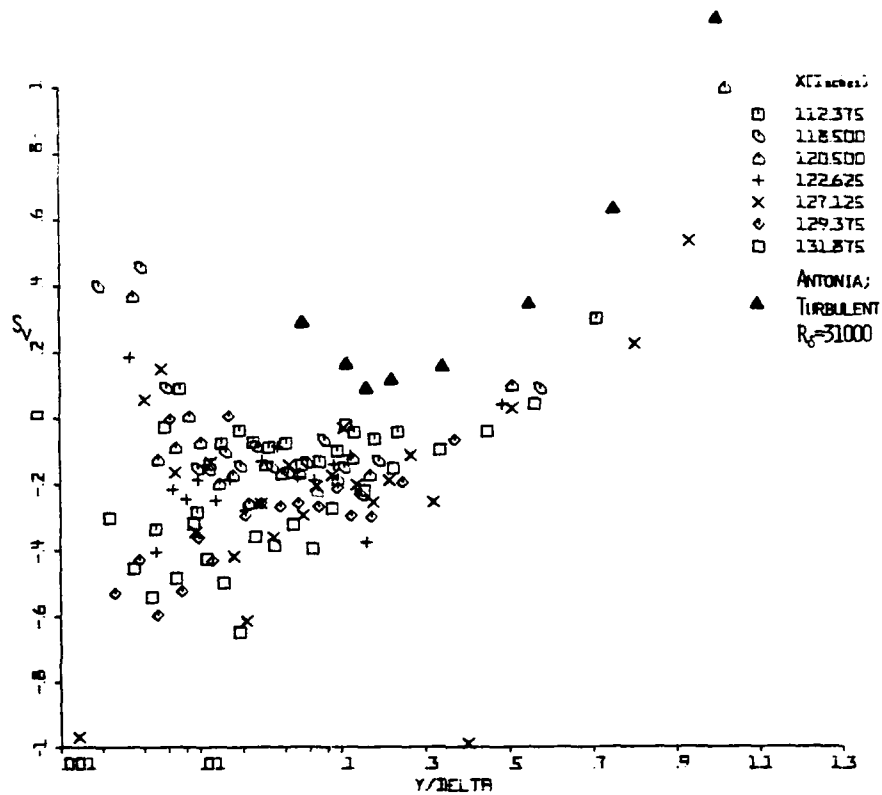


Figure 49(a). Skewness factor S_y vs. y/δ from laser anemometer data: $v_{upstream}$ results.

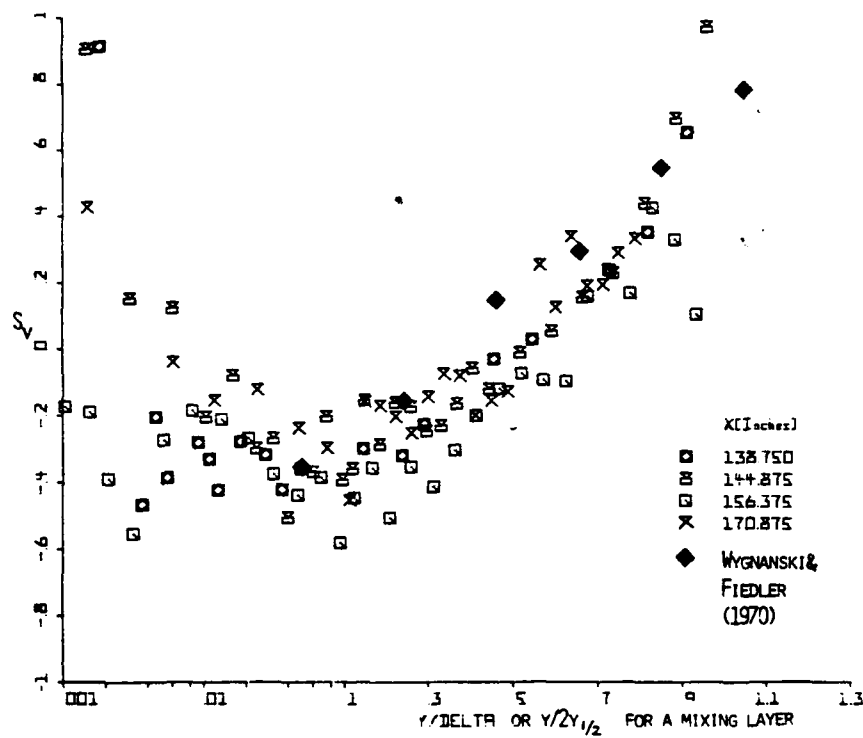


Figure 49(b). Skewness factor S_v vs. y/δ from laser anemometer data: results downstream of separation.

$$1/2 \overline{q^2 v} = 1/2 (\overline{u^2 v} + \overline{v^3} + \overline{w^2 v}) \quad (24)$$

was estimated using $\overline{u^2 v}$ and $\overline{v^3}$ cross-wire anemometer measurements and the approximation proposed by Bradshaw (1967b), $\overline{w^2 v} = (\overline{u^2 v} + \overline{v^3})/2$.

Figures 50 (a) and (b) show the present results. The flux of turbulence kinetic energy is positive in the regions where data have been plotted, indicating that the flux is directed away from the wall. For locations downstream of 117.6 inches the data are limited only to the region near the outer edge of the boundary layer. Nearer the wall at these locations the flux is expected to be negative, since most of the turbulence energy production is in the middle of the boundary layer and previous strong adverse pressure gradient data (East and Sawyer, 1979) have this behavior.

East and Sawyer proposed a gradient model based on a mixing length formulation

$$\overline{q^2 v} = 0.4 \lambda \frac{d}{dy} (\overline{q^2})^{3/2} \quad (25)$$

They obtained experimental data for seven equilibrium turbulent boundary layers with $U \sim x^R$ and R approximately equal to 0.4, 0.2, 0, -0.2, -0.4, -0.6, and -0.8. The above model agreed with those data satisfactorily in the outer half of the boundary layer in all cases. Agreement in the inner regions improved for increasingly adverse pressure gradients. Using the mixing length and turbulence kinetic energy distributions obtained from the present equilibrium experiments, the results from this model are shown in Figures 50. Agreement in the outer region is within the uncertainty of the measurements. In the inner region only the general shape of the predictions agree with measurements.

It can be observed from Figures 51 (a) and (b) that the diffusion is small at the upstream stations, becoming appreciable downstream from 117 inches. Farther

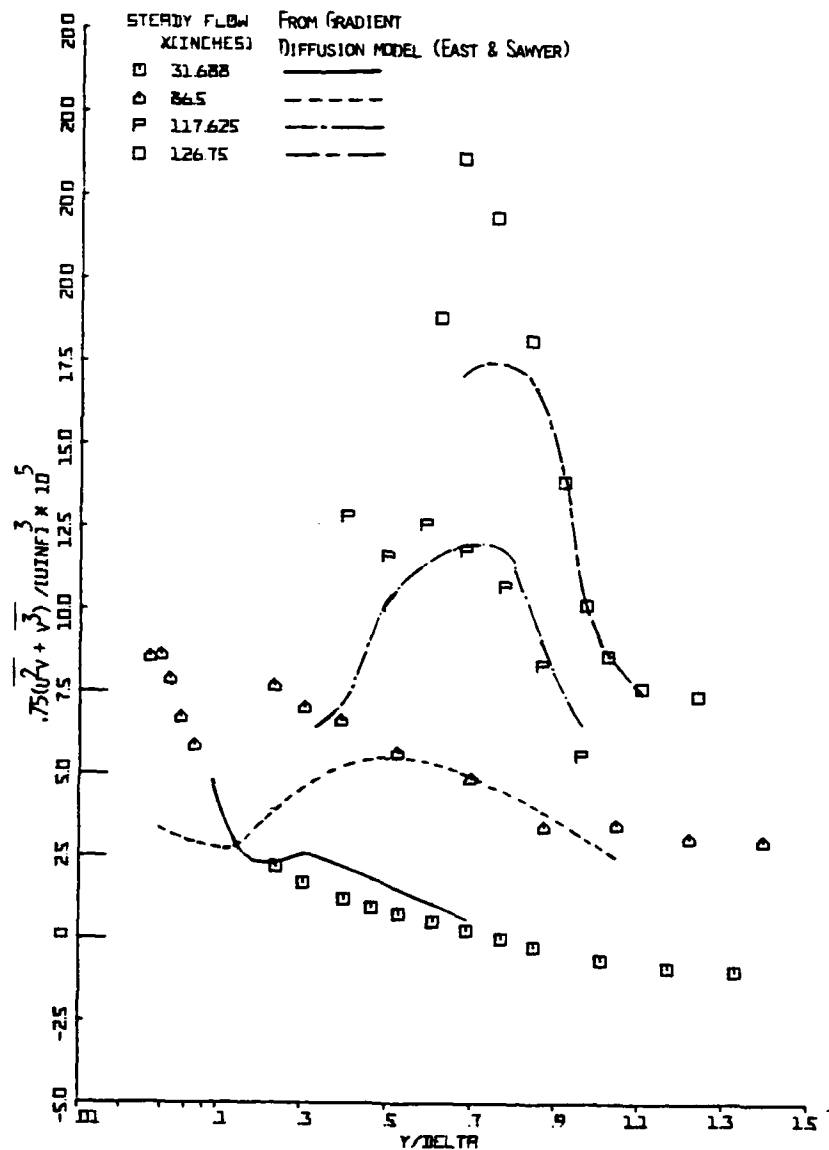


Figure 50(a). Turbulent kinetic energy diffusion flux vs. y/δ - hot-wire anemometer results compared to East and Sawyer's gradient diffusion model: upstream of separation.

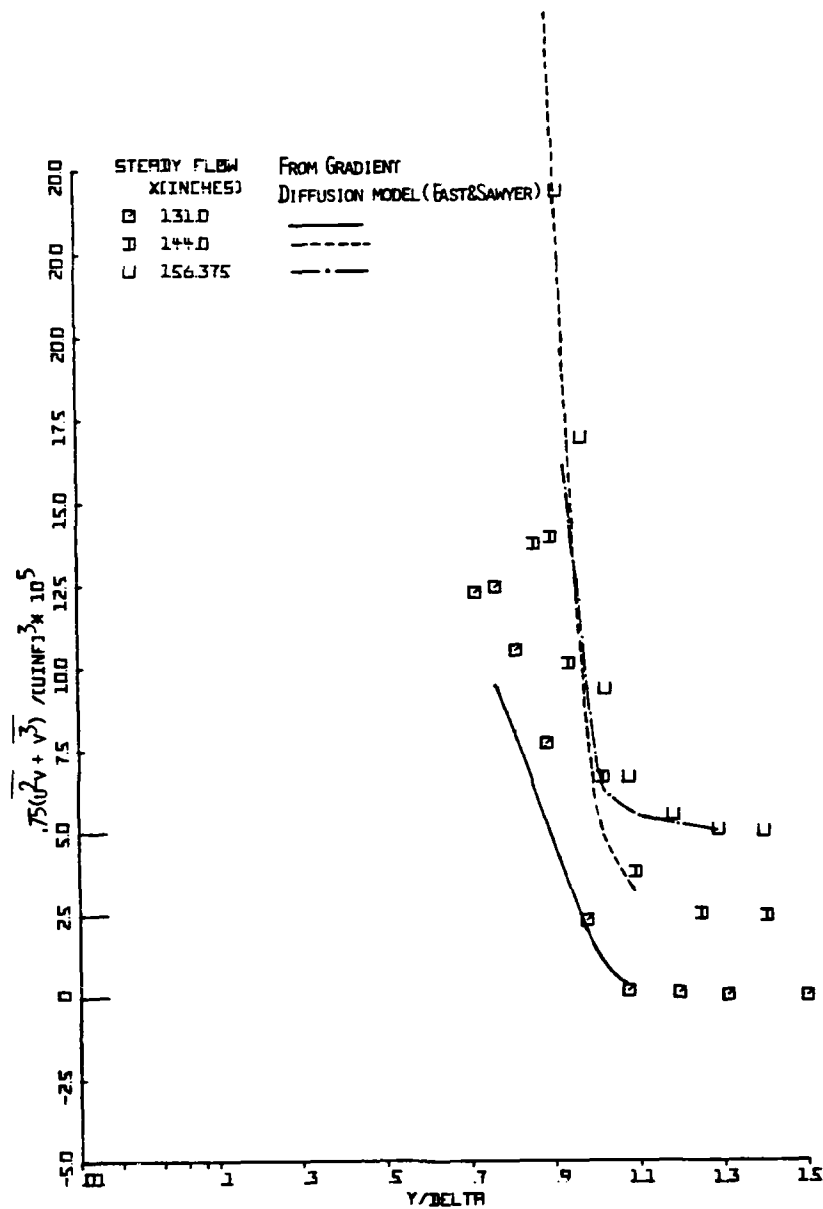


Figure 50(b). Turbulent kinetic energy diffusion flux vs. y/δ - hot-wire anemometer results compared to East and Sawyer's gradient diffusion model: downstream of separation.

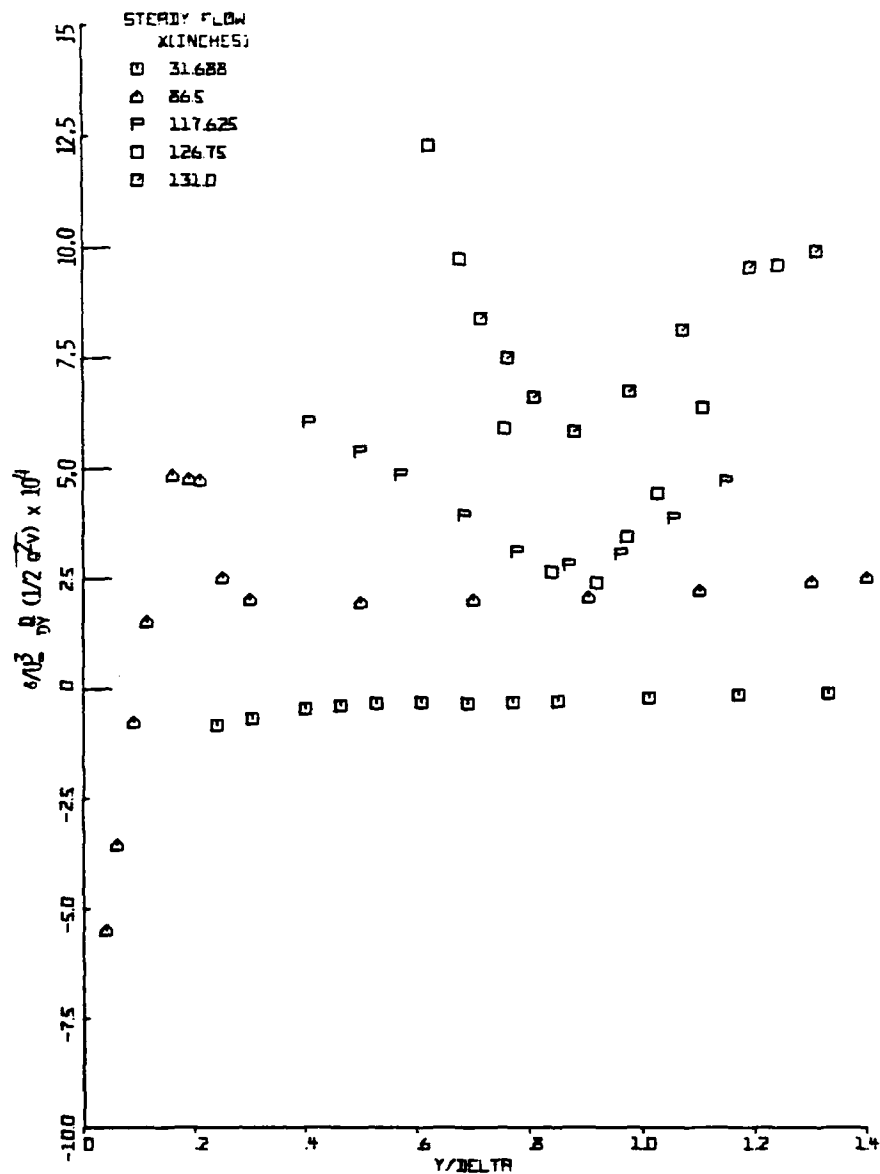


Figure 51(a). Turbulent kinetic energy diffusion vs. y/δ downstream of separation.

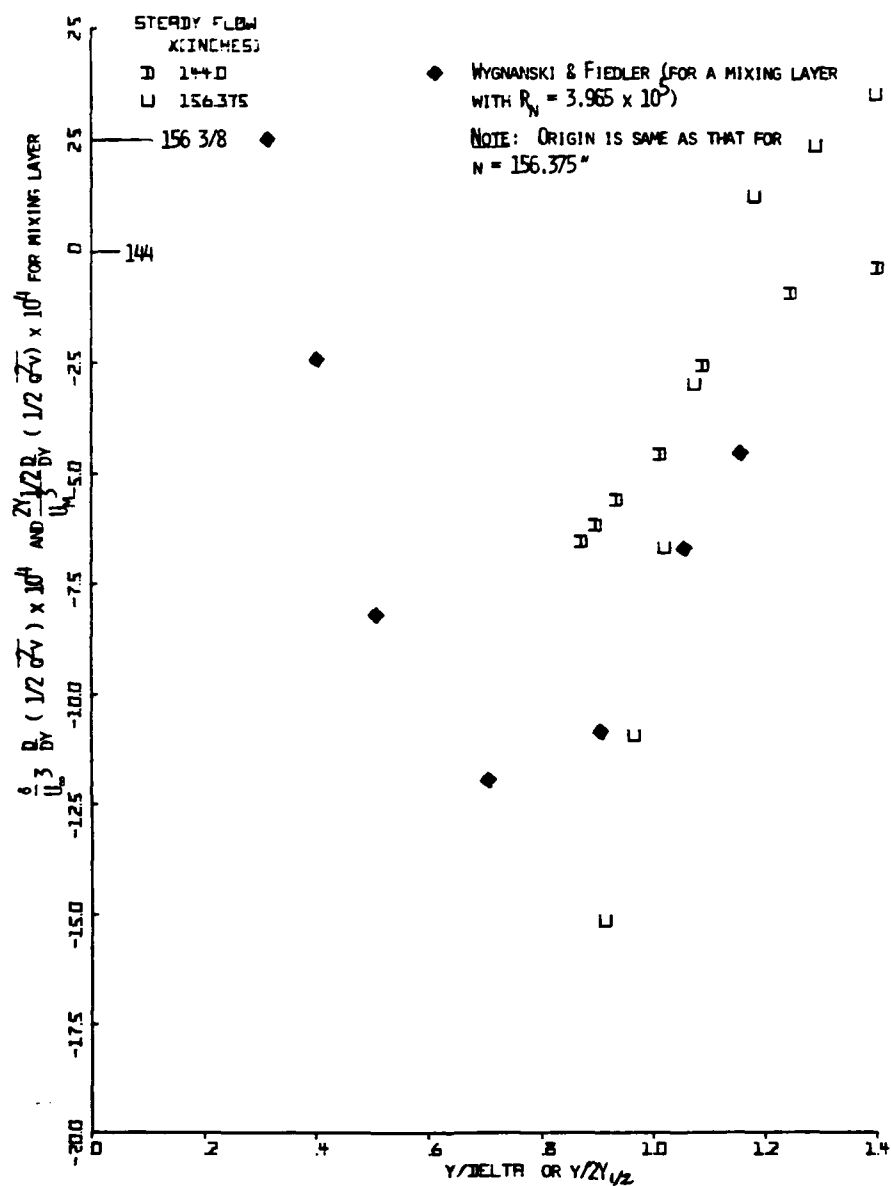


Figure 51(b). Turbulent kinetic energy diffusion vs. y/δ : downstream of separation.

downstream as separation is approached, the diffusion increases continuously. It is interesting to note that such large negative diffusion rates occur on the low velocity side of mixing layers also. This can be seen in Fig. 51 (b) which has the data of Wygnanski and Fiedler (1970) plotted for comparison with the present data at $x = 156 \frac{3}{8}$ inches. The maximum velocity in the mixing layer U_m and the total shear layer thickness $2y_{1/2}$ were used for nondimensionalizing those data. This similarity in behavior with the mixing layer suggests that the diffusion, which is responsible for the lateral spread of mixing layers, is also responsible for the rapid growth of separated boundary layers. The large gain of energy by diffusion in the outer region and the associated increase in entrainment of the nonturbulent fluid seems to be responsible for the maintenance of the large eddies and the large growth rates of separated boundary layers.

The increase in entrainment rate of free-stream fluid as separation is approached is demonstrated in Figure 52 in terms of the entrainment velocity, V_p , obtained from mean velocity measurements using the relationship

$$V_p = \frac{d}{dx} \left[U_\infty (\delta_{0.995} - \delta^*) \right] \quad (26)$$

Upstream of separation these results are in good agreement with Bradshaw's (1967) correlation

$$\frac{V_p}{U_\infty} = 10 \frac{\tau_{\max}}{\rho U_\infty^2} \quad (27)$$

for boundary layer and mixing layers. Downstream of separation there is poor agreement, in contrast to the good agreement obtained by Simpson et al. (1977) for their separating flow. This might be because of some three-dimensionality which seems to exist in that region.

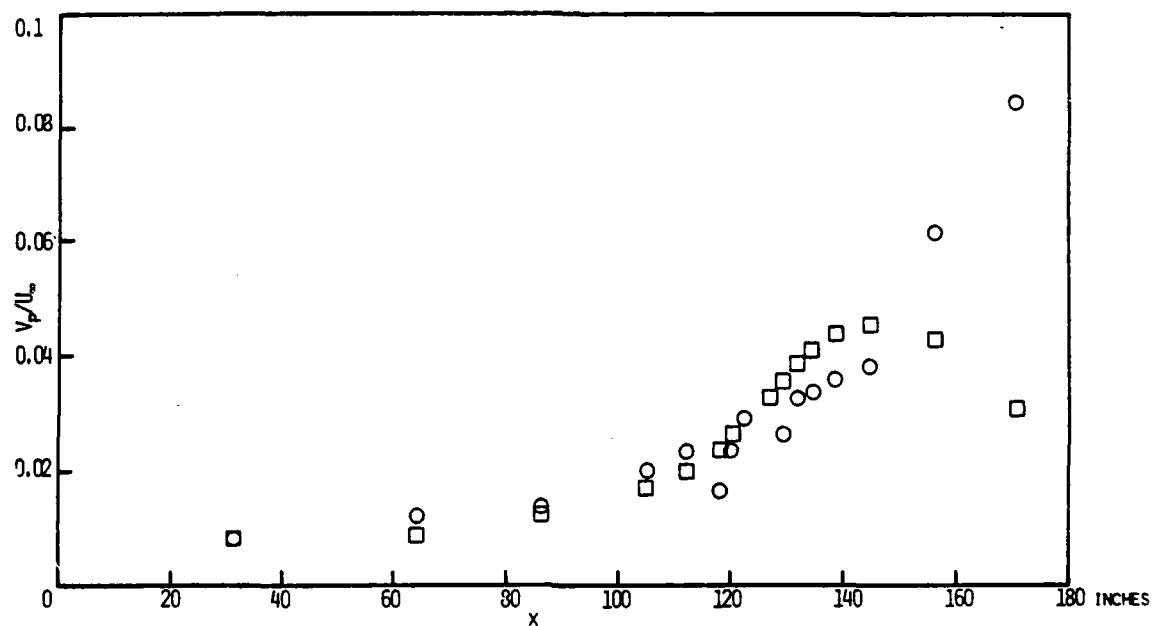


Figure 52. Entrainment velocity V_e/U_∞ vs. X : $\square$ from equation (26); $\circ$ from equation (27).

Figure 53 shows the distribution of the diffusion function $G/(\tau_{\max}/\rho)^{1/2}$, which was defined by Bradshaw (1967a) to relate the turbulence kinetic energy diffusion to the turbulent shear stress.

$$G = \frac{(\overline{pv}/\rho + \frac{1}{2} \overline{q^2 v})}{(\tau/\rho)(\tau_{\max}/\rho)^{1/2}} \quad (28)$$

The diffusion function used by Bradshaw and that computed from the data of East and Sawyer (1979) are also shown. Although there are large differences up to half of the boundary layer thickness, the present data blend in with their data in the outer region. When compared with Bradshaw's diffusion function, the differences are larger and there is no region of agreement of all. The diffusion function given by Bradshaw was derived from the zero pressure gradient boundary layer data of Klebanoff (1955). These results indicate that the diffusion function is dependent upon pressure gradient conditions.

V.4 Momentum and Turbulence Energy Balances

In order to further understand the effect of separation on the transport of momentum and turbulence kinetic energy, terms of the governing equations were obtained using the measured quantities described above. The x-direction and y-direction momentum equations are, respectively

$$U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\partial(-\overline{uv})}{\partial y} - \frac{\partial \overline{u^2}}{\partial x} \quad (29)$$

$$U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\partial(-\overline{uv})}{\partial x} - \frac{\partial \overline{v^2}}{\partial y} \quad (30)$$

For each equation the terms on the left side are inertia or convective terms while the terms on the right side describe the pressure gradient, the shearing stress gradient, and the normal stress gradient, respectively. The turbulence energy

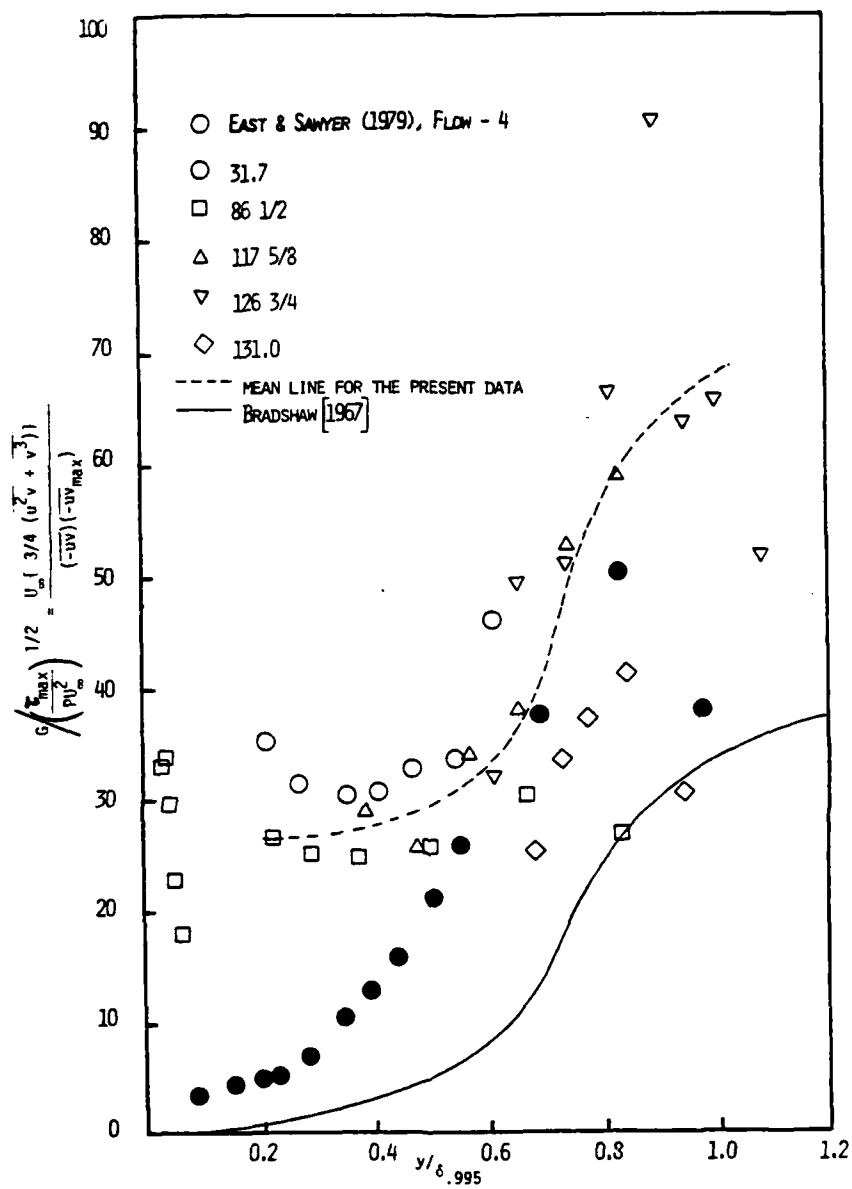


Figure 53. Bradshaw's (1967) diffusion parameter vs. $y/\delta_{.995}$ for several sets of data.

equation is

$$\frac{U}{2} \frac{\partial \overline{q^2}}{\partial x} + \frac{V}{2} \frac{\partial \overline{q^2}}{\partial y} = -\frac{\partial}{\partial y} \left(v \left(\frac{p}{\rho} + \frac{q^2}{2} \right) \right) - \overline{uv} \frac{\partial U}{\partial y} - (\overline{u^2} - \overline{v^2}) \frac{\partial U}{\partial x} + \epsilon \quad (31)$$

The terms on the left side are advection terms while the terms on the right side describe turbulent diffusion, turbulent shear stress production, normal stresses production, and dissipation, respectively. Dissipation was not measured. In all three equations the viscous terms have been neglected since they are much smaller than the other terms.

An estimate of uncertainties of all the significant terms for a few typical points across the boundary layer are given in Table 8 for 118.5 inches and 131.875 inches. Very near the wall the uncertainties are high, but beyond $y/\delta \approx 0.02$, the uncertainties of most of the dominant terms are less than 30% - 40% at many points. In general, the terms involving derivatives with respect to y have less uncertainty as compared to those involving derivatives with respect to x , since the latter terms are much smaller and were computed from data acquired on different days. Hence each data point used to determine x derivatives corresponded to slightly different experimental conditions.

An exception to this is the inertia terms of the x -direction momentum equation. In this case the two-dimensional continuity equation can be used to obtain a single term involving only a y derivative of a given velocity profile.

$$U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = -U^2 \frac{\partial (V/U)}{\partial y}$$

This expression was used only when U was much larger than V , since the uncertainty in V/U becomes large as U approaches zero. The relative uncertainty in this term is large in the outer region because y -direction gradients are small.

Estimate of Uncertainties for the terms of the Momentum and Energy equations.

Table 8a. Terms involving derivatives with respect to x at x = 118.5 inches.

y/δ	0.00385		0.0192		0.192		0.962	
	Uncertainty (±)	Absolute Value	Uncertainty (±)	Absolute Value	Uncertainty (±)	Absolute Value	Uncertainty	Absolute Value
$-10^2 x \frac{\delta}{U_\infty^2} \frac{\partial u'^2}{\partial x}$	0.02	0.149	0.05	0.075	0.02	0.024	0	-0.138
$-10^2 x \frac{\delta}{U_\infty^2} \frac{1}{\rho} \frac{\partial p}{\partial x}$	30.36	-5.04	3.2	-5.66	1.7	-2.14	4.68	-3.73
$-10^2 x \frac{\delta}{U_\infty^2} \frac{\partial (u'^2 - v'^2)}{\partial x}$	0	0.148	0	0.057	0.01	0.012	0	-0.084
$-10^2 x \frac{1}{\rho} \frac{\partial (p_\infty - \rho v'^2)}{\partial x}$	0	-1.86	0	-1.87	0.02	-1.87	0	-1.8
$10^2 x \frac{\delta}{U_\infty^2} U^2 \frac{\partial (V/U)}{\partial x}$	0.007	0.002	0.013	-0.004	0.35	0.035	0.57	0.968
$-10^2 x \frac{\delta}{U_\infty^2} \frac{1}{\rho} \frac{\partial p}{\partial y}$	4.9	6.42	1.01	4.28	0.28	0.55	0.08	-1.42
$10^3 x \frac{\delta}{U_\infty^3} \frac{U}{2} \frac{\partial (u'^2 + v'^2)}{\partial x}$	0.034	-0.073	0.112	-0.109	0.045	-0.071	0.855	0.937
$10^3 x \frac{\delta}{U_\infty^3} (u'^2 - v'^2) \frac{\partial U}{\partial x}$	0.01	-0.041	0	-0.276	0.01	-0.426	0.03	-0.044

Estimate of Uncertainties for the terms of the Momentum and Energy equations.

Table 8b. Terms involving derivatives with respect to y at x= 118.5 inches.

y/δ	0.0038		0.02		0.2		0.8	
	Uncertainty (%)	Absolute Value	Uncertainty (%)	Absolute Value	Uncertainty (%)	Absolute Value	Uncertainty	Absolute Value
$10^2 \times \frac{\delta}{U_\infty^2} \frac{\partial(-uv)}{\partial y}$	1.261	6.28	0.276	0.77	0.118	0.32	0.26	-0.34
$10^2 \times \frac{\delta}{U_\infty^2} U^2 \frac{\partial(V/U)}{\partial y}$	26.445	0.52	3.685	4.95	1.746	1.76	3.5	3.98
$10^2 \times \frac{\delta}{U_\infty^2} v \frac{\partial^2 U}{\partial y^2}$	2.914	-2.15	0.031	-0.32	0.001	0	0.001	0
$10^2 \times \frac{\delta}{U_\infty^2} v \frac{\partial^2 V}{\partial y^2}$	0.375	0	0	0	0.001	0.02	0	0
$-10^2 \times \frac{\delta}{U_\infty^2} \frac{\partial v^2}{\partial y}$	2.205	-6.42	1.041	-4.18	0.29	-0.56	0.13	0.52
$-10^3 \times \frac{\delta}{U_\infty^3} (-uv \frac{\partial U}{\partial y})$	3.597	-5.1	0.302	-2.42	0.464	-1.29	0.51	-0.42
$10^3 \times \frac{\delta}{U_\infty^3} \frac{V}{2} \frac{\partial(u'^2 + v'^2)}{\partial y}$	2.495	0.43	0.072	0.19	0.08	0.2	0.455	-1.33

Estimate of Uncertainties for the terms of the Momentum and Energy equations.

Table 8c. Terms involving derivatives with respect to x at x = 131.875 inches.

y/δ	0.0022		0.019		0.112		0.562	
	Uncertainty	Absolute Value	Uncertainty (%)	Absolute Value	Uncertainty (%)	Absolute Value	Uncertainty	Absolute Value
$10^2 x \frac{\delta}{U_\infty^2} \frac{\partial u'^2}{\partial x}$	0.211	-0.061	0.038	0	0.15	0.06	0.09	-0.599
$10^2 x \frac{\delta}{U_\infty^2} \frac{1}{\rho} \frac{\partial p}{\partial x}$	1.23	5.71	0	-3.02	0.34	-1.75	8.84	1.06
$10^2 x \frac{\delta}{U_\infty^2} \frac{\partial (u'^2 + v'^2)}{\partial x}$	0.2	-0.059	0.02	0.01	0.19	0.056	0	-0.451
$10^2 x \frac{1}{\rho} \frac{\partial (P_\infty - \rho v'^2)}{\partial x}$	0.02	-1.98	0.01	-1.98	0.04	-1.98	0.09	-1.83
$10^2 x \frac{\delta}{U_\infty^2} \frac{\partial (V/U)}{\partial x}$	0	0	0.004	0	0.3	-0.172	0.26	0.671
$10^2 x \frac{\delta}{U_\infty^2} \frac{1}{\rho} \frac{\partial p}{\partial y}$	0.53	4.05	0.77	4.62	0.61	2.0	0.07	-1.42
$10^3 x \frac{\delta}{U_\infty^3} \frac{\partial (u'^2 + v'^2)}{\partial x}$	0.003	0.003	0.013	0.05	0.035	-0.04	0.55	2.29
$10^3 x \frac{\delta}{U_\infty^3} (u'^2 + v'^2) \frac{\partial U}{\partial x}$	0.045	-0.039	0.09	-0.32	0.05	-0.652	0.1	-1.9

Estimate of Uncertainties for the terms of the Momentum and Energy equations.

Table 8d. Terms involving derivatives with respect to y at x = 131.875 inches.

y/δ	0.0022		0.02		0.2		0.8	
	Uncertainty	Absolute Value	Uncertainty	Absolute Value	Uncertainty	Absolute Value	Uncertainty	Absolute Value
$10^2 \times \frac{\delta}{U_m^2} \frac{\partial(-uv)}{\partial y}$	5.598	-4.62	0.434	2.54	0.039	0.69	0.015	-0.52
$10^2 \times \frac{\delta}{U_m^2} U^2 \frac{\partial(V/U)}{\partial y}$	1.158	0	0.108	0.44	0.119	0.08	0.35	0.7
$10^2 \times \frac{\delta}{U_m^2} v \frac{\partial^2 U}{\partial y^2}$	2.843	-1.07	0.066	-0.05	0.001	0	0.002	0
$10^2 \times \frac{\delta}{U_m^2} v \frac{\partial^2 V}{\partial y^2}$	0.706	0	0.003	0	0	0	0	0.3
$-10^2 \times \frac{\delta}{U_m^2} \frac{\partial v'^2}{\partial y}$	1.218	-4.05	0.841	-4.4	-0.208	-1.22	0.363	1.2
$-10^3 \times \frac{\delta}{U_m^3} (-uv \frac{\partial U}{\partial y})$	1.66	-2.38	0.184	-0.54	0.854	-2.38	0.68	-0.71
$10^3 \times \frac{\delta}{U_m^3} \frac{v}{2} \frac{\partial(U'^2 + V'^2)}{\partial y}$	1.675	0	0.091	0.05	0.09	0.66	0.62	-3.02

On the whole, even though the uncertainties are large it is still possible to arrive at certain conclusions regarding the relative importance of the various terms in the momentum and turbulence energy equations as the boundary layer passes through separation.

Although the momentum and energy balances were examined at a number of stations, the results are presented here for three representative stations only. They correspond to a location upstream of separation (118.5 inches), a location in the intermittent separation region (131 7/8 inches), and one in the fully-separated region (156 3/8 inches). Figures 54 and 55 show the distributions of the various non-dimensional terms of the momentum equations and Figure 57 represent the terms of the energy equation. The locations of the maximum shear stress $-\overline{uv}$ and the maximum $(u'^2 + v'^2)$ are shown on all the plots.

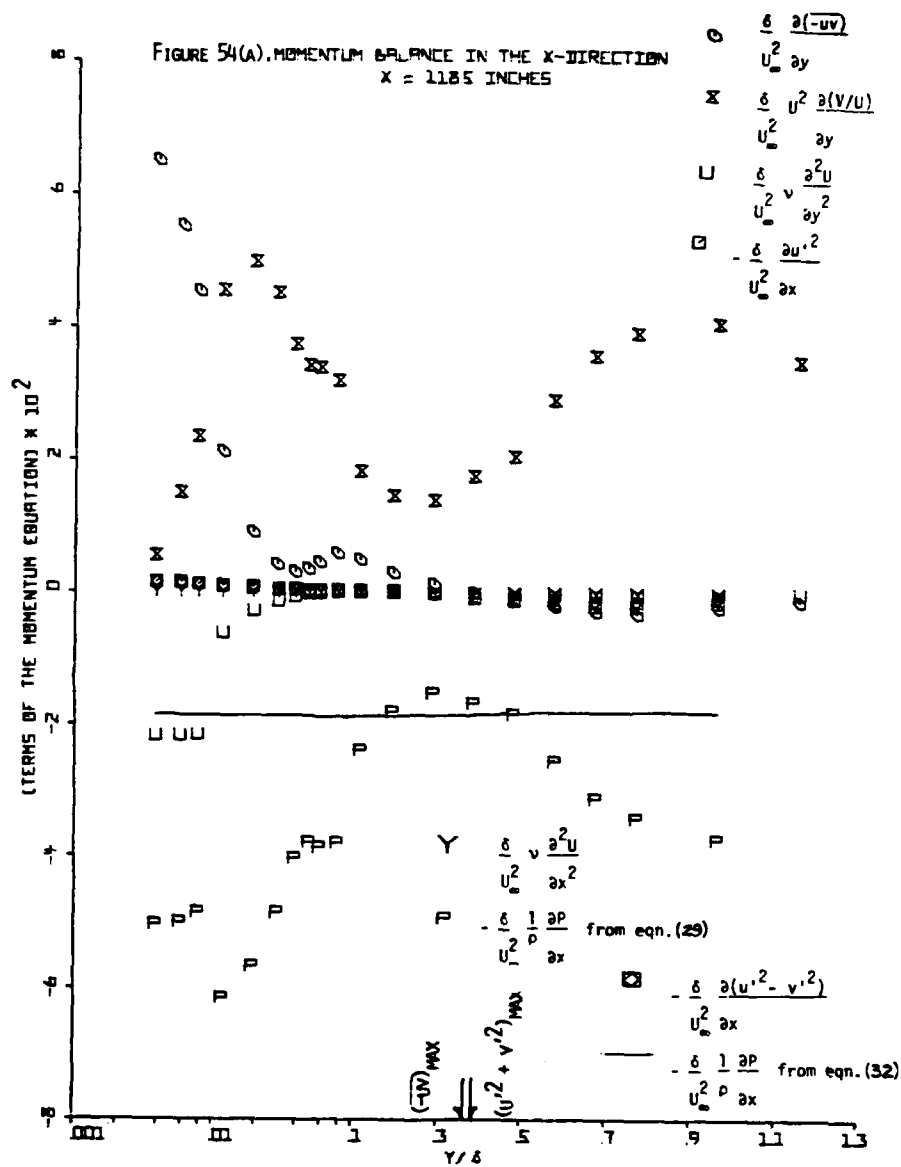
Figure 55 indicates that the only important terms in the equation for momentum transport in the y-direction are the pressure gradient and the normal stress terms. This is true both upstream and downstream of separation and leads to the following simplification of eqn. (30):

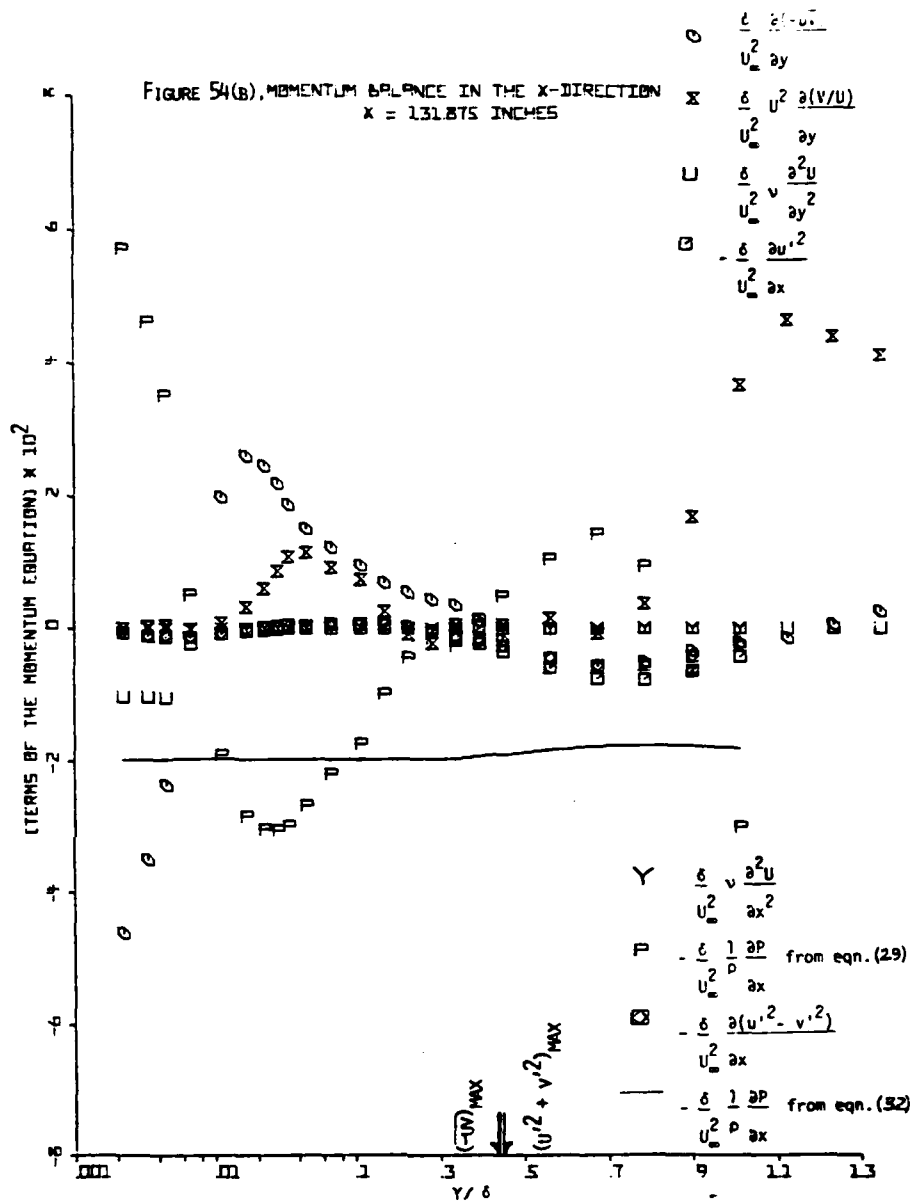
$$\frac{-1}{\rho} \frac{\partial P}{\partial y} = \frac{\partial v'^2}{\partial y}$$

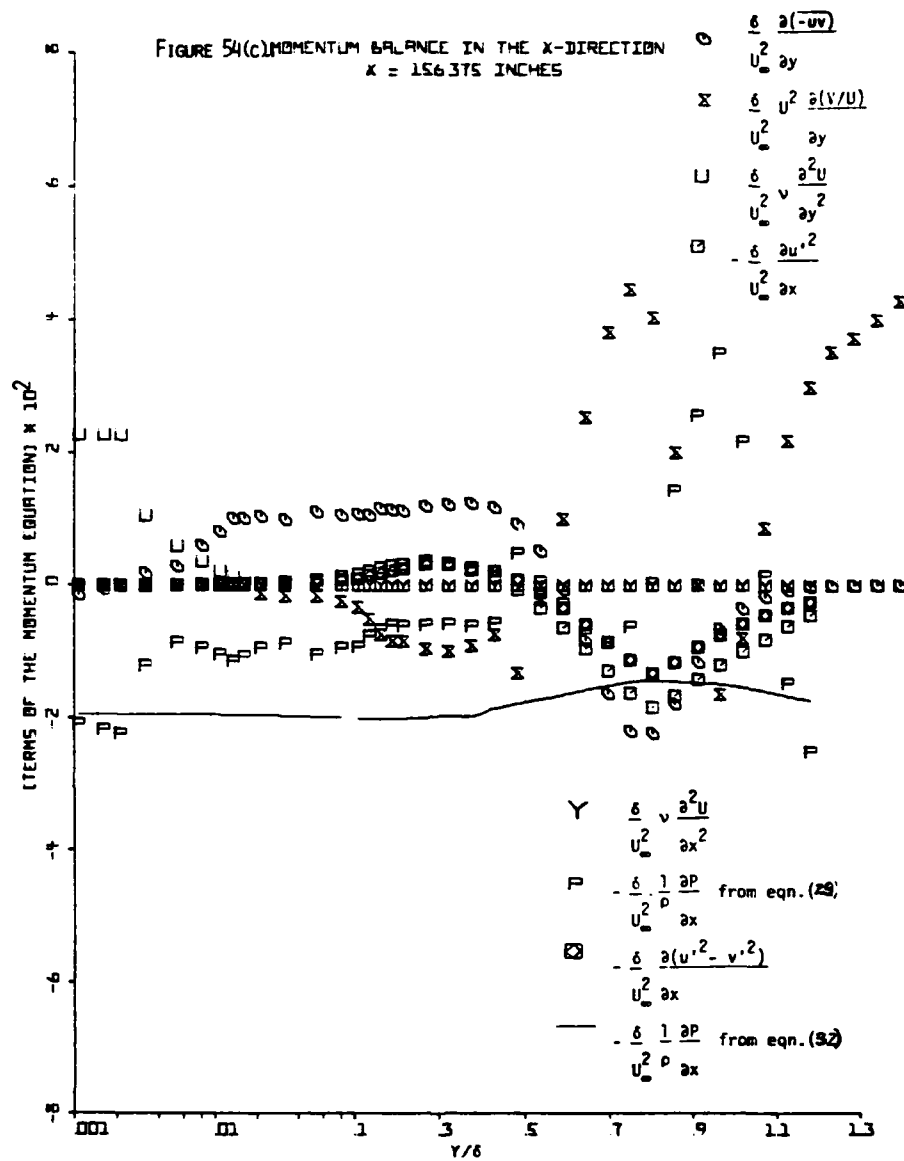
Upon integration it becomes $P(x,y) = P_{\infty} - \rho v'^2$. Differentiating this equation with respect to x produces

$$\frac{-1}{\rho} \frac{\partial P}{\partial x} = \frac{-1}{\rho} \frac{\partial P_{\infty}}{\partial x} + \frac{\partial v'^2}{\partial x} \quad (32)$$

The pressure gradient $\frac{\partial P}{\partial x}$ evaluated using eqn. (32) is also plotted in Figure 54. A first look at Figure 54 indicates large discrepancies between $\frac{\partial P}{\partial x}$ computed using eqns. (29) and (32). However, in view of the uncertainties of $\partial P / \partial x$ derived from







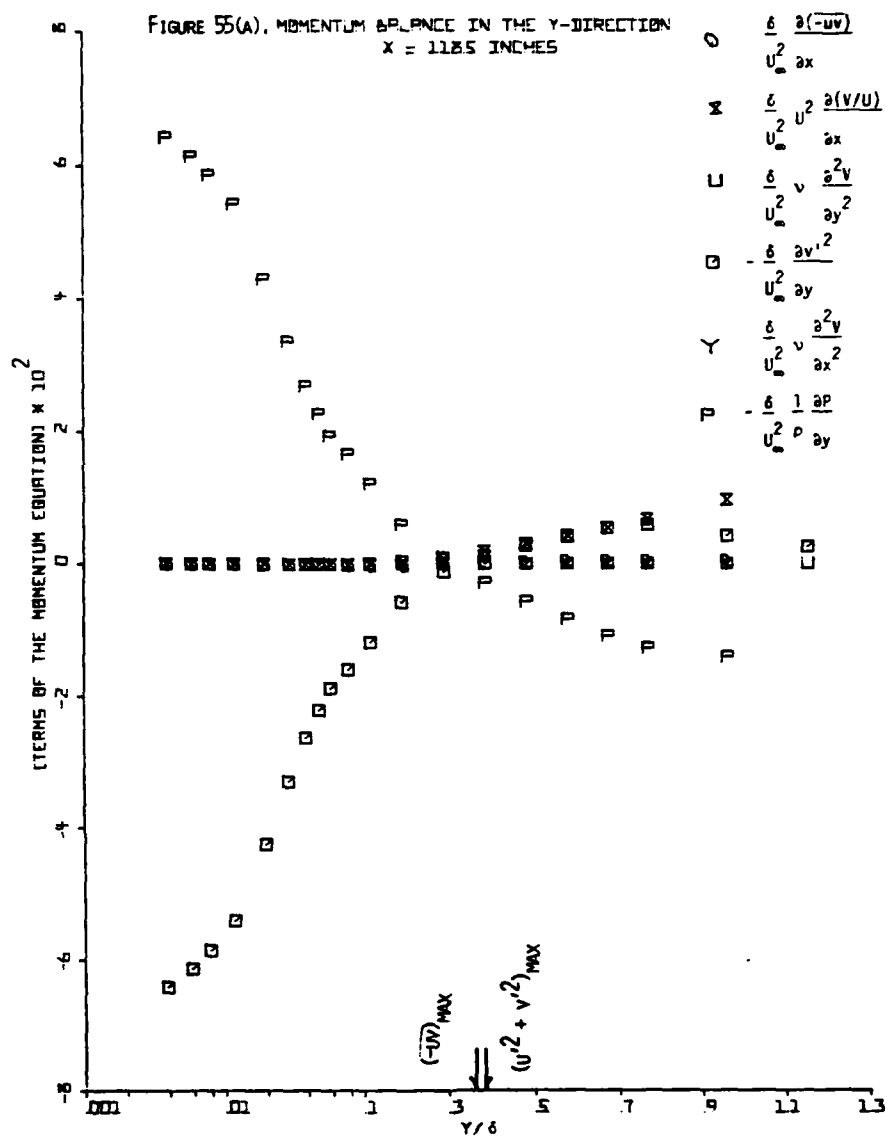


FIGURE 55(b).

MOMENTUM BALANCE IN THE Y-DIRECTION
 $x = 131.875$ INCHES

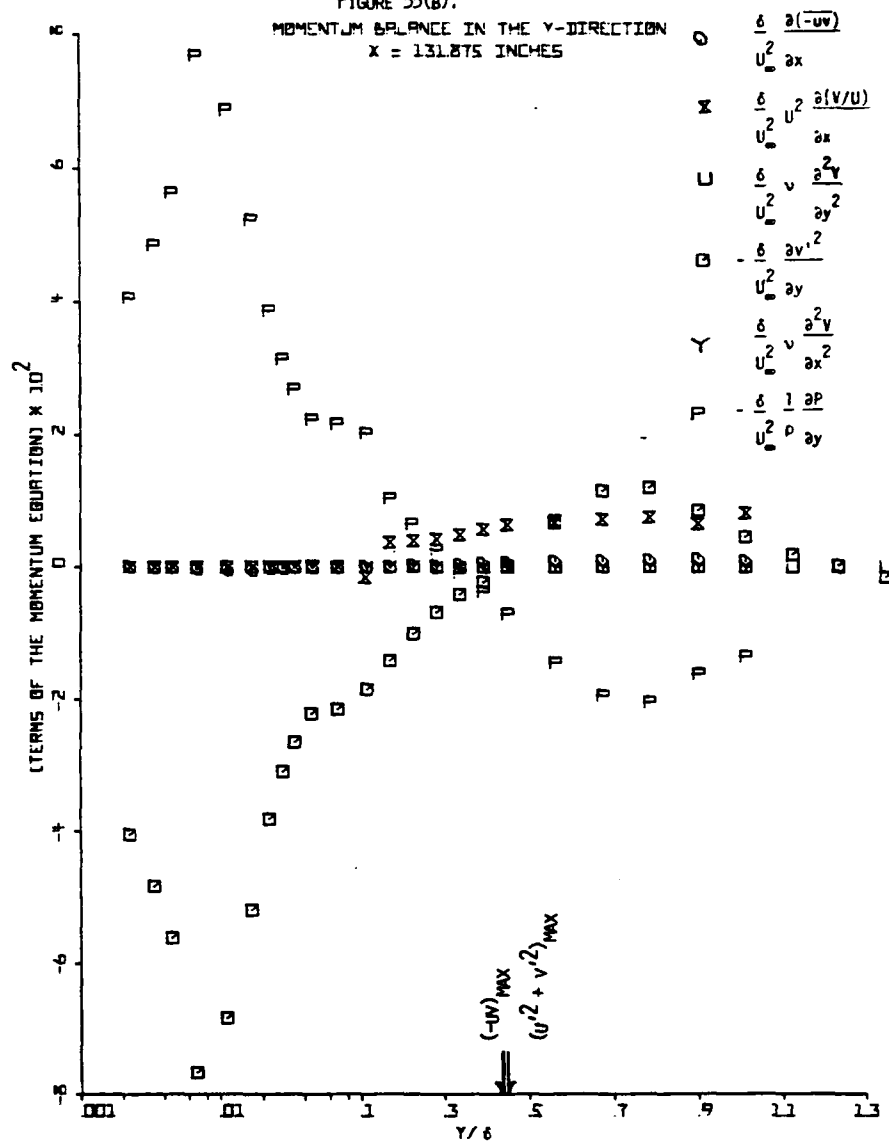
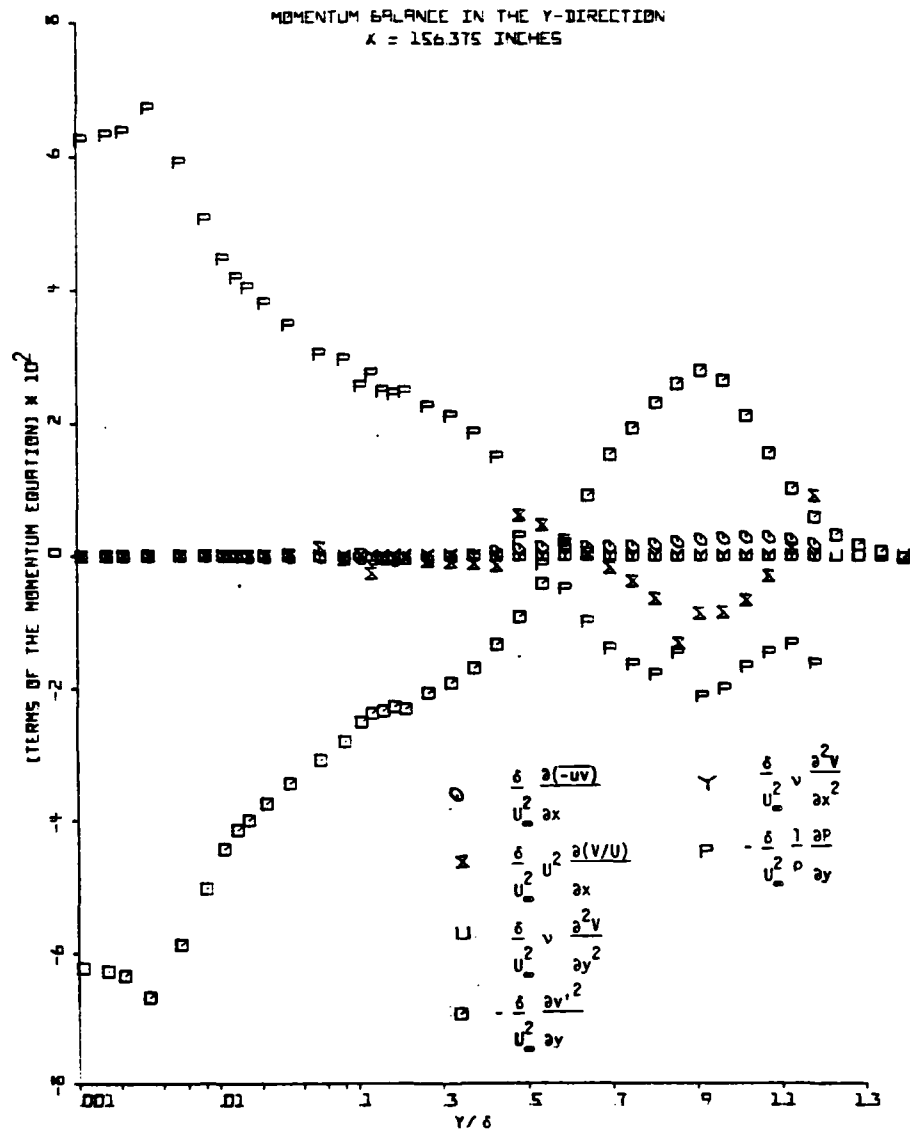


FIGURE 55(c).
MOMENTUM BALANCE IN THE Y-DIRECTION
X = 156.375 INCHES



eqn. (29), the results are in agreements within these uncertainties.

A comparison of Figure 54 indicates that in the separated region the convective terms become unimportant in the inner layer. The momentum transfer due to shear mainly balances the x-direction pressure gradient. In the outer region in addition to the important convective terms, the normal stresses term becomes important as separation is approached, as has already been shown by Simpson et al. (1977). The normal stresses play an important role in the vicinity of the maximum shear stress. At 118 inches, the normal stresses term is still quite small. The momentum balance at 112 inches shows that the normal stresses term is more important. Its importance increases progressively downstream as can be seen from Figures 54 (b) and (c), which show that this term contributes up to half of the momentum transport in the outer region. This is shown more clearly in Figures 56 (a) and (b) by the distributions of the ratio of the normal stresses term to the shear stress term. However, due to uncertainties in the gradients the uncertainty of these results in the outer region is large, as shown in Table 5. Thus the inner layer in the separated region could be modeled by neglecting the convective terms while in the outer layer the additional effect of the normal stresses must be included.

Figures 57 show the importance of the normal stresses turbulence energy production from just upstream of intermittent separation to far downstream. The results for the Bradshaw (1967) flow are in qualitative agreement with the data shown in Figure 57. (a). Figures 58 (a) and (b) show the ratio of the normal stresses production to the shear production for the several locations in the vicinity of separation. As indicated by the present data and the data of Simpson et al. (1977) and Schubauer and Klebanoff (1950), the normal stresses

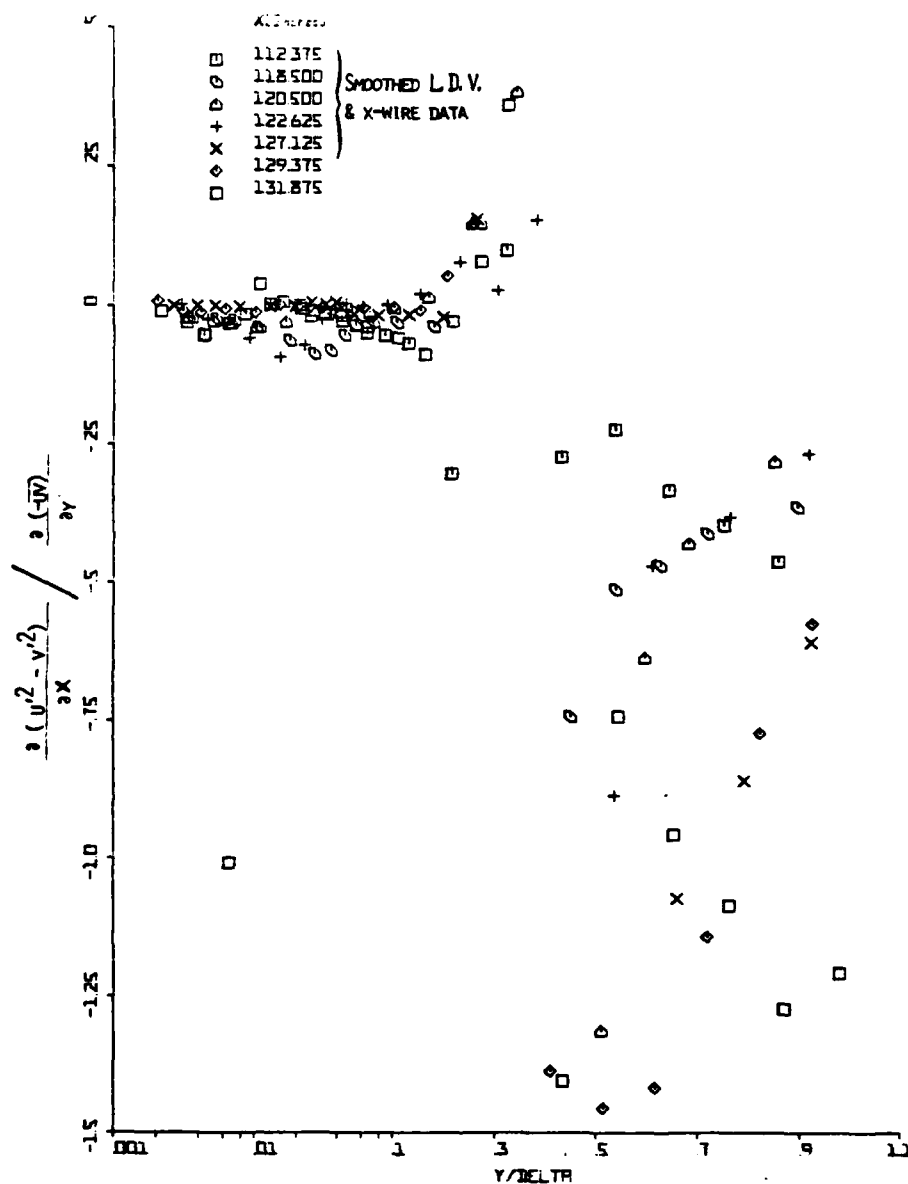


Figure 56(a), Ratio of normal stresses to shear stress terms in the momentum equation: upstream of separation.

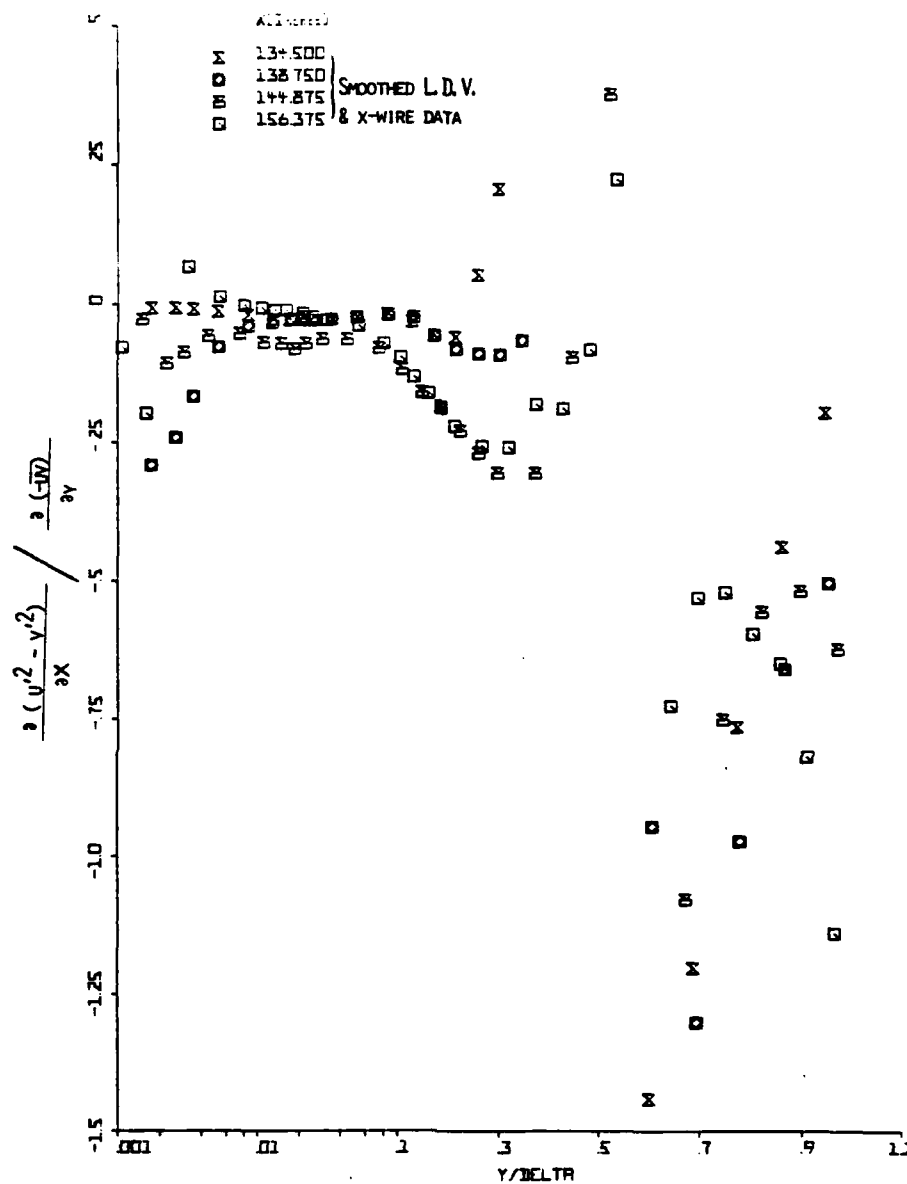


Figure 56(b). Ratio of normal stresses to shear stress terms in the momentum equation: downstream of separation.

FIGURE 57(A).
ENERGY BALANCE
 $x = 11.85$ INCHES

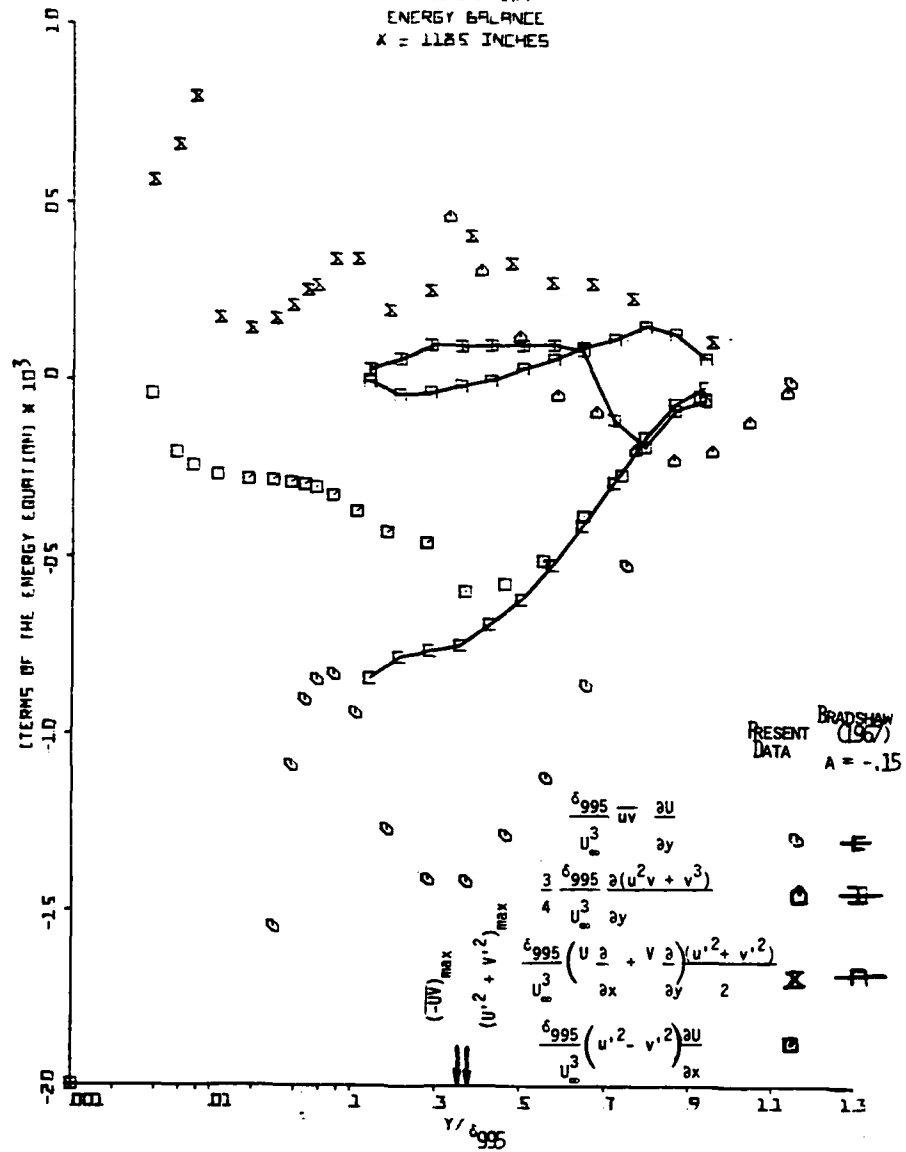


FIGURE 57(B).
ENERGY BALANCE
X = 131.875 INCHES

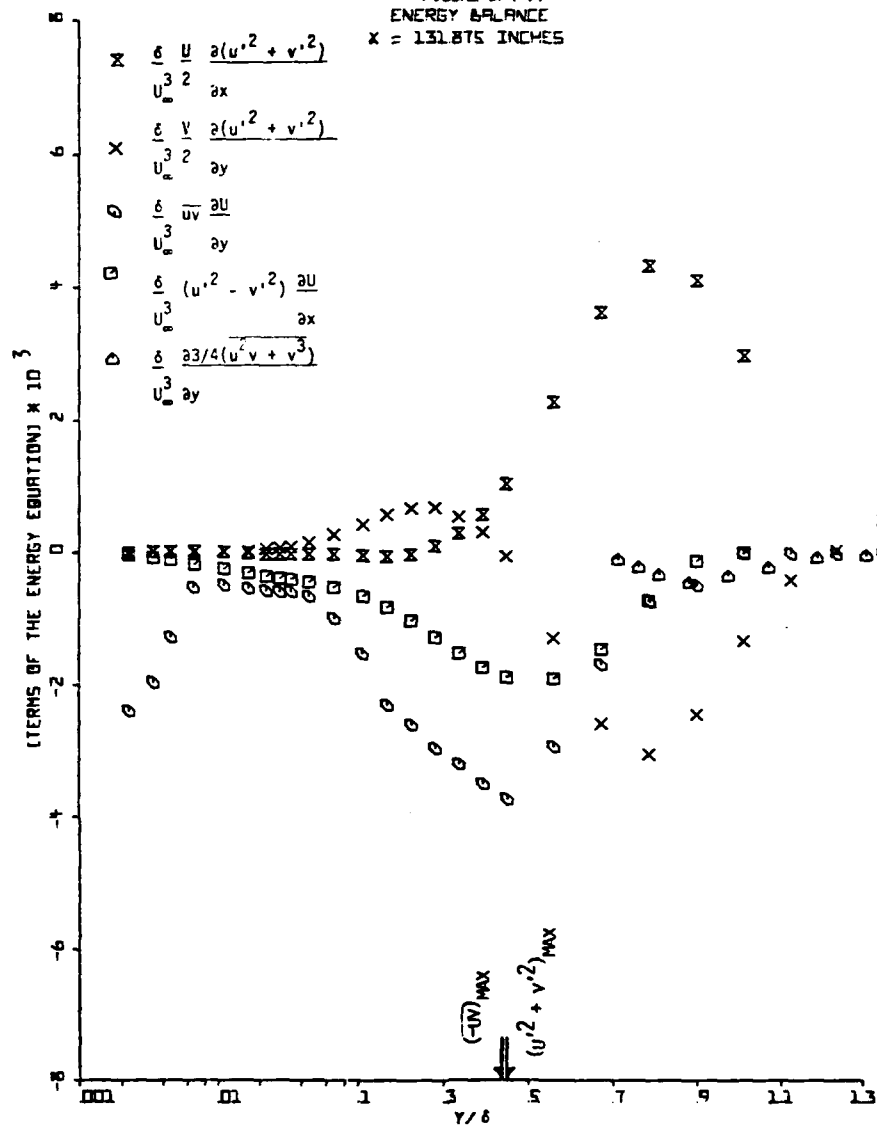
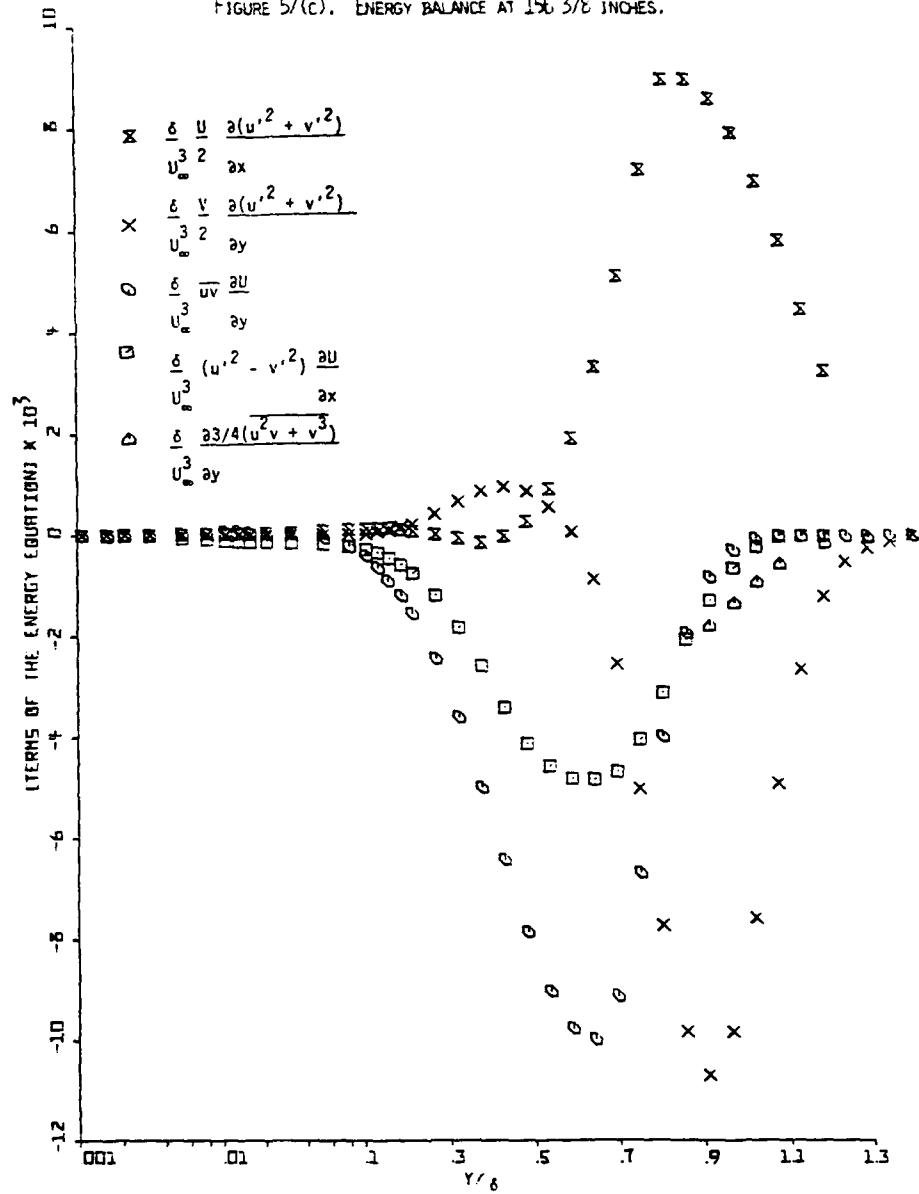


FIGURE 57(c). ENERGY BALANCE AT 156 3/8 INCHES.



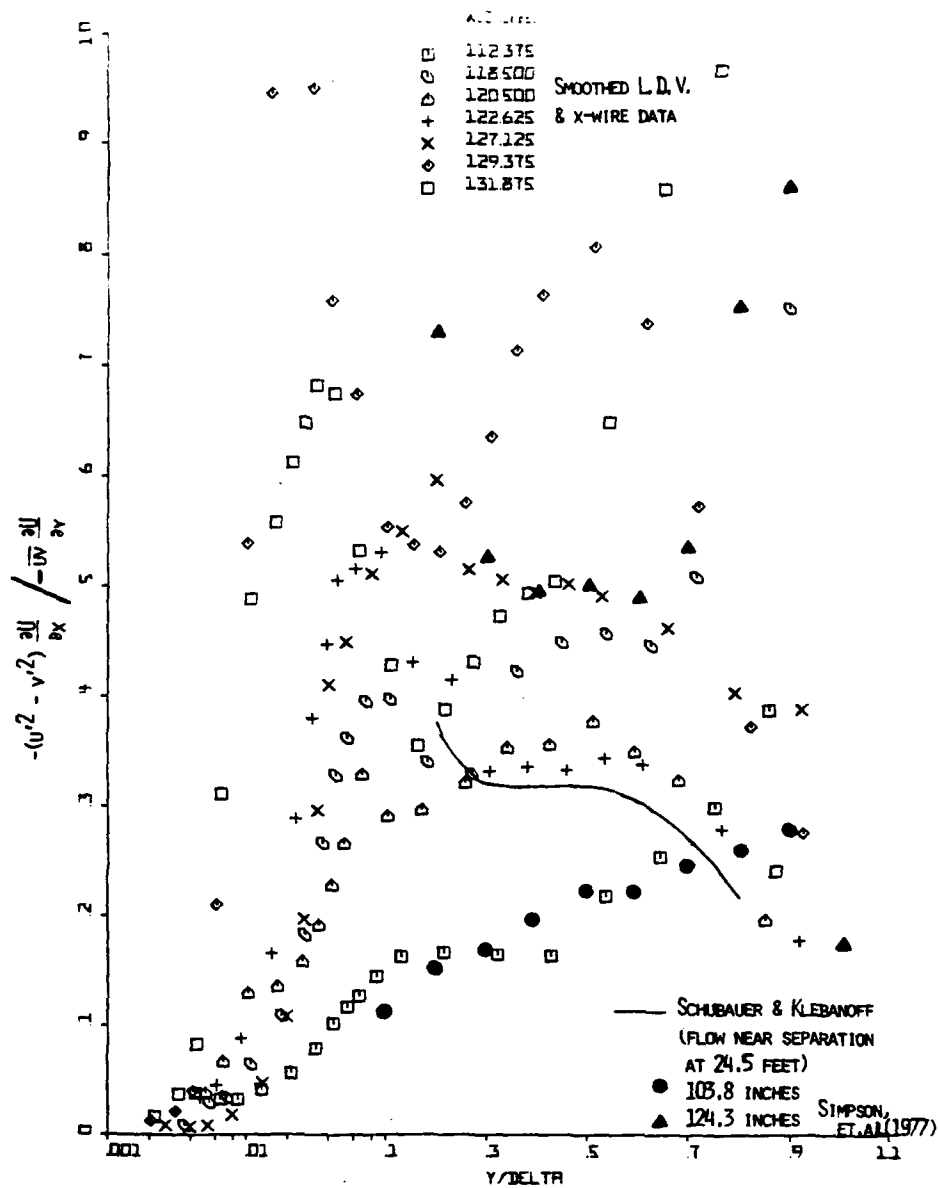


Figure 58(a). Ratio of normal stresses production to shear stress production upstream of separation.

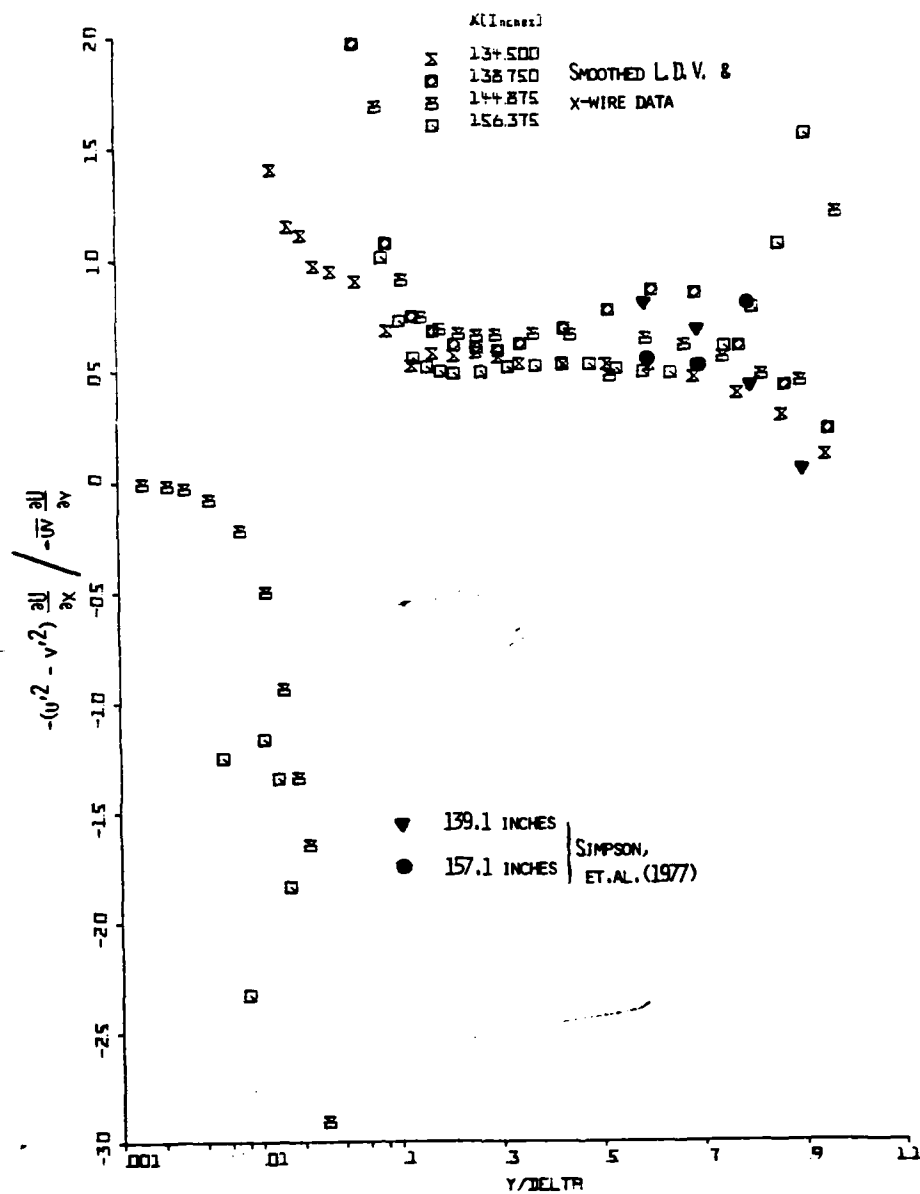


Figure 58(b). Ratio of normal stresses production to shear stress production downstream of separation.

effect becomes increasingly important as separation is approached. In fact both sets of SMU data show good agreement in the corresponding regions of development, with a near doubling of the ratio in the intermittent separation region. The present data in that region indicate the presence of a hump in the distributions near y/δ of 0.05 to 0.1, which becomes more significant as separation is approached. This is a result of the mean velocity profiles becoming inflexional in nature, which produces a reduced $\partial U/\partial y$ in that region. In fact these humps increase rapidly along the flow until $\partial U/\partial y$ attains a zero value for each profile in the backflow region where the velocity reaches a minimum value. The earlier data of Simpson et al. (1977) at 124.3 inches also suggest the presence of a hump. In the backflow region the two types of production oppose each other as shown in Figure 58 (b), but they aid one another in the forward flow region. The distributions in the outer layer tend toward similarity and the ratio seems to be almost a constant of 0.6 for $0.2 \leq y/\delta \leq 0.7$.

As far as shear production alone is concerned, the present data in the region upstream of separation is in agreement with those of Spangenberg et al. (1967) and others who observed two peaks in distributions for boundary layers subjected to large adverse pressure gradients. The present data indicate that as separation is approached, the peak near the wall becomes weaker until it vanishes in the region of fully-developed separation. In the backflow zone of the separated region there is no shear production as indicated by Figure 57 (c) and advection is also insignificant. Hence the only mode by which turbulence energy can reach the backflow zone is by turbulent diffusion. This conclusion is consistent with the results discussed in section IV.3.D above: diffusion plays a major role in transporting the turbulent kinetic energy in separated flows from the middle part of the layer, where it is mainly produced, to the outer region and

the region near the wall. The absence of production near the wall in separated flow also leads one to conclude that the backflow near the wall is controlled by the large-scaled outer region flow, rather than by some wall-shear-stress-related "law of the wall".

V.5 Effects of Normal Stresses on Turbulence Correlations

As noted above in section V.4 and in the earlier work of Simpson et al. (1977), the normal stresses turbulence energy production terms are important in separating flows. Simpson et al. defined a nondimensional factor F as the ratio of total turbulence energy production to the shear-stress-related turbulence energy production

$$F = 1 - \frac{(u'^2 - v'^2)\partial U/\partial x}{-\overline{uv} \partial U/\partial y} \quad (33)$$

Figures 58 show $F-1$. Following Collins and Simpson (1976), the turbulence parameters in the expression for F can be inter-related so that F can be expressed as a function of the rate of strain ratio. The F factor can then be incorporated into some of the turbulence models and correlations to account for normal stresses effects.

Collins and Simpson expressed

$$(u'^2 - v'^2) = C_1 \overline{q^2} \quad (34)$$

However, the present data available at a number of streamwise locations indicate that at the location of the maximum shearing stress a better expression is

$$(u'^2 - v'^2) = \frac{C_2 \overline{q^2}}{F^{1/3}} \quad (35)$$

This reduces to equation (34) for flat plate flow with $F = 1$. Collins and Simpson found C_1 to be a constant equal to 0.32 for Klebanoff's (1954) zero

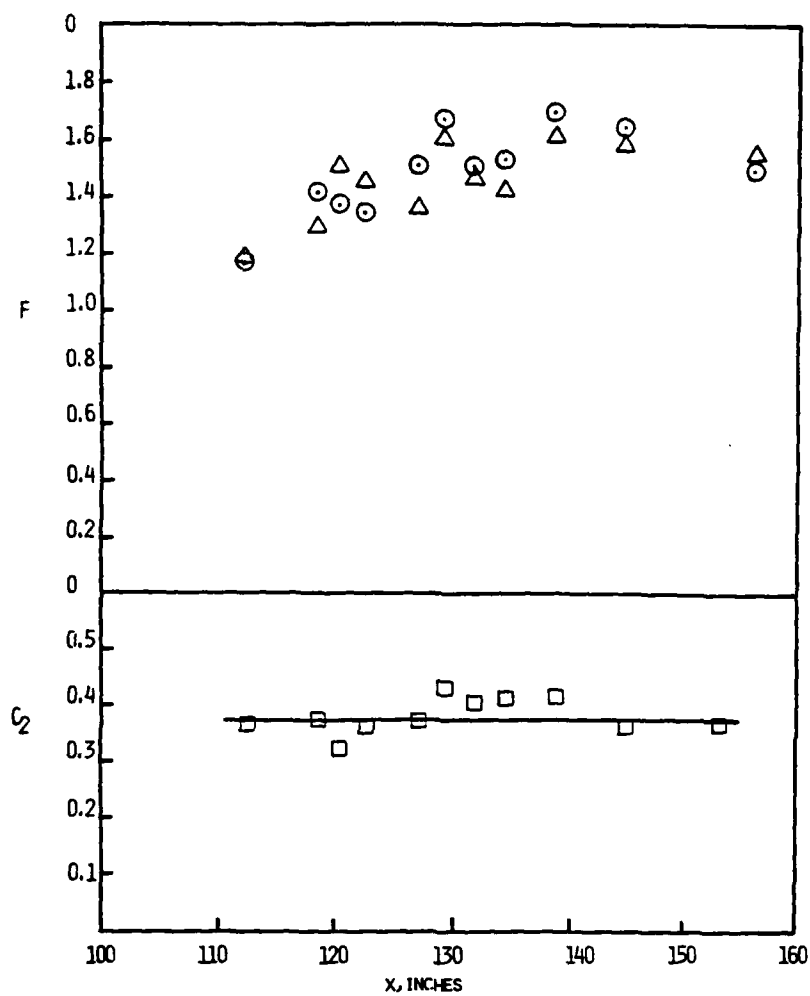
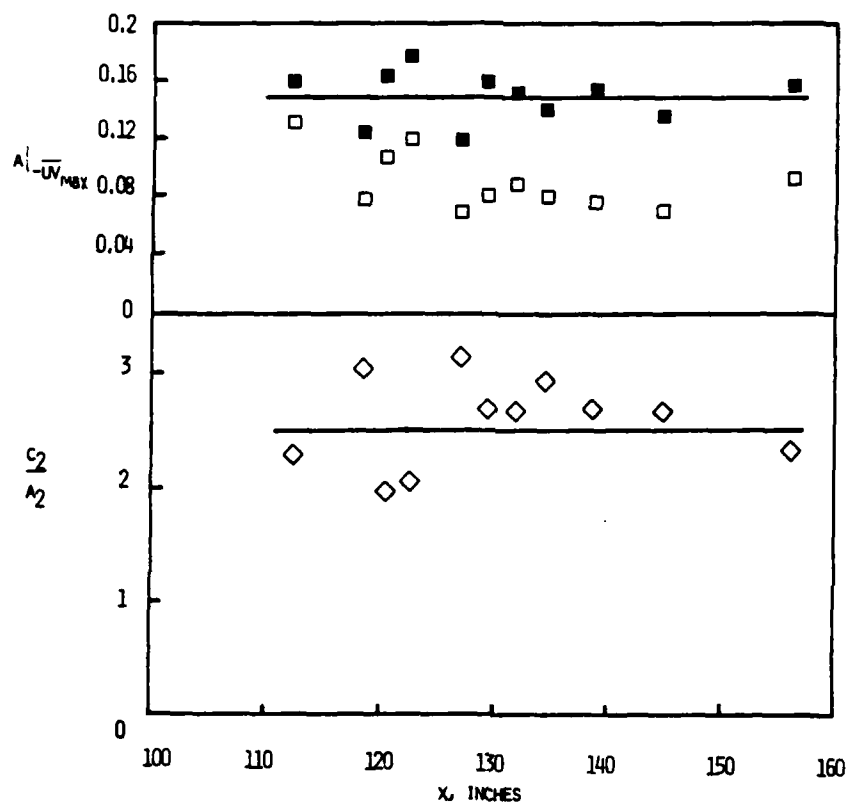


FIGURE 59 (A). NORMAL STRESSES PRODUCTION FACTOR F GIVEN BY $\odot$, FROM EQUATION (35) AND Δ , FROM EQUATION (37). (B) $\square$ CONSTANT C_2 FROM EQUATION (35). SOLID LINE IS AVERAGE VALUE.

FIGURE 59 (c). $\square$, $-\overline{uv}/a^2$; $\blacksquare$, A_2 GIVEN BY EQUATION (36); SOLID LINE FOR FLAT PLATE BOUNDARY LAYER WITH $F = 1$. (d) $\diamond$, c_2/A_2 FROM EQUATION (37) AT THE MAXIMUM SHEAR STRESS LOCATION; SOLID LINE IS AVERAGE VALUE.



pressure gradient flow and 0.28 and 0.23 for Bradshaw's (1967) adverse pressure gradient flow. In view of the definition for C_2 in equation (35) the separating flow of Simpson et al. (1977) yields values for C_2 of 0.33 at 88 inches where $F = 1$ and 0.44 at 103.8 and 124.3 inches. The distribution of C_2 for present data is shown in Fig. 59 (b) and an average value of 0.375, which lies within the experimental uncertainty of 26%, was chosen for further analysis.

The Reynolds shearing stress can also be related to F and q^2 by a modification to Bradshaw's correlation

$$-\overline{uv} = a_2 q^2 / F^{4/3} \quad (36)$$

Figure 59 (c) shows that this is a good fit to the present data at the location of the maximum shearing stress with $a_2 = 0.15$. Equations (33), (35), and (36) can be combined into the form

$$F = \frac{1}{1 + \frac{C_2}{a_2} \frac{\partial U / \partial x}{\partial U / \partial y}} \quad (37)$$

at the location of the maximum shearing stress. As shown in Figure 59 (d), C_2/a_2 is nearly a constant within the experimental uncertainty of $\pm 17\%$ with an average value of 2.5, which is close to the value of 2.0 used by Collins and Simpson in the prediction model for separating flows. Figure 59 (a) shows that equation (37) agrees with equation (33) within the experimental uncertainty of $\pm 14\%$.

A two term binomial expansion of equation (37) is similar to Bradshaw's (1973) F factor used to account for the effect of extra strain rates in complex

turbulence flows. However, unlike the case with Bradshaw's factor the constant C_2/a_2 is derived directly from the turbulence structure and is not just an empirical constant derived from tuning a prediction method.

As shown in Figures 41 and 42, the mixing length and eddy viscosity distributions in the outer region decrease in magnitude in the downstream direction. This seems to be consistent with Gartshore's (1967) suggestion of decreased Reynolds stress in flows with an extra strain rate $\partial V/\partial y$, as in his own experiments on retarded wakes. Figures 60 (a) and (b) show these parameters at the maximum shearing stress for each location. F was fit to these data with the following results.

$$\frac{\ell}{\delta} = \left(\frac{1}{F^{1.25}} \right) \frac{\ell}{\delta} \bigg|_{F=1} \quad (38)$$

and

$$\frac{v_e}{U_\infty \delta_1} = \left(\frac{1}{F^{1.5}} \right) \frac{v_e}{U_\infty \delta_1} \bigg|_{F=1} \quad (39)$$

These fits were obtained in the following manner. The normally accepted value of 0.08 was used for ℓ/δ at $F = 1$. Using this, an average value for ℓ/δ in the outer region, and the value of F at the location of the maximum shearing stress, the exponent on F in equation (38) was determined at each streamwise location. This exponent was within 12% of 1.25 and the modified correlation $F^{1.25} \ell/\delta$ agrees within the limits of experimental uncertainty of 21% with the normally accepted value of 0.08.

For evaluating the exponent in equation (39), all values were taken at the location of the maximum shearing stress; 105.3 inches was considered the location where $F = 1$. Equation (39) agrees with the data within the uncertainty of 26%.

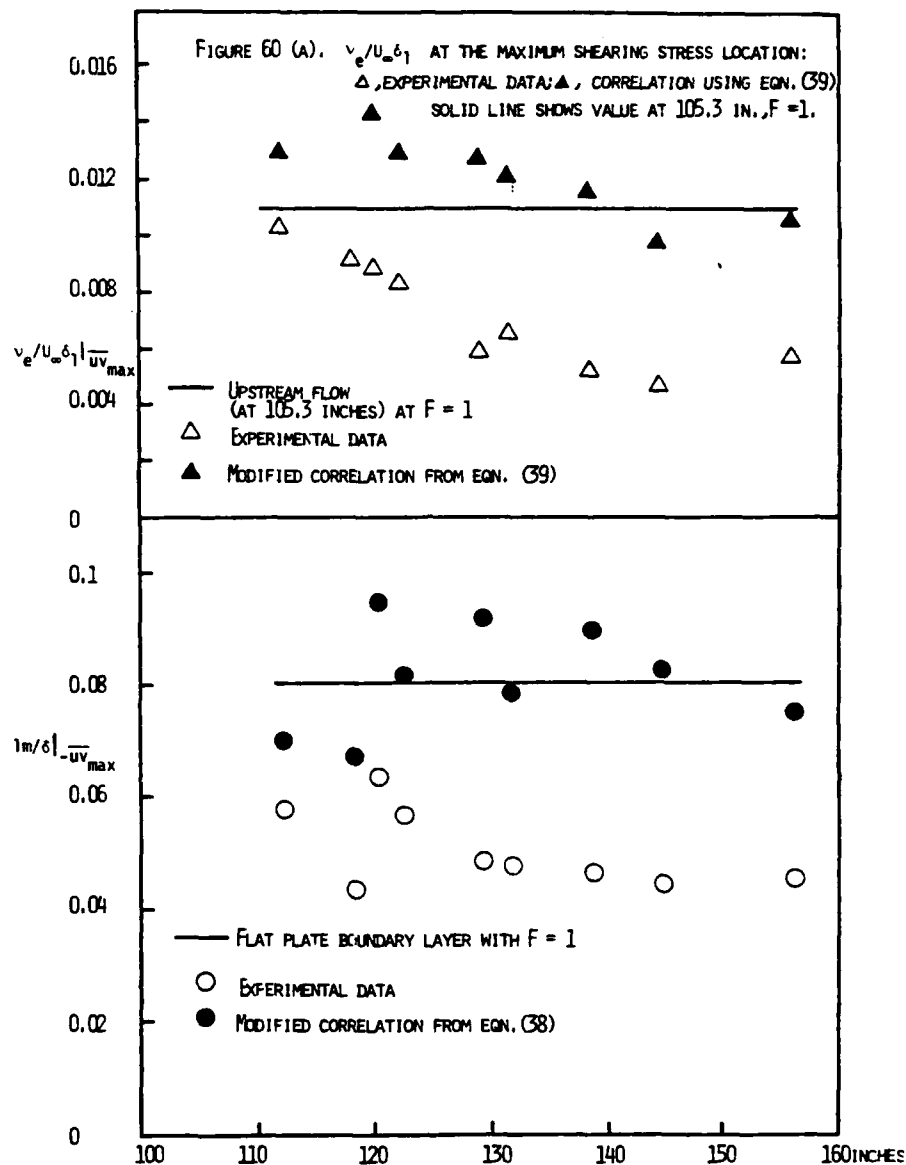


FIGURE 60 (B). $1m/\delta$ AT THE MAXIMUM SHEARING STRESS LOCATION:
 $\circ$, EXPERIMENTAL DATA; $\bullet$, CORRELATION USING
 EQUATION (38); SOLID LINE FOR FLAT PLATE
 BOUNDARY LAYER WITH $F=1$.

V.6 Characteristic Frequencies from Spectra in Separated Flow

Strickland and Simpson (1975) showed that the characteristic bursting frequency could be determined by the peak in the first moment of the spectra $nF(n)$ of the wall shearing stress. These characteristic frequencies for the Simpson et al. (1977) separating flow correlated with the outer flow velocity and length scales, U_∞ and δ , as do the bursting frequencies for the zero-pressure-gradient case. However, $U_\infty/\delta n_b$ was between 11.7 and 8.35 for that separating flow, whereas values of about 5 are reported for the zero-pressure-gradient case. The basic conclusion of these earlier results is that the characteristic frequency of the most energetic turbulent fluctuations scale on the large-scale structure of the shear flow.

In the earlier work of Simpson et al. (1977) no spectral measurements in the separated flow were made. In the present flow spectral data for u were obtained from the laser anemometer velocity signals. Since the LDA signal data rate was under 400 signals per second and signal dropout was present, the spectra are only reliable under 100Hz. The first moment of each spectral distribution $nF(n)$ was obtained and the frequency of the peak was selected as the characteristic frequency n_b . In many cases the $nF(n)$ peak was constant over a frequency range, which is represented in Figures 61 as a line over the range of $U_\infty/\delta n_b$ values for a spectrum at a given y/δ .

Figure 61a shows that upstream of intermittent separation $U_\infty/\delta n_b$ is essentially constant throughout the inner flow region with a value of about 10 ± 3 . At successive downstream locations the range of $U_\infty/\delta n_b$ for a given $nF(n)$ peak becomes progressively larger near the wall as shown in Figure 61 (b-f). In most cases a single frequency characterises the $nF(n)$ peak in the outer region. $U_\infty/\delta n_b$

FIGURE 61(A).
 $x = 112.375$ INCHES

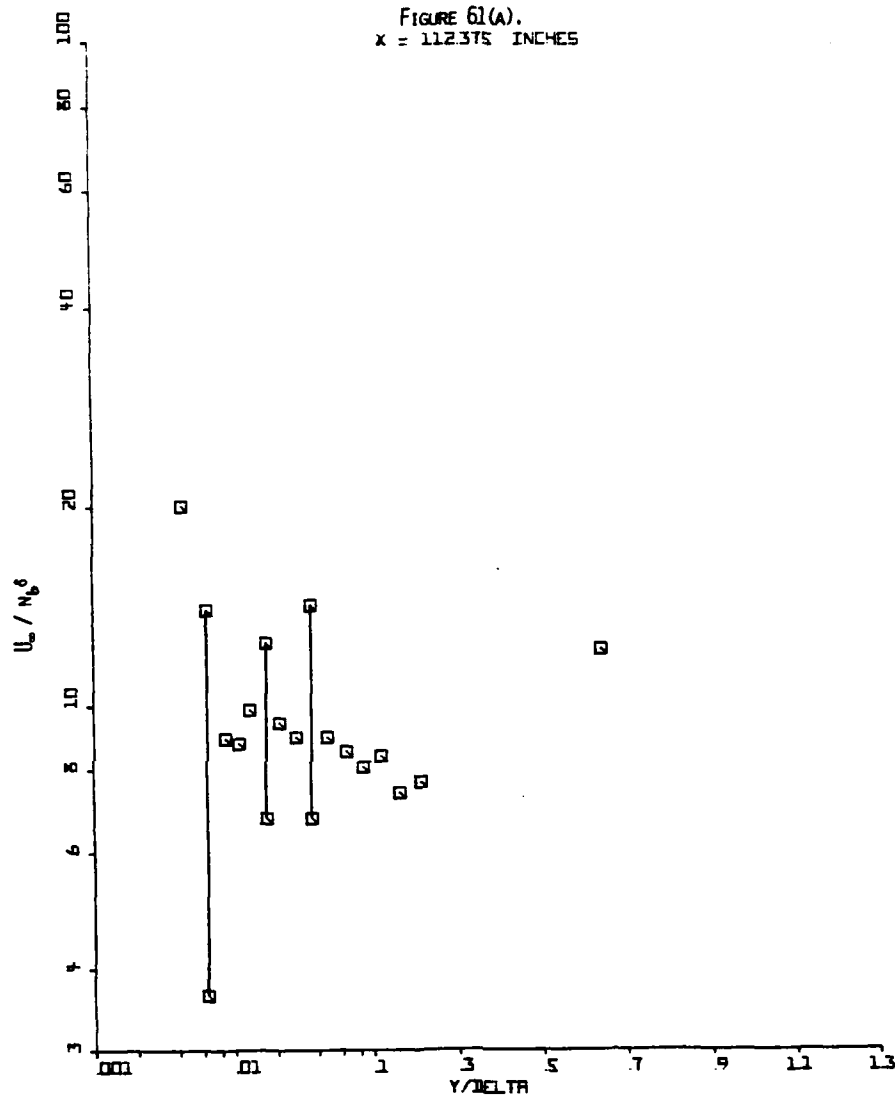


Figure 61(a). Characteristic frequency parameter $U_\infty / N_b \delta$
 vs. y/δ .

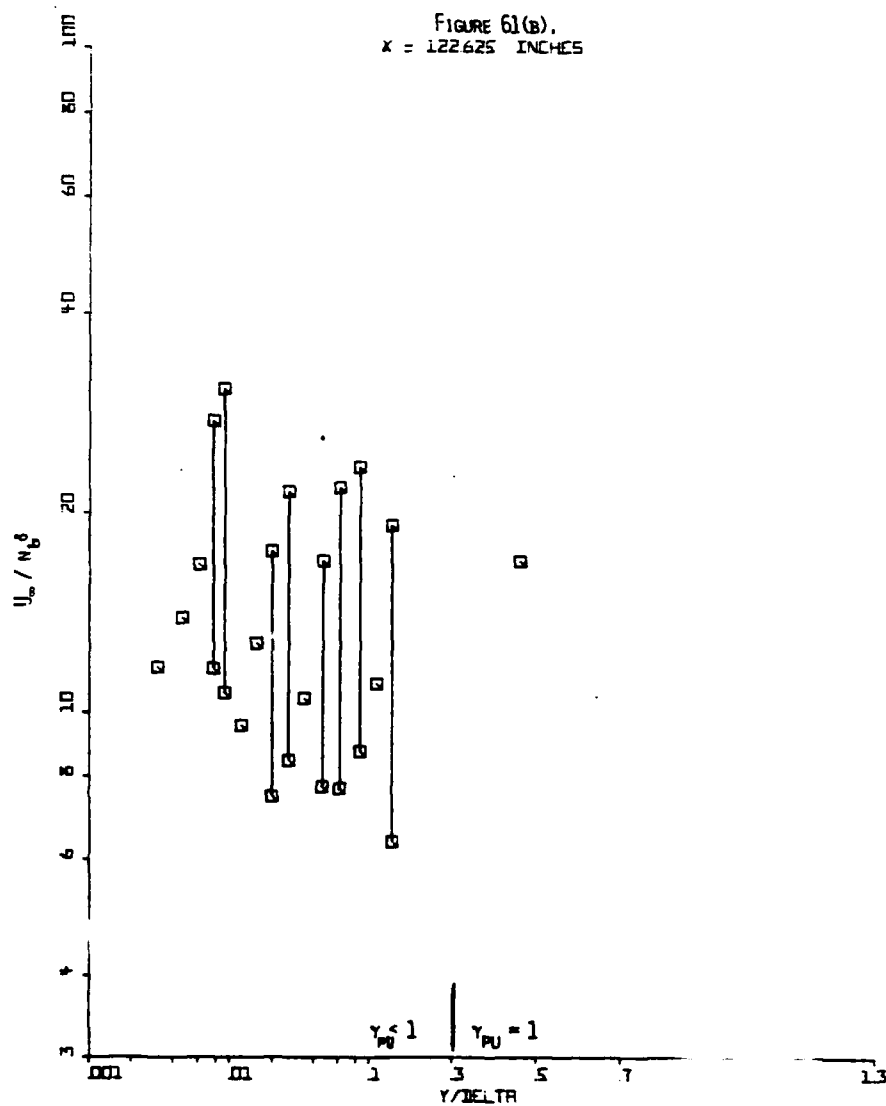


Figure 61(b). Characteristic frequency parameter $U_{\infty} / n_b \delta$ vs. y / δ .

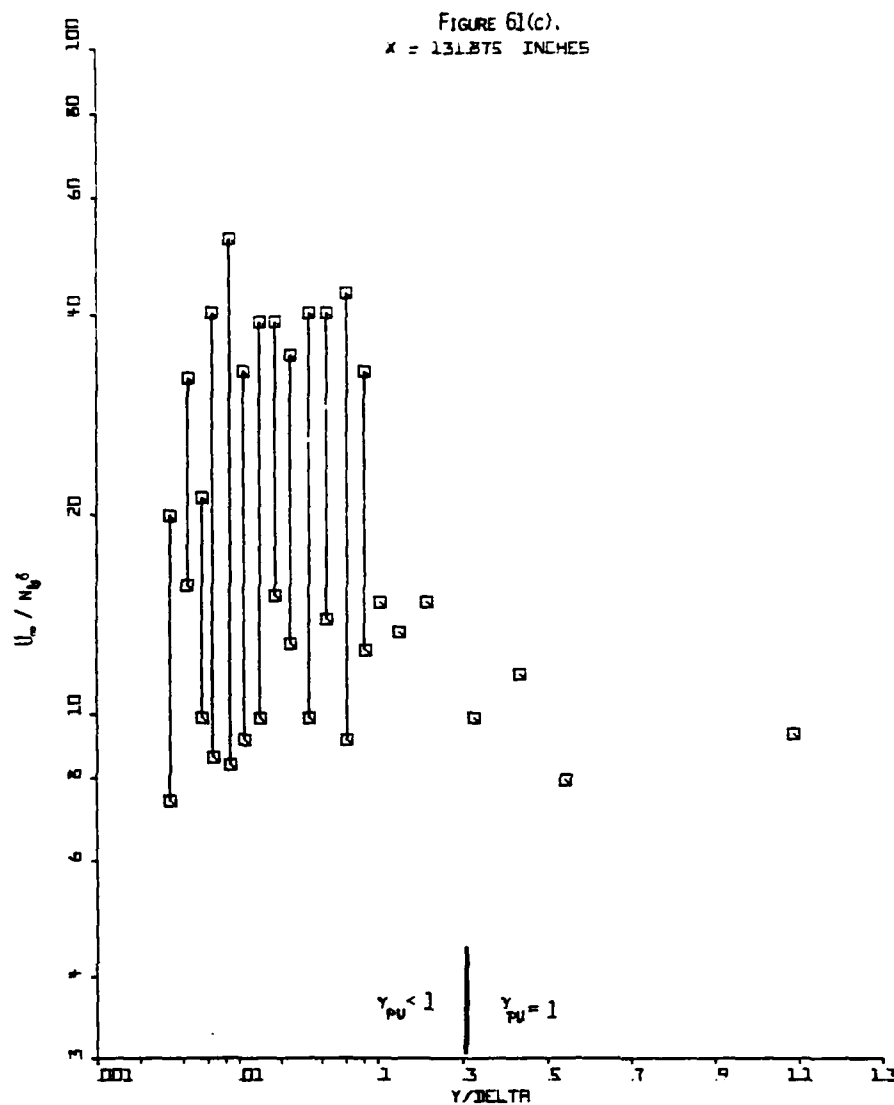


Figure 61(c). Characteristic frequency parameter $U_\infty / n_b \delta$ vs. y / δ .

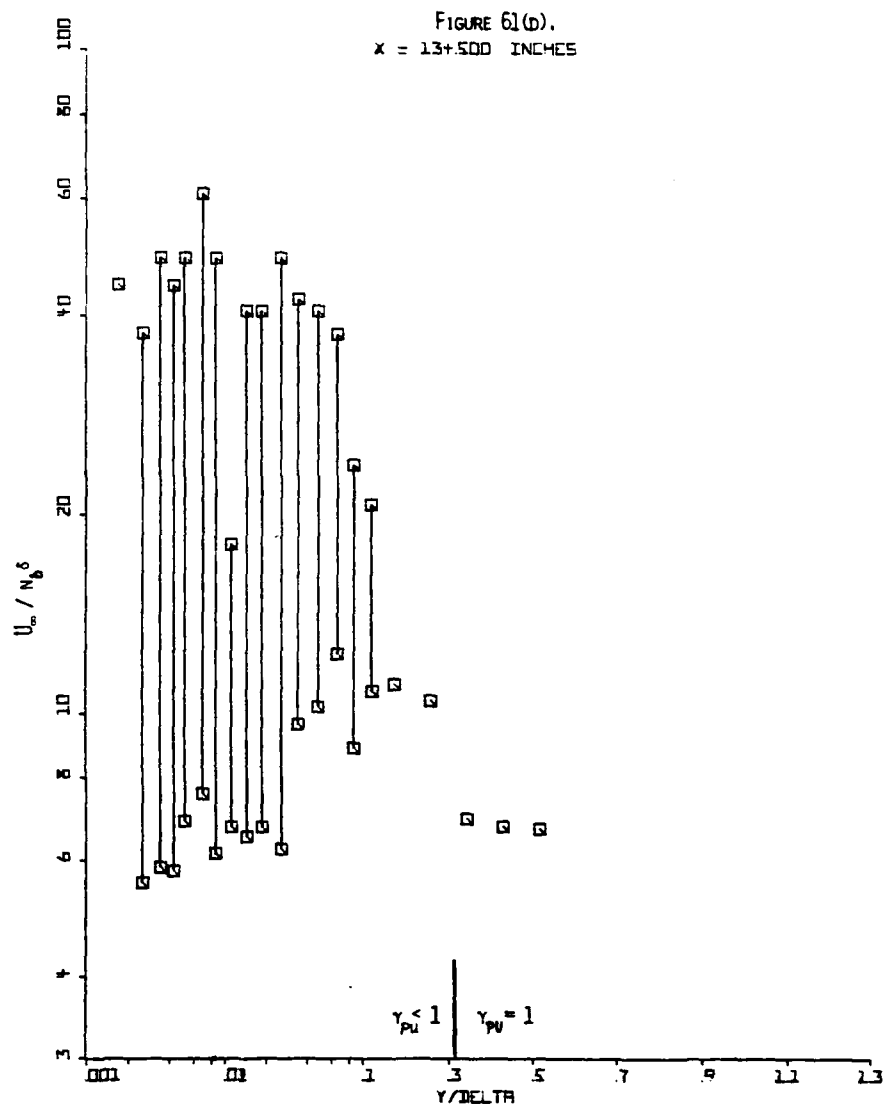


Figure 61(d). Characteristic frequency parameter $U_{\infty} / n_b \delta$ vs. y/δ .

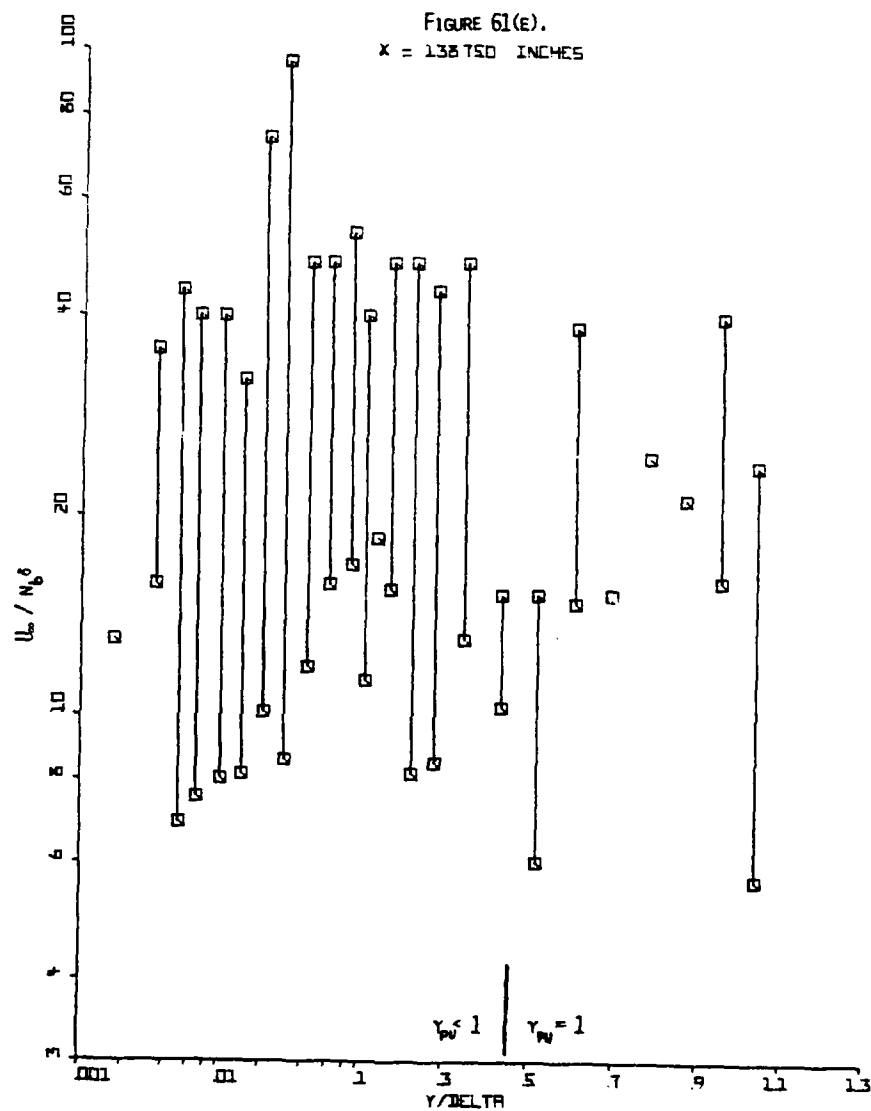


Figure 61(e). Characteristic frequency parameter $U_{\infty} / n_b \delta$ vs. y/δ .

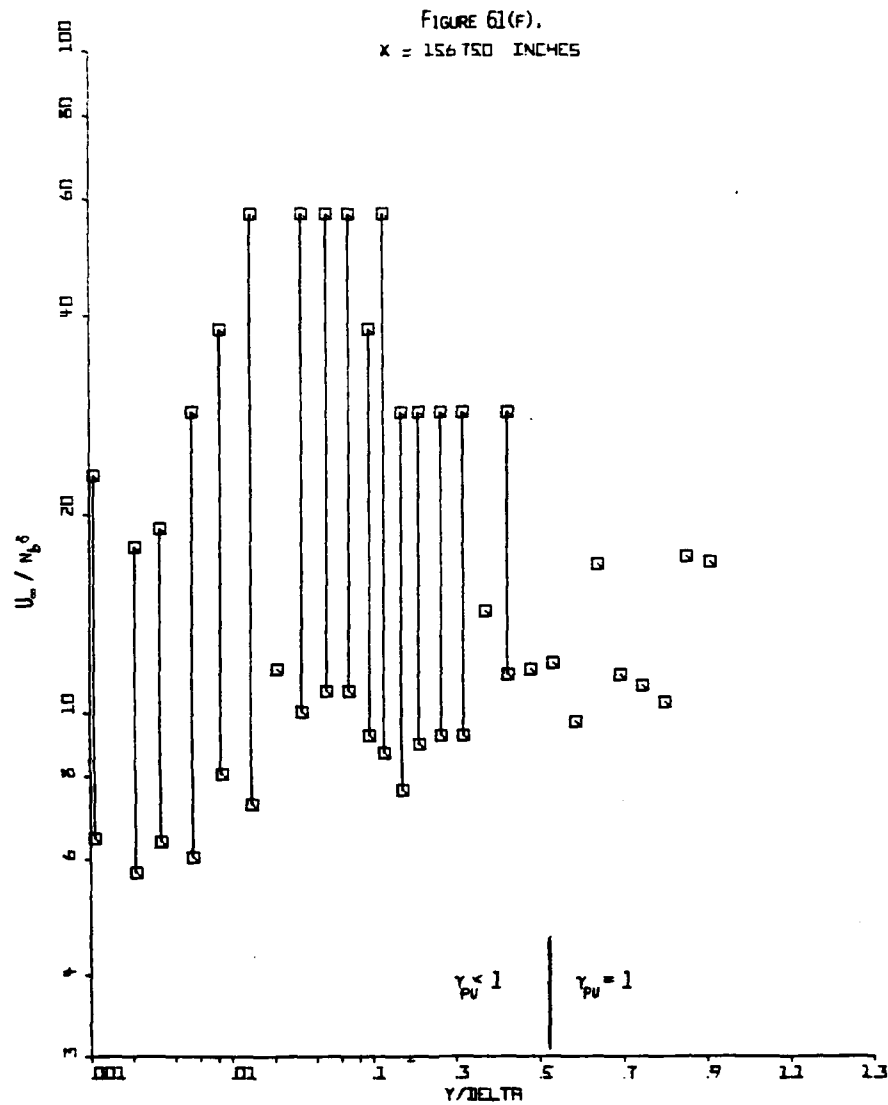


Figure 61(f). Characteristic frequency parameter $U_{\infty} / n_b \delta$ vs. y/δ .

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is about 10 ± 3 at the lower end of the $U_\infty/\delta n_b$ bands. The upper values of $U_\infty/\delta n_b$ are about 40 or so in the inner region.

These results indicate that the characteristic frequency of the outer region correlate with U_∞ and δ along the flow, with an approximately constant value of $U_\infty/\delta n_b$ of about 10 ± 5 . This is consistent with the earlier work of Simpson et al. (1977). Nearer the wall the frequency range of the energetic turbulent motions descends to frequencies one-fourth as large.

For attached boundary layers the spectra for the near wall flow have a range of frequencies over which the peak of each $nF(n)$ distribution is constant (Rotta, 1962). This is a consequence of the logarithmic law-of-the-wall velocity profile. For a separated flow the law-of-the-wall is not valid, so a different explanation of the $nF(n)$ distribution near the wall is needed. The upper frequency end of the $nF(n)$ peak is at approximately the same frequency as the outer region peak frequency. Note from Figs. 61 (b-f) that the wide frequency spectral peaks seem to occur at locations near the wall where $\gamma_u < 1$.

One simple speculation is that the celerity or speed of the eddies in the backflow region is much lower than that in the outer region. Fig. 17 of Simpson et al. (1977) supports this idea. Thus, as large scale structures pass through the outer flow at a frequency of about $U_\infty/10\delta$, these same structures move at a much lower average celerity in the backflow region, producing a much lower frequency spectrum.

VI. CONCLUSIONS - The Nature of a Separating Turbulent Boundary Layer

These experiments confirm the conclusions of Simpson et al. (1977) regarding a separating airfoil type turbulent boundary layer. The mean flow upstream of the beginning of intermittent separation obeys the law-of-the-wall and the Perry and Schofield (1973) velocity profile correlation for the outer region.

Sandborn's correlations for the locations of intermittent separation ($\gamma_u = 0.8$) and fully-developed separation hold. Pressure gradient relaxation begins upstream of intermittent separation near the wall jet control in this flow and continues until the location of fully-developed separation. The upstream-downstream intermittency γ_u , u' , and v' , and $-\overline{uv}$ profiles each approach similarity profiles downstream of separation. The frequency of passage of the outer region large scale eddies n_b scales on the free-stream velocity U_∞ and the boundary layer thickness δ . Normal stresses effects contribute significantly to the momentum and turbulence energy equations.

Much new information about the separated region has been gathered and leads to significant conclusions about the nature of the separated flow. For reference the most important results are summarized below.

1. The backflow mean velocity profile scales on the maximum negative mean velocity U_N and its distance from the wall N . A U^+ vs. y^+ law-of-the-wall velocity profile is not consistent with this correlation since both U_N and N increase with streamwise distance, while the law-of-the-wall length scale ν/U_τ varies inversely with the velocity scale U_τ . It does not appear possible to describe the separated flow mean velocity profiles by a universal "backflow function" that is added to a universal "wake function".
2. High turbulence levels exist in the backflow. u' and v' are of the same order as $|U|$. Since the free-stream velocity in the separated region is rather steady, this means that the near wall fluctuations are not mainly due to a flapping of the entire shear layer, but are due to turbulence within the separated shear layer.

3. Low levels of Reynolds shearing stress occur in the backflow. $-uv/u'v'$ and $-\overline{uv}/(\overline{u'^2} + \overline{v'^2})$ correlations are low in the backflow, but are comparable with those for mixing layers in the outer region.
4. Mixing length and eddy viscosity models are adequate upstream of separation and in the outer region, but are physically meaningless in the backflow. Normal stresses effects appear to account for the lower mixing length and eddy viscosity values observed in the outer region of the separated flow.
5. In the separated flow between the wall and the locations of the minimum mean velocity, the skewness factor for u , S_u , is negative. Between this point and the locations of the maximum shearing stress, S_u is positive. The flatness factor F_u reaches a local maximum of about 4 at the minimum mean velocity location. S_v has a profile shape and magnitudes that are approximately the mirror image or negative of S_u .
6. Negligible turbulence energy production occurs in the backflow. Normal and shear stresses production in the outer region supply turbulence energy to the backflow by turbulent diffusion. These results are consistent with the absence of a logarithmic mean velocity profile in the backflow, since classical turbulence energy production arguments indicate that the rate of production must equal the rate of dissipation in such a region.

These turbulence energy results lead to the conclusion that the backflow is controlled by the large-scale outer region flow. Movies of laser-illuminated smoke also have clearly revealed that the large eddy structure supplies most of

near wall backflow. The small mean backflow does not come from far downstream as suggested in Figure 62(a), but appears to be supplied intermittently by large-scale structures as they pass through the separated flow as suggested by Figure 62(b).

A simple qualitative experiment was performed to determine qualitatively the influence of the downstream near wall conditions on the separation behavior. A deflection plate was located at the end of the second section (200 inches) as shown in Figure 63. For heights of this deflection plate up to 7 inches, no appreciable change in the separation zone location (122-140 inches) and behavior were noted. This result also seems to support the flow model suggested in Figure 62(b) where the backflow is supplied locally by outer region large-scale structures. Only after the deflection plate was high enough to begin to change the free-stream pressure gradient did the location of the separation zone change.

Of course, this mechanism for supplying the backflow may be dominant only when the thickness of the backflow region is small as compared with the turbulent shear layer thickness, as in the present case. Experiments (Fox and Kline, 1962) on separation in wide-angle diffusers indicate that the mean backflow can come from far downstream when the thickness of the backflow region is comparable to the thickness of the forward flow.

Downstream of fully-developed separation in these experiments, the mean backflow region appears to be divided into three layers: a viscous layer nearest the wall that is dominated by the turbulent flow unsteadiness but with little Reynolds shearing stress effects; a rather flat intermediate layer that seems to act as an overlap region between the viscous wall and outer regions; and the outer backflow region that is really part of the large-scaled outer region flow.

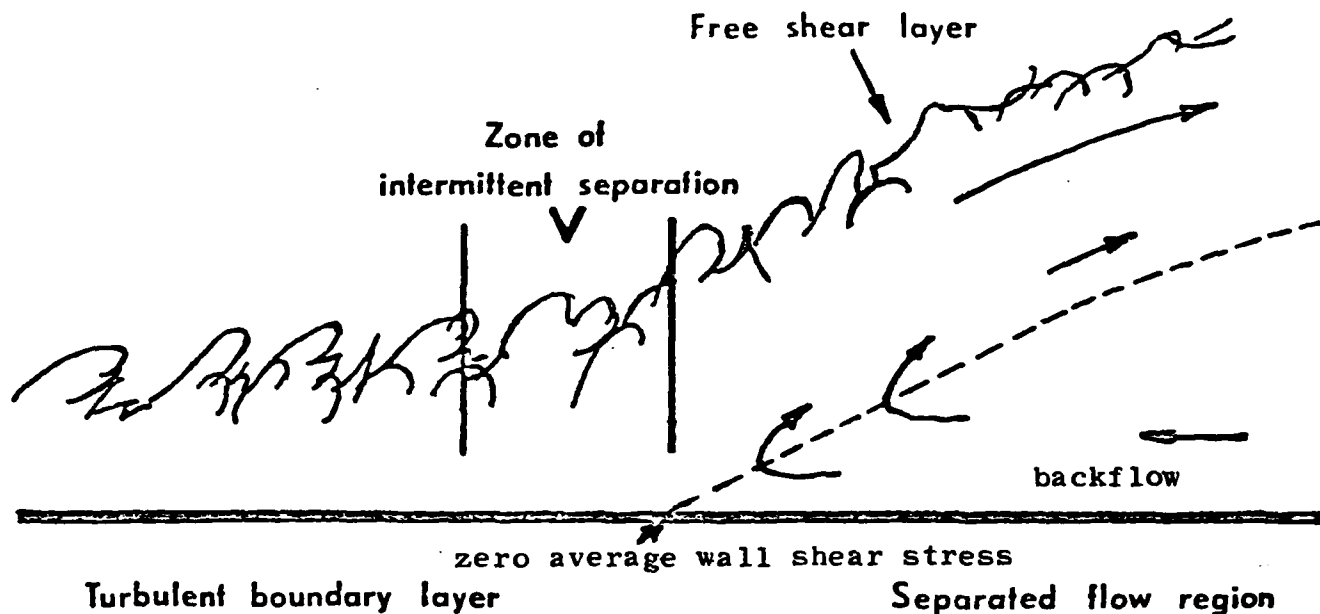


FIGURE 62 (A). TRADITIONAL VIEW OF TURBULENT BOUNDARY LAYER SEPARATION WITH THE MEAN BACKFLOW COMING FROM FAR DOWNSTREAM.

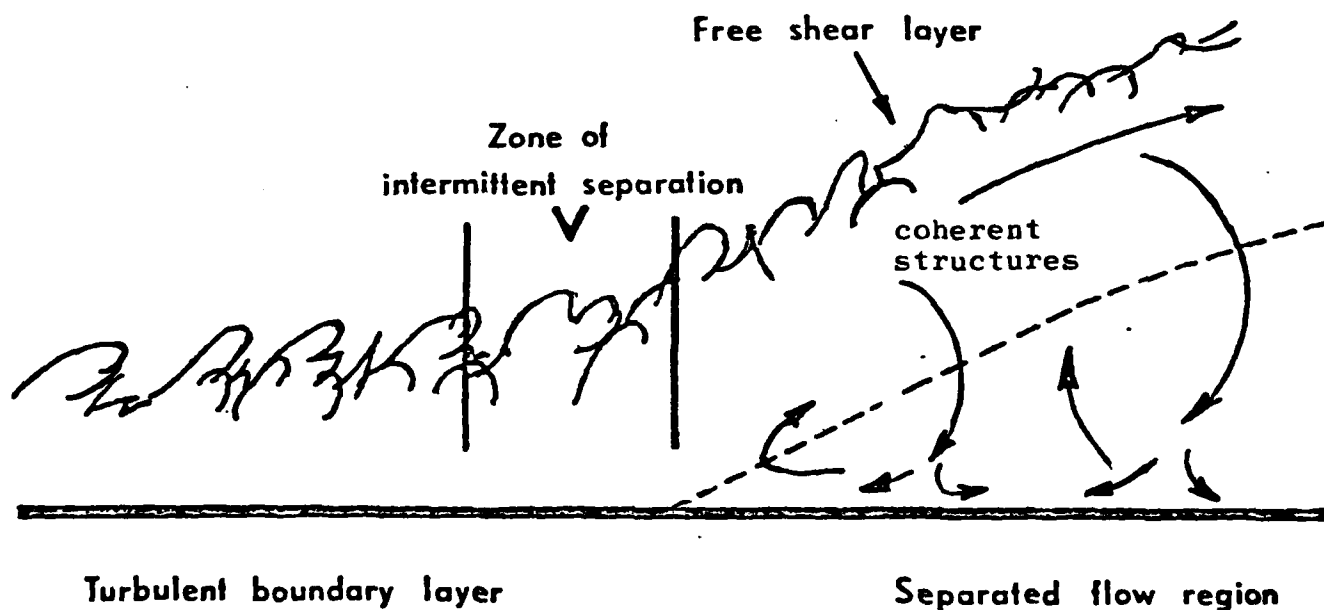


FIGURE 62 (B). A POSSIBLE FLOW MODEL WITH THE COHERENT STRUCTURES SUPPLYING THE SMALL MEAN BACKFLOW.

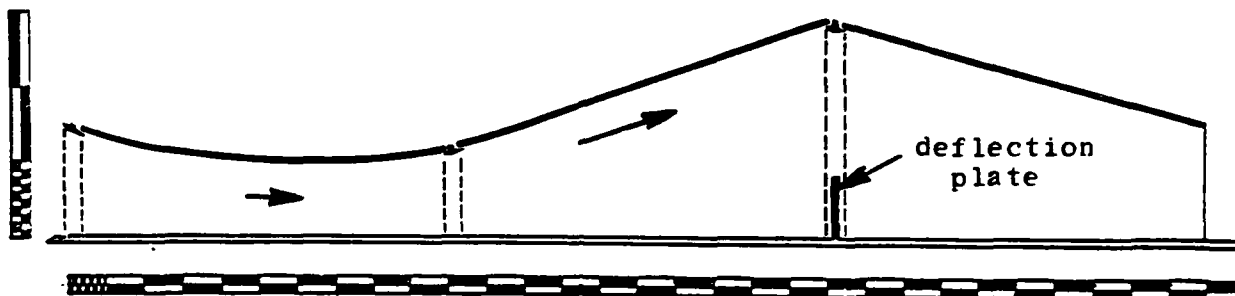


FIGURE 63. SIDEVIEW SCHEMATIC OF THE TEST SECTION FOR QUALITATIVE EXPERIMENT;
SAME AS FIGURE 1 EXCEPT FOR THE DEFLECTION PLATE.

The Reynolds shearing stresses in this region must be modeled by relating them to the turbulence structure and not to local mean velocity gradients. The mean velocity profiles in the backflow are a result of time-averaging the large turbulent fluctuations and are not related to the cause of the turbulence. In contrast, in flows for which the eddy viscosity and mixing length models appear to be useful, the instantaneous velocity gradients are not extremely different from the local mean velocity gradient and significant local turbulence energy production occurs, i.e., the Reynolds shearing stresses is physically related to the mean velocity gradient.

VII. FUTURE WORK

Currently measurements of w' and S_w are being made in the separated flow to completely document this flow. During the 1980-81 period a scanning laser anemometer system will be developed to obtain almost instantaneous velocity profiles. These instantaneous profiles should prove useful in relating the instantaneous backflow to the outer region flow.

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APPENDIX

TABULATION OF LASER,
CROSS HOT-WIRE AND SINGLE
HOT-WIRE ANEMOMETER DATA

(Note that only first three digits in
each number are valid.)

AD-A095 252

PURDUE UNIV LAFAYETTE IN PROJECT SQUID HEADQUARTERS
MEASUREMENTS OF A SEPARATING TURBULENT BOUNDARY LAYER. (U)
APR 80 R L SIMPSON, Y CHEW, B G SHIVAPRASAD
SQUID-SMU-4-PU

F/G 20/4

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3-11-81

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V=112.375 INCHES

DATE: 4- 7-75
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L.O.V. MEASUREMENTS

V (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	S_U	E_U	Z_U
.01000	11.95000	21.94370	.35406	2.77098	1.00000
.01500	13.48600	22.70751	.23337	2.66509	1.00000
.02000	15.02200	22.61649	.16510	2.72763	1.00000
.02500	16.55800	22.15052	.14478	2.72477	1.00000
.03000	18.09400	21.84142	.12810	2.75458	1.00000
.04000	17.55700	21.57794	.15934	2.78176	1.00000
.05000	18.88000	21.54157	.20783	2.84562	1.00000
.06000	19.98000	21.72912	.16491	2.78376	1.00000
.08000	19.94400	21.43528	.20304	2.77496	1.00000
.11000	22.75700	22.54575	.17754	2.72841	1.00000
.15000	22.71000	23.54954	.14433	2.76498	1.00000
.20000	23.17400	23.5529	.17042	2.76777	1.00000
.28000	24.26500	25.31549	.12687	2.67902	1.00000
.36000	26.87100	27.17316	.06782	2.59182	1.00000
.50000	29.09500	26.94491	.04668	2.66371	1.00000
1.50000	46.43000	18.12390	-.53236	3.20990	1.00000
2.50000	64.49200	7.4911	-.29460	4.14666	1.00000 (F.S.)

V (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_V	E_V	Z_V
.01000	.10200	.49735	N.A.	6.46840	.62021
.01500	N.A.	.77533	.06833	5.19506	.65195
.02000	N.A.	1.60329	N.A.	4.45116	.64567
.02500	-.04000	2.00715	-.13454	3.32442	.46303
.03000	.02500	2.49817	-.07648	3.80561	.48725
.04000	-.04400	3.21596	-.03630	3.62061	.50859
.05000	-.01200	3.85493	-.07193	3.42187	.47937
.06000	-.00600	4.24565	-.09791	3.32124	.47975
.08000	.05900	5.03454	-.07443	3.36641	.51765
.11000	.07400	5.69132	-.14431	3.27096	.57503
.15000	.61900	9.34154	-.13300	3.21242	.57416
.20000	.50400	7.22050	-.09841	3.12960	.56532
.28000	.71900	8.47133	-.04774	3.17595	.56417
.36000	.74900	9.73498	-.05381	2.96190	.58252
.50000	1.10400	9.65525	-.04168	2.93787	.46940
1.50000	2.60500	9.12708	.30220	3.09020	.83918
2.50000	3.00300	.83546	.96568	5.38553	1.00000 (F.S.)

V (INS.)	(U-V) (F.P.S.)	$-(U-V)^2$ (F.P.S.) ²	S_{U-V}	E_{U-V}	Z_{U-V}
.01000	12.77305	2.93440	.17147	3.26567	.99321
.01500	12.23753	2.50280	.32267	2.66254	1.00000
.02000	14.66785	2.66450	.17553	2.75435	1.00000
.02500	15.55854	2.57560	.13270	2.54201	.69940
.03000	16.31235	3.11540	.06645	2.71376	1.00000
.04000	17.47325	3.33940	.10777	2.55596	.69945
.05000	18.71389	3.57540	.12237	2.45035	1.00000
.06000	19.50422	3.47830	.15352	1.94472	1.00000
.08000	19.59800	4.13070	.15526	2.20015	1.00000
.11000	20.14952	4.05319	.05953	3.00051	.69934
.15000	21.44735	4.62410	.12356	2.84435	.69946
.20000	22.46174	4.68110	.04884	3.07570	1.00000
.28000	24.20444	5.71120	.07548	3.03142	1.00000
.36000	24.22462	6.62510	.02544	2.66394	1.00000
.50000	29.97963	7.49370	-.04450	2.77751	1.00000
1.50000	43.86545	3.22707	-.48376	3.12650	1.00000
2.50000	51.32415	-.25914	-.30892	4.32420	1.00000 (F.S.)

VALLEY, 400 INCHES

DATE: 3-17-74
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L.D.V. MEASUREMENTS

V (INS.)	U (F.P.S.)	$\frac{U^2}{2}$ (F.P.S.) ²	S_u	F_u	Z_u
.00500	2.24500	1.03954	.95547	4.14150	.99973
.01000	4.49000	2.07908	.44135	2.49507	1.00000
.01500	7.73500	3.11862	.29711	3.05001	1.00000
.02000	9.98000	4.15816	.41349	2.87594	.99931
.02500	12.22500	5.19770	.35029	2.82674	.99960
.03000	14.47000	6.23724	.35632	2.82537	.99958
.04000	17.71500	8.47450	.27299	2.76315	1.00000
.05000	20.96000	10.71176	.23650	2.76341	1.00000
.06000	24.20500	12.94902	.22893	2.77673	1.00000
.07000	27.45000	15.18628	.26329	2.56206	1.00000
.08000	30.69500	17.42354	.21792	2.74020	1.00000
.09000	33.94000	19.66080	.20933	2.70510	1.00000
.10000	37.18500	21.89806	.18587	2.70053	1.00000
.15000	47.43000	32.43100	.20055	2.92608	.99981
.20000	57.67500	42.96394	.17890	2.76364	1.00000
.25000	67.92000	53.49688	.14855	2.62719	1.00000
.30000	78.16500	64.02982	-.22393	2.72255	1.00000
.35000	88.41000	74.56276	-.33653	5.00845	1.00000

(F.S.)

V (INS.)	V (F.P.S.)	$\frac{V^2}{2}$ (F.P.S.) ²	S_v	F_v	Z_v
.00500	.27900	.02241	.30996	N.A.	.99196
.01000	.55800	.04482	N.A.	5.78263	.99260
.01500	.83700	.06723	.09230	4.59006	.99317
.02000	1.11600	.08964	-.26539	4.74966	N.A.
.02500	1.39500	.11205	-.15182	4.42680	.99812
.03000	1.67400	.13446	-.15717	4.19062	.99474
.04000	2.23200	.19768	-.10376	3.45158	.99446
.05000	2.79000	.26090	-.14557	3.61496	.99171
.06000	3.34800	.32412	-.05643	3.67269	.99769
.08000	4.03200	.40512	-.14990	3.44937	.99732
.10000	4.71600	.48612	-.16729	3.40459	.99679
.15000	6.55200	.84024	-.13607	3.19555	.99198
.20000	8.38800	1.20236	-.06542	3.44441	.99123
.25000	10.22400	1.56448	-.14937	3.05196	.99224
.30000	12.06000	1.92660	-.23170	3.24160	.99615
.35000	13.89600	2.28872	-.12839	2.98996	.99143
.40000	15.73200	2.65084	.09017	2.69582	.99550
.45000	17.56800	3.01296	.98558	5.35647	1.00000

(F.S.)

V (INS.)	U-V (F.P.S.)	$\frac{(U-V)^2}{2}$ (F.P.S.) ²	S_{U-V}	F_{U-V}	Z_{U-V}
.00500	2.02513	.02459	N.A.	3.39162	.99839
.01000	4.27026	.04530	.09174	2.76588	1.00000
.01500	6.51539	.06601	N.A.	3.17733	.99755
.02000	8.76052	.08672	.30412	2.85068	.99253
.02500	1.00515	1.49270	.34277	2.74600	.99753
.03000	3.24528	1.59820	.34637	2.41925	.99656
.04000	11.43505	1.74931	.21517	2.83301	.99719
.05000	11.98292	2.63590	.22628	2.50790	.99842
.06000	12.53079	1.64300	.12714	2.75432	.99715
.08000	13.11571	1.91240	.16480	2.82060	.99957
.10000	13.70063	1.71930	.16468	3.04447	.99833
.15000	14.46424	2.00600	.23938	2.91510	.99965
.20000	15.22785	2.34440	.16322	2.80477	1.00000
.25000	16.27121	2.60322	.20011	2.82514	.99971
.30000	17.31457	3.47330	.23474	2.84454	1.00000
.35000	18.35793	4.34338	.11251	2.76253	1.00000
.40000	19.40129	N.A.	-.29935	2.76004	1.00000
.45000	20.44465	-.07255	-1.35006	7.82474	1.00000

(F.S.)

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DATE: 3-14-74
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L.D.V. MEASUREMENTS

V (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	S_U	F_U	∂_U
.01000	N.A.	N.A.	N.A.	2.80055	.69052
.01500	4.06400	16.51776	.55478	3.00259	.69113
.02000	7.12	50.6944	.55504	3.27151	.69115
.02500	7.44100	55.36881	.46507	2.95947	.69434
.03000	6.54800	42.87642	.42006	3.03393	.69723
.04000	6.50600	42.32836	.41505	3.65274	.69954
.05000	10.12300	102.47429	.37557	2.91207	.69950
.06000	10.63900	113.19621	.27745	2.55246	.69953
.07000	11.89500	141.49003	.24354	2.86059	1.00000
.10000	17.40200	301.87364	.27710	2.53832	1.00000
.15000	19.33700	373.91809	.25983	2.82195	1.00000
.20000	14.10300	198.8929	.21114	2.75807	1.00000
.25000	15.33700	235.2236	.22106	2.79010	1.00000
.30000	16.66200	277.46757	.21056	2.75386	1.00000
.50000	18.43700	339.84169	.15956	2.80825	1.00000
1.50000	34.34600	1179.63740	-.21217	2.78640	1.00000
3.00000	50.17700	2517.7512	-1.01656	5.94677	1.00000 (F.S.)

V (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_V	F_V	∂_V
.01000	.10100	.010201	.37014	N.A.	.58052
.01500	.21000	.0441	-.12819	5.71255	.63074
.02000	.30500	.093025	-.09036	6.47046	.71233
.02500	.29900	.089401	.00431	6.42627	.70254
.03000	.41100	.168921	-.07200	4.14806	.70554
.04000	.18500	.034225	-.20524	3.70061	.57036
.05000	.27900	.077841	-.17527	3.58632	.60414
.06000	.29300	.085849	-.26110	3.54070	.63167
.07000	.15700	.024649	-.14315	3.39364	.57575
.10000	.20000	.04	-.16673	3.22725	.56407
.15000	.37000	.1369	-.17103	3.28105	.56404
.20000	.21200	.044944	-.22356	3.36434	.55262
.25000	.74300	.552049	-.19575	3.10449	.65669
.30000	1.74700	3.052009	-.12435	3.01432	.61770
.50000	1.20500	1.452025	-.17359	3.03586	.66788
1.50000	2.78200	7.741524	.10091	2.60363	.60057
3.00000	4.57500	20.930625	.09886	4.92981	1.00000 (F.S.)

V (INS.)	U-V (F.P.S.)	$-(U-V)^2$ (F.P.S.) ²	S_{U-V}	F_{U-V}	∂_{U-V}
.01000	N.A.	N.A.	N.A.	2.82225	1.00000
.01500	4.41700	19.51189	.52821	3.10214	.97730
.02000	5.67043	32.14178	.74915	3.46903	.98439
.02500	4.98332	24.83358	.50605	3.02450	.93357
.03000	7.97400	63.58416	.38442	2.79421	.98670
.04000	2.14700	.461009	.33552	3.02270	.99346
.05000	9.00200	81.03604	.22150	2.85834	.99313
.06000	10.77100	116.00441	.21970	2.95823	.99474
.07000	11.73500	137.70025	.20151	2.85353	.99514
.10000	12.78500	163.45625	.24432	2.47913	.99555
.15000	17.95000	322.2025	.23093	2.33555	.99645
.20000	13.73000	188.5089	.26122	2.55454	.99646
.25000	16.89900	285.57021	.17096	2.77440	.99740
.30000	17.87700	319.59709	.19814	2.74755	.99843
.50000	17.54500	307.8275	.17232	2.75320	.99972
1.50000	21.51900	463.76201	-.21442	2.76341	1.00000
3.00000	45.27900	2050.20241	-1.25127	5.60459	1.00000 (F.S.)

L.D.V. MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	S_U	S_{U^2}	Σ_U
.01000	7.94501	6.31227	.78556	3.50135	.55446
.01500	8.39000	11.70000	.63517	3.26765	.64025
.02000	8.79000	13.70000	.48305	3.07943	.65709
.02500	9.21000	15.02000	.43547	2.96314	.65456
.03000	9.74800	15.07940	.34461	2.83409	.69331
.04000	11.74000	15.59416	.34650	2.87015	.64075
.05000	11.73000	16.05490	.37073	2.89168	.69434
.06000	11.75000	16.47000	.21788	2.91472	.65566
.06500	11.75000	17.16401	.25707	2.86440	.69669
.11000	11.79000	17.67429	.26653	2.96757	.69627
.15000	11.76000	15.53526	.75415	2.89380	.69794
.20000	11.71000	20.00000	.23695	2.81057	.69635
.25000	11.99000	21.15096	.21477	2.86783	.69666
.30000	14.14000	22.10000	.18450	2.74266	1.00000
.50000	15.64600	25.15273	.15592	2.75630	1.00000
1.50000	30.34900	31.20742	-.13485	2.66172	1.00000
3.50000	40.64600	.65299	-.13621	4.02406	1.00000

(F.S.)

V (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_V	S_{V^2}	Σ_V
.01000	-.02220	.17657	.15730	6.29043	.47546
.01500	.13400	.50461	N.A.	N.A.	.61429
.02000	.11400	.75000	-.21440	5.54654	.55674
.02500	.00900	1.00000	-.74834	4.71314	.51201
.03000	.06500	1.32400	-.18513	4.43162	.51458
.04000	-.02300	1.64400	-.25108	4.11125	.43701
.05000	-.03900	2.12816	-.18606	3.80941	.50030
.06500	.04400	2.07716	-.26137	4.22460	.55605
.07500	.00500	3.06501	-.12980	3.42028	.44267
.11000	.00100	3.76845	-.08741	3.26717	.50911
.15000	.06900	4.35415	-.17883	3.50174	.54431
.20000	.14500	5.06733	-.19052	3.26679	.55665
.25000	.50900	6.65026	-.13938	3.23454	.59716
.30000	.00400	6.31000	-.11400	3.34482	.67060
.50000	1.07100	9.74020	N.A.	N.A.	.62768
1.50000	2.67400	10.52660	.04392	2.90634	.76860
3.50000	4.69000	.79171	1.08204	6.96020	1.00000

(F.S.)

V (INS.)	U-V (F.P.S.)	$\overline{U-V}$ (F.P.S.) ²	S_{U-V}	S_{U-V^2}	Σ_{U-V}
.01000	4.17755	.53919	.68671	3.29496	.64378
.01500	5.74731	.69359	.55754	3.34769	.67548
.02000	6.73861	.67400	.41890	3.05606	.67409
.02500	7.31283	1.06540	.42103	2.99165	.68105
.03000	7.65789	1.50000	.36612	2.85624	.67431
.04000	8.18470	1.35350	.31103	2.84773	.65421
.05000	9.00131	1.35760	.26346	2.86090	.65426
.06500	8.96815	1.02400	.27763	2.85764	.65431
.07500	6.44743	1.47000	.27522	2.61357	.64115
.11000	10.46205	1.56270	.24833	2.56691	.66231
.15000	10.93984	1.59920	.21739	2.45032	.65479
.20000	11.51017	2.32410	.22393	2.95670	.68629
.25000	12.44472	2.34410	.26806	2.90554	.68409
.30000	13.56765	2.67340	.21065	2.42584	.69544
.50000	18.17628	3.51613	.22370	2.63589	.99609
1.50000	27.76357	7.66727	-.21794	2.77763	1.00000
3.50000	44.96732	.39010	N.A.	N.A.	1.00000

(F.S.)

4-127, 174 INCHES

DATE: 2- 3-73
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L.O.V. MEASUREMENTS

V (INS.)	U (F.P.S.)	V^2 (F.P.S. ²)	S_u	F_u	Z_u
.00200	.64100	.41081	.53945	4.11623	.54540
.00400	N.A.	N.A.	N.A.	N.A.	.97567
.00700	1.04900	.00980	.44902	3.20946	.93004
.01000	1.05100	.01102	.35969	2.95557	.90017
.01500	1.72200	1.30000	.29146	2.96959	.93968
.02000	2.64900	1.60553	.12175	2.60372	.98652
.02500	2.97700	1.74754	N.A.	2.74669	.95552
.03500	N.A.	N.A.	N.A.	2.85271	.99940
.04500	3.47900	12.10149	.17435	2.61494	.85344
.04500	N.A.	16.13083	.16809	3.30014	.94605
.08000	5.18000	16.67230	N.A.	3.47524	.90143
.10000	N.A.	16.67230	.39658	3.39314	.85943
.12500	5.88700	16.14334	.28669	3.27115	.92055
.16000	6.92700	19.00000	.27541	3.26783	.92497
.20000	6.92700	17.19149	.11573	3.81016	.64449
.25000	6.92700	21.55240	.37327	3.46044	.94315
.32000	8.77000	17.47551	.13742	3.19401	.95551
.40000	6.64700	21.65477	.24272	2.84291	.98241
.50000	9.88700	23.13812	N.A.	2.96692	.98540
.60000	10.55300	29.13317	.37334	3.50150	.93141
.80000	12.81500	31.57313	.16250	2.80301	.99556
1.00000	15.07900	32.63093	.11725	2.71467	1.00000
1.20000	17.40700	30.15987	.04304	2.65290	1.00000
1.50000	21.92100	31.89778	-.00026	2.67700	1.00000
1.80000	27.64700	32.75007	-.04057	2.57229	1.00000
2.40000	35.85900	24.56100	-.10257	3.27674	1.00000
3.00000	43.83700	11.74453	N.A.	3.28774	1.00000
3.50000	67.04200	4.39140	N.A.	4.99043	1.00000
4.00000	68.43300	.71910	-.59780	12.47213	1.00000

(F.S.)

V (INS.)	V (F.P.S.)	V^2 (F.P.S. ²)	S_v	F_v	Z_v
.00200	-.00400	.01021	N.A.	3.31442	N.A.
.00500	.14200	.02916	N.A.	N.A.	N.A.
.00700	.19300	.03609	N.A.	N.A.	N.A.
.01000	.17500	.02448	N.A.	N.A.	N.A.
.01500	-.11100	.01536	.05563	N.A.	N.A.
.02000	-.14400	.04637	.14851	4.04021	N.A.
.03500	-.10400	.16520	-.16791	3.99970	.98825
.04500	N.A.	.52023	-.34794	4.06299	N.A.
.04500	N.A.	.76415	-.17752	3.36490	.94330
.06500	N.A.	1.66054	-.41667	4.04372	.92626
.08000	N.A.	2.35529	N.A.	N.A.	.93545
.10000	-.10200	2.04240	-.26139	3.48180	.97464
.12500	-.20700	3.14001	-.76337	3.69723	.93023
.14000	N.A.	N.A.	N.A.	N.A.	.23547
.16000	-.11200	3.93557	-.29761	2.97479	.94747
.32000	-.74900	9.00001	-.17339	2.91510	.99137
.40000	-.03000	9.83104	-.02955	3.13646	.99023
.50000	.77300	6.71929	-.20231	3.02266	.94349
.60000	.38300	8.51467	-.25718	2.49751	.95395
.80000	.64200	4.52277	-.18955	2.91612	.98542
1.00000	1.08100	9.93204	-.11279	3.18805	.95853
1.20000	1.65500	11.82500	-.25739	N.A.	.86044
1.50000	1.97500	12.75004	N.A.	N.A.	.71063
1.80000	2.46100	11.10209	.02919	3.21933	.76943
2.40000	4.72000	10.73007	-.19050	N.A.	.91870
3.00000	5.78400	5.20376	.22564	2.81544	.99576
3.50000	4.57500	3.30271	.53524	3.76546	.96097
4.00000	N.A.	.51493	N.A.	7.92031	.99875

(F.S.)

γ (F.S.)	$U-V$ (F.S.)	$\frac{U-V}{\gamma^2}$ (F.S.)	S_{uv}	F_{uv}	Z_{uv}
.00200	N.A.	-.14142	.10587	3.11164	.67328
.00500	N.A.	-.02009	.20852	2.57292	.69143
.00700	1.26339	.12191	N.A.	N.A.	.92727
.01000	N.A.	.31063	.08426	2.66710	.65457
.01500	1.41754	-.13712	.20003	2.94205	.64796
.02000	2.47620	-.15504	-.01077	2.83020	.65346
.02500	3.29504	-.09503	-.05706	2.71386	.63714
.03000	3.67544	N.A.	.27745	2.79406	N.A.
.04000	4.92737	2.37212	N.A.	N.A.	.65529
.04500	5.04162	3.45730	N.A.	N.A.	.65903
.05000	5.34103	2.94010	N.A.	N.A.	.69476
.06000	5.71461	2.41370	.09204	2.73964	.65730
.07500	4.10934	2.82010	.38530	N.A.	.65610
.10000	4.63767	2.31270	.17743	2.95222	.65205
.12000	4.64184	2.45020	.34934	3.20790	.65214
.15000	6.78104	2.44310	.37254	2.95022	.62697
.17000	8.49207	2.92590	.47070	3.32001	.62349
.20000	8.34375	2.77060	.32653	3.05019	.63543
.25000	9.17535	3.18340	.26290	2.92546	.63647
.30000	10.65443	3.47750	.27231	2.92561	.64994
.40000	11.92297	3.47550	.12411	2.62154	.67300
1.00000	14.11796	4.35140	.13757	2.66151	.67567
1.20000	16.74976	4.36000	.09661	2.54173	.69199
1.50000	22.40543	4.62950	-.08602	2.62961	1.00000
1.70000	23.07267	4.52170	-.31357	3.17899	.64507
2.40000	31.17150	3.90100	-.25522	3.06927	1.00000
3.00000	35.39302	3.14210	-.54651	3.12281	1.00000
3.50000	39.05546	2.75250	-1.44010	N.A.	1.00000
4.00000	40.46331	1.00010	-1.01252	7.42363	1.00000

(F.S.)

AS21 SC

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L.T.V. MEASUREMENTS

V (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	S_U	F_U	Z_U
.01000	.21700	4.95512	.38198	3.77343	.53375
.01500	1.18700	6.35001	.34745	3.57149	.64007
.02000	1.44900	8.75043	.41719	3.75046	.64042
.02500	1.42100	9.23145	.25332	3.35451	.64064
.03000	1.70900	10.45391	.36219	3.26622	.70994
.04000	1.97000	11.85000	.23515	3.18735	.73205
.05000	1.95100	13.33355	.17532	2.95985	.69317
.06500	2.25400	14.64735	.25453	3.07433	.69547
.08500	2.77700	16.42319	.16008	2.96297	.71239
.11000	2.55900	16.02759	.15338	2.93293	.71693
.15000	3.21400	17.61125	.20507	2.99309	.78056
.20000	3.19400	15.37135	.21502	2.99443	.74259
.28000	3.80300	19.62472	.18253	2.94142	.60532
.38000	4.70500	22.30749	.19443	2.90749	.85403
.50000	5.76400	23.31007	.20751	3.06856	.88274
.70000	7.43900	26.34532	.24572	2.95214	.92897
1.00000	10.16200	24.88765	.16079	2.91979	.96943
1.50000	15.85400	37.93549	.04544	2.32936	.99537
2.00000	21.44700	40.33360	-.10539	2.77192	1.00000
2.50000	28.70200	39.21452	-.20073	2.85409	1.00000
3.00000	46.70900	.94257	.04208	2.96491	1.00000 (F.S.)

V (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_V	F_V	Z_V
.01000	-.17300	.11577	-.30372	5.03226	.24920
.01500	-.08900	.19355	-.45611	5.99691	.41035
.02000	.03700	.32774	-.54311	7.24324	.59799
.02500	.08600	.44565	N.A.	6.48745	.62410
.03000	.05100	.65675	-.48579	5.36349	.56345
.04000	.04700	1.14559	-.32116	5.43808	.52905
.05000	-.01600	1.51577	-.42534	4.80436	.55679
.06500	-.03500	1.96171	-.46855	4.30563	.51705
.08500	-.02400	2.41812	N.A.	4.70917	.52156
.11000	.05600	2.56775	-.36048	4.19327	.56824
.15000	.12300	3.43187	-.38901	3.90837	.57164
.20000	-.01700	4.70220	-.22318	3.53616	.54365
.28000	.10400	4.62509	-.39473	3.56246	.54339
.38000	.06900	5.64007	-.27367	3.66957	.61008
.50000	.01600	7.96325	N.A.	4.22609	.65360
.70000	.00000	9.71135	-.27048	3.24136	.64632
1.00000	1.00300	10.0609	-.15206	3.43124	.71647
1.40000	2.15700	11.45543	-.09517	3.02528	.75271
2.00000	7.71300	12.44319	-.04090	2.91797	.80453
2.50000	7.27400	12.15747	.04343	2.95881	.87068
3.00000	4.24700	.92337	.27551	3.29304	1.00000 (F.S.)

V (INS.)	U-V (F.P.S.)	$U-V$ (F.P.S.) ²	S_{U-V}	F_{U-V}	Z_{U-V}
.01000	.57134	.99555	.25314	3.65532	.56952
.01500	1.73743	.60477	.35045	3.76060	.67841
.02000	1.40229	.45493	.43100	4.02233	.68392
.02500	1.60517	.40780	.31039	3.67770	.70728
.03000	1.71967	.48293	.27762	3.51237	.66999
.04000	1.34977	.44071	.30047	3.16559	.67274
.05000	2.15934	.82515	.19305	3.42614	.67321
.06500	2.64798	.84430	.30456	3.19215	.68674
.08500	2.55794	.97120	.20707	2.93345	.71323
.11000	2.58940	1.35340	.23719	3.00935	.70958
.15000	3.06943	1.70430	.27515	3.00935	.71819
.20000	3.77711	2.34410	.27194	3.00003	.75409
.28000	3.49307	2.72400	.22114	3.07040	.74210
.38000	4.52444	2.94440	.21354	2.97574	.75457
.50000	5.00124	3.11570	.33427	3.13017	.51517
.70000	7.35523	4.07600	.00427	3.57414	.84516
1.00000	6.44400	5.65370	.13443	2.96787	.93151
1.50000	14.22094	5.63400	.02130	2.74534	.94717
2.00000	19.14907	9.91455	-.07714	2.44042	.99385
2.50000	24.40904	5.94337	-.07473	2.40055	.93674
3.00000	40.38433	-.07434	N.A.	4.59144	1.00000 (F.S.)

134.537 INCHES

DATE: 3-31-72
DS 134d

L.O.V. MEASUREMENTS

V (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	S_u	F_u	Z_u
.01000	.33900	3.47000	.24184	3.15624	.81260
.01500	.41900	7.34900	.21034	3.43660	.53791
.02000	.55600	3.93747	.21894	3.43970	.54916
.02500	.51300	4.68310	.20759	3.26640	.56294
.03000	.37400	10.31772	.26780	3.23090	.53907
.04000	.40700	12.27073	.19478	3.12903	.53243
.05000	.49700	13.37490	.29786	3.17101	.51202
.06000	.29500	13.40162	.20914	3.09034	.51733
.08000	.45100	14.47950	.12563	3.00533	.56030
.11000	.96300	15.04650	.15657	2.90602	.60437
.15000	.78300	17.64490	.16898	3.06947	.56576
.20000	1.10900	18.45530	.20457	2.95707	.57391
.25000	1.49300	20.26458	.23411	3.00765	.65500
.30000	2.24500	21.21000	.24213	2.96616	.65899
.50000	2.76400	25.64572	.16656	2.87303	.70554
.70000	4.22600	25.86710	.15054	2.79474	.77025
1.00000	6.49300	32.61372	.17075	2.95400	.89313
1.50000	11.40000	39.34902	.10327	2.71173	.97507
2.00000	17.12000	45.85567	-.00179	2.90113	.99227
2.50000	22.72400	46.54303	-.11832	2.59830	1.00000
3.00000	29.01900	44.23793	-.32813	3.16629	.69939
4.00000	46.82400	.52534	-.09223	3.01351	1.00000 (F.S.)

V (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_v	F_v	Z_v
.01000	.24400	.09200	.38233	4.92660	.79967
.01500	.28700	.26611	-.41647	5.54092	.63126
.02000	.25300	.43743	-.27529	5.46025	.59831
.02500	.04700	.49303	-.25961	5.42470	.55136
.03000	.07800	.57483	-.24252	4.95882	.54564
.04000	.03700	1.00192	N.A.	4.92931	.59270
.05000	.04300	1.10774	-.28344	3.36377	.54150
.06000	.07300	1.42299	-.24370	4.02676	.52159
.08000	.01700	1.45035	-.20446	4.04400	.50992
.11000	.10500	2.51470	-.34843	4.05561	.53506
.15000	.05100	2.22514	-.34921	4.17885	.51952
.20000	.11500	3.47335	-.43192	4.10288	.52703
.25000	.17700	4.47313	-.34717	3.90705	.55269
.30000	.56300	6.53312	-.30036	3.64063	.59540
.50000	.60700	6.77342	-.40978	3.59738	.65268
.70000	.85400	7.65216	-.25574	3.30762	.60711
1.00000	.94700	10.45222	-.23711	3.37784	.64009
1.50000	1.47100	12.94946	-.21428	3.15069	.71602
2.00000	2.52100	13.33359	-.02707	3.10857	.75890
2.50000	3.72400	14.22747	-.00734	2.97514	.79751
3.00000	4.33100	13.77917	.20108	3.05343	.82230
4.00000	6.72400	.50000	N.A.	2.76465	1.00000 (F.S.)

V (INS.)	U-V (F.P.S.)	$U-V$ (F.P.S.) ²	S_{u-v}	F_{u-v}	Z_{u-v}
.01000	.08764	1.23321	.31159	3.88743	.47686
.01500	.93174	.26620	.26238	3.60976	.55694
.02000	.36349	.36470	.17834	3.51075	.54639
.02500	.38466	.44130	.16324	3.46380	.53650
.03000	.45820	.58750	.08626	3.44939	.52033
.04000	.47800	.73550	.15567	3.51765	.56222
.05000	.32244	.91910	.24249	3.39088	.49230
.06000	.61235	1.04310	.16444	3.12684	.57313
.08000	.68737	1.24570	.21373	3.28938	.57216
.11000	1.09752	1.33640	.23463	N.A.	.57871
.15000	.99418	1.67240	.21063	3.51713	.54572
.20000	.93475	1.43440	.24916	3.24147	.55533
.25000	1.17520	2.25510	.27393	3.16943	.57253
.30000	1.38124	2.24530	.26270	3.10223	.61758
.50000	2.51940	N.A.	.30552	3.11425	.63655
.70000	3.41025	3.39350	.23773	3.13253	.70162
1.00000	4.71747	N.A.	.26417	2.97574	.82266
1.50000	9.71414	9.44427	.01433	3.10341	.87629
2.00000	14.71192	7.09141	.02131	2.87288	.99039
2.50000	19.43575	7.45279	-.11941	2.76013	.99589
3.00000	24.36394	7.33492	-.22309	2.82905	.99657
5.00000	39.87425	-.11593	-.16023	3.34267	1.00000 (F.S.)

X=138.750 INCHES

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L.O.V. MEASUREMENTS

Y (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_u	F_u	Z_u
.01000	-.78300	3.01760	-.14094	3.97360	.30476
.01500	-.85500	5.23673	-.04006	3.50813	.34828
.02000	-1.16100	7.39405	-.02055	3.39462	.31531
.03000	"A."	9.33604	.03129	3.24254	.45544
.04000	-1.43600	10.65415	.06161	3.13007	.33547
.06000	-1.79300	12.31329	.13471	3.24062	.34677
.08000	-1.74400	12.40550	.19365	3.08570	.30463
.12000	-1.47500	14.74441	.15847	2.92504	.32071
.17000	-1.51500	15.15330	.17770	3.01325	.32244
.25000	-1.92700	17.17008	.24987	2.93569	.35344
.25000	-1.92700	17.17008	.22284	2.46551	.38470
.50000	-2.98000	23.26000	.17735	2.46272	.45210
.55000	.37900	21.41777	.24508	2.95780	.49252
1.00000	2.94100	29.33302	.20017	2.00207	.64525
2.00000	10.38700	45.33349	.09473	2.77415	.95530
3.50000	27.05700	49.81225	-.25147	3.16067	.99556
5.50000	44.47300	47.6269	-1.38128	10.83774	1.07000

Y (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_v	F_v	Z_v
.01000	-.14400	.15515	-.45587	5.73408	.33219
.01500	-.10200	.25982	-.39277	5.67716	.38539
.02000	-.03000	.37440	-.37516	5.07588	.47315
.03000	-.11300	.60923	-.23035	4.90009	.47598
.04000	-.04600	.79943	-.36062	5.13535	.50384
.06000	.11600	1.14364	-.31007	4.42000	.60131
.08000	.02900	1.63000	-.22319	4.19740	.50407
.12000	-.02800	2.05500	-.18311	4.08810	.49624
.17000	.08900	2.95737	-.34543	3.84225	.53412
.25000	.09000	3.45297	-.39322	3.72592	.57050
.35000	.14500	4.55750	-.40800	3.67768	.57554
.50000	.45000	5.67720	-.49524	3.71336	.64019
.65000	.33100	6.89950	-.34071	3.36018	.61095
1.00000	.63100	9.28516	-.23698	3.18935	.57636
2.00000	1.48900	14.10971	-.16252	2.93606	.69200
3.50000	4.33600	14.55575	.11790	3.04685	.69039
5.50000	9.47300	47.6269	1.09771	5.20888	1.00000

Y (INS.)	U-V (F.P.S.)	$\frac{-UV}{(F.P.S.)^2}$	S_{u-v}	F_{u-v}	Z_{u-v}
.01000	-1.04792	.24253	.07257	4.15682	.24786
.01500	-1.01115	.42315	-.02444	4.12702	.32396
.02000	-1.32085	.05177	-.05452	3.27493	.32415
.03000	-1.08469	.47434	-.04908	3.27307	.35721
.04000	-1.15540	.09932	.05563	3.27923	.32965
.06000	-1.16672	.06972	.05957	3.27380	.35347
.08000	-1.10075	.05554	.13047	3.18244	.28532
.12000	-1.19641	-.09800	.19276	3.04497	.36915
.17000	-1.37177	.04946	.24245	3.13959	.37030
.25000	-1.30531	.80189	.24540	3.05455	.39816
.35000	-.82155	1.35070	.26251	3.06533	.39002
.50000	-.45962	2.29020	.33618	3.09698	.44104
.65000	.52451	2.60140	.33565	2.97966	.49746
1.00000	2.49843	4.11215	.32258	2.93101	.60571
2.00000	9.69243	6.57900	.16998	2.93399	.89997
3.50000	22.40315	6.15350	-.25251	2.82521	.99350
5.50000	35.77485	1.00200	-1.57787	6.57157	1.00000

V=139.750 INCHES

DATE: 3- 9-79
05 134W

L.O.V. MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S. ²)	S_U	F_U	Z_U
.01000	N.A.	2.55350	N.A.	3.21155	.65040
.02000	-.95100	7.75477	-.03907	3.48540	.36086
.03000	-1.18500	9.88227	-.00415	3.26037	.32050
.04000	-1.28400	9.86314	.03284	3.17653	.30452
.05000	-1.22700	11.57775	.11191	3.04190	.36942
.06000	-1.14300	12.75233	.06244	3.17640	.33694
.07000	-1.39400	13.34777	.10622	2.93561	.31335
.08000	-1.28300	13.65542	.13949	3.00361	.34518
.09000	-1.44700	15.93734	.14495	2.56343	.34755
.10000	-1.47300	17.13207	.15014	2.95570	.36749
.11000	1.41200	25.51544	.23676	2.31428	.59016
.12000	4.96300	33.51338	.12166	2.79334	.74433
.13000	3.79300	34.25915	.10096	2.74210	.61753
.14000	14.44000	43.65525	-.05995	2.80490	.93053
.15000	21.54000	51.37045	-.14935	2.56866	.69857
.16000	33.07000	41.22513	-.47534	3.34529	1.00000
.17000	37.74000	31.69403	-.65104	3.33419	1.00000
.18000	41.49300	16.59555	-1.01656	4.20475	1.00000
.19000	45.76000	1.09514	.20037	4.73606	1.00000 (F.S.)

Y (INS.)	V (F.P.S.)	V^2 (F.P.S. ²)	S_V	F_V	Z_V
.01000	.07200	.07491	.91492	11.20118	.65753
.02000	.01700	.29343	N.A.	6.55218	.55539
.02500	.14400	.36443	-.20629	4.62397	.66979
.03000	.13700	.51151	-.39103	5.52327	.62751
.05000	.09700	.90244	-.28372	5.09237	.58456
.06000	.10700	1.09424	-.33341	4.59653	.56084
.07000	-.07000	1.32751	-.42748	4.30615	.46415
.10000	-.07500	2.01319	-.29050	4.36160	.53630
.15000	.01100	2.52575	-.31439	4.01913	.50500
.20000	.10500	3.14544	-.42194	3.29653	.58437
.25000	.79400	7.90173	-.29989	3.42440	.62827
.30000	.99000	11.20335	-.37055	3.17979	.62425
.40000	1.22000	12.72941	-.22716	3.06562	.63976
.50000	2.42700	15.45335	-.03115	2.47473	.73950
.60000	3.29500	15.92752	.02912	2.49400	.79717
.70000	5.26200	12.17570	.23457	3.19029	.93833
.80000	6.45700	4.70584	.35186	3.63097	.99676
.90000	7.79200	7.33424	.65317	6.22700	.99627
.97000	7.03400	1.26421	.71720	N.A.	1.00000 (F.S.)

Y (INS.)	U-V (F.P.S.)	$-UV$ (F.P.S. ²)	S_{U-V}	F_{U-V}	Z_{U-V}
.01000	.76367	.11670	.18990	3.03908	.65288
.02000	-1.06205	.19410	.07965	3.47520	.34803
.02500	-.75235	.28690	.07810	3.36909	.41669
.03000	-.78347	.35350	.06942	3.35349	.42959
.05000	-.25034	.39550	.11622	3.27106	.39921
.06000	-1.33359	.35630	.15523	3.25156	.35535
.07000	N.A.	.35380	.17020	3.11047	.41969
.10000	-1.43117	.22910	.16320	3.25529	.36465
.15000	-1.25429	-.25620	.21274	3.25436	.35592
.20000	-1.04507	.98770	.29308	3.06974	.37902
.30000	1.29775	3.06780	.31728	2.94704	.53497
.40000	4.47043	5.03540	.28104	2.90745	.71952
.50000	5.43543	5.91750	.16772	2.75056	.77371
.60000	13.97035	7.40830	.02442	2.72742	.64356
.70000	19.52652	7.03430	-.13411	2.71778	.67056
.80000	27.44275	5.55140	-.58172	3.47776	.69933
.90000	30.71540	N.A.	-.89414	N.A.	.99735
.93000	34.14565	N.A.	-1.00547	4.35775	1.00000
.97000	38.71090	-.05851	-1.16344	7.27312	1.00000 (F.S.)

L.S.V. MEASUREMENTS

V (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	S_U	F_U	Z_U
.01000	-.77001	1.004500	-.02655	9.45345	N.A.
.02000	-1.54003	4.99964	-.23408	3.43131	.29765
.04000	-3.08006	9.49152	.19773	3.76782	.23340
.07000	-5.14009	15.84536	.09734	3.23725	.15459
.11000	-7.17301	15.80271	.23384	3.32680	.18830
.16000	-9.26901	15.11701	.22932	2.93502	.18702
.21000	-11.31001	15.31055	.45449	4.36378	.14677
.27000	-13.50901	15.71485	.35564	3.74737	.16619
.33000	-15.77500	N.A.	N.A.	N.A.	.21133
.40000	-18.64401	15.00245	.23400	3.15267	.17397
.50000	-23.99000	20.49254	N.A.	3.97982	.21765
.65000	-29.67800	19.40773	.26500	3.65964	.28049
.80000	-35.94900	25.59273	.29664	3.02316	.34504
1.00000	-43.00000	25.68599	.22418	2.95127	.39665
1.25000	-52.50000	30.27729	.28311	2.87981	.50794
1.50000	-63.76000	36.88121	.17257	2.75157	.57785
1.75000	-76.23000	35.71167	.20868	2.76126	.70249
2.00000	-90.83000	43.28850	.16556	2.85592	.74779
2.25000	-107.47000	46.66960	.11642	2.84613	.84546
2.50000	-126.53000	51.48694	.12746	2.73159	.87966
2.75000	-147.13000	54.47518	.01202	2.68246	.90605
3.00000	-169.33000	54.21318	-.00448	2.69935	.95905
3.50000	-194.01000	59.10719	-.09715	2.77363	.98150
4.00000	-224.93000	58.55081	-.20873	2.77380	.99826
4.50000	-262.72000	57.31079	-.29486	2.72914	1.00000
5.00000	-307.96300	43.54745	-.45196	2.89629	1.00000
5.50000	-37.77200	36.55085	-.65730	3.52120	1.00000
6.00000	-43.50900	16.44595	-.74497	3.68516	1.00000
6.50000	-42.83000	12.56454	-1.30237	5.89676	1.00000

V (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_V	F_V	Z_V
.01000	.04300	.00275	.90802	7.98595	.58961
.02000	.08100	.00950	.15208	4.33164	.53914
.04000	.15900	.06359	.12324	3.50741	.57634
.07000	.29200	1.02526	-.20736	3.52256	.64594
.11000	.03900	1.53195	-.07871	3.57592	.55803
.16000	.17900	2.43232	-.30086	4.13189	.56484
.21000	.18100	2.57964	-.27176	3.54656	.59112
.27000	.09400	3.28077	-.50655	4.25705	.57780
.33000	.38200	3.27656	-.36060	3.34350	.59921
.40000	.07900	4.47086	-.35865	3.86202	.53399
.50000	.30700	4.39070	-.20326	3.13062	.59598
.65000	-.02400	7.15573	-.39506	3.74863	.54371
.80000	.33000	9.73276	-.36096	3.79622	.56999
1.00000	.79000	11.03263	-.15245	3.38836	.62670
1.25000	.49000	12.50853	-.28666	3.56727	.56997
1.50000	.77300	13.44916	-.15935	3.14646	.59449
1.75000	.98700	14.23984	-.17438	3.03292	.63630
2.00000	1.21600	17.74827	-.24534	3.44763	.61653
2.25000	1.40400	17.99794	-.22977	3.00117	.63336
2.50000	1.74900	18.15237	-.16251	2.94993	.69209
2.75000	1.97500	22.43633	-.05516	3.25307	.69297
3.00000	1.74500	21.11972	-.12000	3.03453	.65615
3.50000	2.32000	20.43085	-.01113	3.03133	.68757
4.00000	3.16500	20.87074	.05576	3.05036	.74819
4.50000	3.98100	19.23631	.15993	3.07503	.80308
5.00000	4.85200	17.37064	.22845	3.32302	.90098
5.50000	6.69500	19.26387	.44123	3.72407	.96957
6.00000	7.42500	N.A.	N.A.	N.A.	.99346
6.50000	7.97200	N.A.	N.A.	N.A.	.99976

Y (INS.)	U-V (F.P.S.)	$\frac{-UV}{(F.P.S.)^2}$	S_{u-v}	F_{u-v}	γ_{u-v}
.01000	-.21755	-.05542	-.00418	8.23711	.46706
.02000	-1.50755	.71176	-.08530	3.52731	.26202
.04000	-2.16455	.33753	.11766	3.79344	.20766
.07000	-3.19751	.44996	.04255	3.58952	.18492
.11000	-2.99810	1.13630	.21770	3.92421	.21311
.16000	-2.57734	.45870	.14840	3.26764	.19566
.21000	-3.41137	-.15370	.15412	3.10045	.18901
.27000	-2.88355	.73430	.30284	3.34410	.25654
.33000	-1.23145	.36370	.37275	3.21585	.23142
.40000	-3.55651	.83460	.40173	3.16986	.21304
.50000	N.A.	.85290	.45956	3.22622	.31480
.65000	-2.60213	1.56740	.57504	3.92339	.27716
.80000	-2.13403	2.22630	.36693	2.93795	.35822
1.00000	-1.43755	2.65330	.36817	2.96556	.39947
1.25000	-.74360	3.55030	.34407	2.92495	.45999
1.50000	1.25753	4.64840	.23054	2.73452	.53618
1.75000	2.10173	5.05000	.20849	3.31619	.59364
2.00000	3.30077	5.54410	-.05315	3.05254	.61204
2.25000	5.28204	6.57540	.09871	2.76590	.73259
2.50000	5.40730	6.75370	-.25227	3.36338	.73992
2.75000	7.06477	7.07050	-.15959	2.97290	.78736
3.00000	10.46973	7.37350	-.07685	2.90053	.85391
3.50000	14.37575	8.07240	-.13193	2.78067	.93202
4.00000	18.49345	8.24320	-.21251	2.88545	.96649
4.50000	22.09824	7.85240	-.32753	2.91433	.98247
5.00000	25.05057	6.75630	-.47848	3.06471	.99566
5.50000	29.10565	5.44340	-.84979	4.12810	.96750
6.00000	32.14613	3.66090	-.83956	3.91698	1.00000
6.50000	34.75532	.53520	-1.00311	4.47264	1.00000

L.D.V. MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	S_U	F_U	Z_U
.01000	-.03650	3.37090	.02182	3.13640	.46065
.01500	N.A.	2.89348	-.00616	2.97163	.65335
.02500	N.A.	3.27170	.24278	3.22209	.53455
.03000	N.A.	4.36534	.15008	2.97566	.43787
.03500	-2.57500	9.67196	-.06410	3.13702	.17259
.05000	-1.81400	10.51369	.02238	3.20293	.26033
.06000	-2.46200	11.13369	.10583	3.14250	.20502
.07000	-2.91900	12.45058	.09625	3.11380	.17840
.08500	-3.43400	13.32559	.16205	3.01422	.18390
.10000	-3.39800	12.42422	.11607	3.02239	.14185
.12000	-3.17300	13.11453	.09004	2.98245	.17441
.14000	-2.84400	13.33411	.19057	2.85763	.15297
.17000	-3.58400	13.49512	.18599	2.93854	.16693
.20000	-3.84400	14.75632	.12070	2.99379	.18356
.24000	-3.24700	14.91226	.15823	2.70433	.21576
.30000	-3.81100	14.93300	.30797	2.71756	.18405
.37000	-3.78300	16.64420	.27735	2.93627	.17127
.45000	-3.57700	17.15037	.33021	2.94199	.18361
.55000	-3.03700	18.10111	.26240	2.91974	.24205
.70000	-3.74400	19.35525	.32089	2.86456	.22997

Y (INS.)	V (F.P.S.)	V^2 (F.P.S.) ²	S_V	F_V	Z_V
.01000	-.09300	.12000	-.00521	6.97596	.35292
.01500	-.00600	.13503	N.A.	6.12675	.49234
.02500	.41100	.26811	.08971	3.96874	N.A.
.03000	.24900	.25199	.16942	3.62107	N.A.
.03500	.00200	.40385	.14252	N.A.	.53257
.05000	-.04300	.60553	-.08705	4.59082	.45433
.06000	.19000	.79698	-.23775	4.55844	.61357
.07000	.04700	1.02045	-.37643	4.74397	.53338
.08500	N.A.	1.32009	-.26423	3.93843	.36367
.10000	-.13800	1.63271	-.27846	4.10075	.47612
.12000	.35900	1.80903	-.33578	4.01040	.61315
.14000	-.03400	1.97698	-.23552	3.96218	.52545
.17000	N.A.	2.30587	-.31054	3.83101	.53064
.20000	-.07500	2.60777	-.25965	4.13706	.51546
.24000	.03100	2.95541	-.28928	4.24428	.54569
.30000	.04600	3.34956	-.28454	3.97417	.50994
.37000	-.06700	3.93983	-.37717	3.92660	.51222
.45000	-.11900	4.47606	-.33687	3.59821	.49058
.55000	.12800	5.41730	-.47672	3.79968	.57630
.70000	.20900	6.41092	-.44745	3.63593	.58324

Y (INS.)	U-V (F.P.S.)	$-(U-V)^2$ (F.P.S.) ²	S_{U-V}	F_{U-V}	Z_{U-V}
.01000	-.22762	N.A.	.06654	N.A.	.44556
.01500	N.A.	.09743	N.A.	3.42736	.45751
.02500	N.A.	.09533	.23379	3.17068	.45874
.03000	1.65461	N.A.	N.A.	2.85412	N.A.
.03500	-1.83845	-.13937	-.06679	3.25508	.25292
.05000	-2.41121	.15024	-.01903	3.16925	.24611
.06000	-2.90732	.48179	.03771	3.04161	.19476
.07000	-2.61703	.07241	.10834	3.24916	.24143
.08500	-3.27579	-.11953	.13174	3.28145	.17769
.10000	-3.25407	.20738	.20595	3.07523	.17238
.12000	-3.83409	.97557	.09997	3.24631	.14262
.14000	-3.41471	.86755	.16715	3.37900	.19634
.17000	-3.37944	.31130	.16417	3.15028	.21129
.20000	-3.57227	.46040	.26701	3.36557	.19111
.24000	-3.52843	.41750	.22741	3.10019	.19430
.30000	-3.52777	.48610	.30291	3.21482	.20229
.37000	-3.41529	.50450	.34532	3.30933	.21443
.45000	-3.34317	.83020	.39556	3.11391	.22307
.55000	-2.82457	1.15350	.45006	3.26098	.27655
.70000	-2.85244	1.21430	.47224	3.18752	.28920

L.D.V. MEASUREMENTS

V (INS.)	V (F.P.S.)	V ² (F.P.S. ²)	Σ	Σ	Σ
0.01000	0.0000	0.000000	-0.04445	4.03194	.12152
0.01500	-1.55300	2.411610	-0.01946	3.88554	.20314
0.02000	-2.26700	5.138889	-0.25622	3.66764	.17137
0.03000	-3.27500	10.725625	-0.14835	3.34261	.15467
0.04000	-4.27200	18.252480	-0.06033	3.12743	.17929
0.05000	-5.26300	27.708049	.13798	3.17638	.13075
0.07000	-6.89100	47.284881	.16407	3.15150	.07604
0.10000	-9.47700	89.813529	.22212	3.17859	.02465
0.30000	-30.00000	900.000000	.30352	3.25407	.00620
0.45000	-45.00000	2025.000000	.33623	3.37264	.13501
0.55000	-55.00000	3025.000000	.45744	3.59359	.12656
0.60000	-60.00000	3600.000000	.41474	3.56060	.16374
1.20000	-120.00000	14400.000000	.41528	3.52918	.17412
1.40000	-140.00000	19600.000000	.49835	3.28384	.24134
1.60000	-160.00000	25600.000000	.45896	3.14839	.34273
2.50000	-250.00000	62500.000000	.39270	2.94055	.47680
3.00000	-300.00000	90000.000000	.29639	2.75304	.62439
3.50000	-350.00000	122500.000000	.30597	3.03368	.73747
4.00000	-400.00000	160000.000000	.17845	2.65590	.65658
4.50000	-450.00000	202500.000000	.06907	2.51383	.93029
5.00000	-500.00000	250000.000000	-.02025	2.65376	.96611
6.50000	-650.00000	422500.000000	-.14110	2.66580	.68736
7.00000	-700.00000	490000.000000	-.19671	2.62891	.99407
7.50000	-750.00000	562500.000000	-.25750	2.76259	1.00000
8.00000	-800.00000	640000.000000	-.59465	3.30146	1.00000
8.50000	-850.00000	722500.000000	-.65868	3.06443	1.00000
9.00000	-900.00000	810000.000000	-.72764	4.01059	1.00000
9.50000	-950.00000	902500.000000	-.81133	6.20931	1.00000
9.70000	-970.00000	940900.000000	-1.66861	7.15491	1.00000
9.80000	-980.00000	960400.000000	-.65559	10.84607	1.00000
10.00000	-1000.00000	1000000.000000	.33140	8.94157	1.00000

V (INS.)	V (F.P.S.)	V ² (F.P.S. ²)	Σ	Σ	Σ
0.01000	-0.0200	0.000400	-.17452	N.A.	.34305
0.01500	-0.11400	0.129960	-.14189	5.80300	.27596
0.02000	-0.05500	0.003025	N.A.	6.04753	.47629
0.03000	-0.0100	0.000100	N.A.	6.83412	.47549
0.05000	0.22300	0.049729	-.27481	6.66094	.67420
0.07000	0.14400	0.020736	-.16750	4.96732	.57566
0.10000	0.11900	0.014161	-.21506	4.02856	.56186
0.20000	0.13300	0.017689	-.26834	4.07776	.48346
0.30000	0.0800	0.006400	-.37514	4.21650	.51259
0.45000	0.09800	0.009604	-.44132	4.31288	.55055
0.50000	0.07500	0.005625	-.38843	3.86686	.52233
0.60000	0.63600	0.404596	-.58457	N.A.	.63015
1.20000	0.50900	0.259081	-.44834	3.78006	.57306
1.50000	0.55200	0.304704	-.35564	3.49814	.62639
2.00000	0.64300	0.413449	-.50653	3.62714	.60940
2.50000	0.89300	0.797349	-.35252	3.32937	.64444
3.00000	1.24800	1.557504	-.41159	3.21996	.64361
3.50000	1.52700	2.331009	-.30246	3.29645	.66529
4.00000	1.95300	3.813809	-.19839	3.17304	.69653
4.50000	2.44700	5.988009	-.11954	3.13017	.68544
5.00000	2.72900	7.457041	-.07214	3.07966	.70131
5.50000	3.53900	12.52721	-.09294	3.07107	.76186
6.00000	4.01000	16.080100	-.09782	3.62464	.79093
6.50000	5.20400	27.081616	.15850	3.09936	.85749
7.00000	6.07300	36.881290	.24030	3.27339	.92034
7.50000	6.68100	44.623681	.16997	3.44497	.95767
8.00000	7.44100	55.366821	.42623	3.72794	.99113
8.50000	8.47900	71.972401	.33086	4.06594	.99723
9.00000	8.45900	71.554801	N.A.	5.34215	.99278
9.50000	8.99000	80.820100	N.A.	N.A.	.99787
10.00000	N.A.	N.A.	2.35971	12.83537	1.00000

V (INS.)	U-V (F.P.S.)	$\frac{U-V}{(F.P.S.)}$	$\frac{U-V}{(F.P.S.)}$	$\frac{U-V}{(F.P.S.)}$	$\frac{U-V}{(F.P.S.)}$
.01000	-2.07403	.39410	N.A.	4.48435	.14182
.01500	-1.99271	.19930	-.09554	4.02440	.21161
.02000	-1.41810	.06370	-.05374	3.52518	.13360
.03000	-2.93971	-.10600	-.12035	3.35340	.15819
.05000	-2.62732	-.16910	-.09513	3.25481	.16506
.10000	-4.05451	-.33910	-.02562	3.15626	.17593
.15000	-4.41513	.13940	.13748	3.29815	.10800
.20000	-4.75950	.34620	.32973	N.A.	.09697
.30000	-4.53317	.97010	.30145	3.24996	.16031
.45000	-4.22707	.45370	.41702	3.75831	.14144
.45000	-4.41252	1.03130	.46343	3.73140	.15909
.70000	-4.78141	1.51420	.54401	3.43627	.15813
1.20000	-4.30641	2.51340	.56435	3.47395	.27351
1.40000	-2.87840	3.74640	.53355	3.13777	.29772
2.00000	-1.35421	4.84300	.67834	3.33080	.39200
2.50000	-.76970	5.44420	.49019	3.16813	.41767
3.00000	2.19423	5.21440	.34083	2.98047	.59084
3.50000	4.40987	7.91330	.29446	2.78199	.65067
4.00000	7.23503	9.75130	.17919	2.67082	.74216
4.50000	9.91354	10.83490	.09781	2.71026	.81071
5.00000	12.70659	11.97730	-.00332	2.66679	.85103
5.50000	15.04704	12.06210	-.12545	2.72487	.93015
6.00000	16.24565	12.02110	-.25929	2.81097	.96139
6.50000	22.42921	10.50170	-.39241	2.93242	.97887
7.00000	25.53404	9.31150	-.54020	3.10105	.93779
7.50000	28.04704	5.93360	-.59808	3.16831	.99622
8.00000	30.92431	2.04430	-.85025	3.59920	.99938
8.50000	37.84752	.63550	-1.21532	4.57962	.99855
9.00000	34.34385	1.56100	-1.34234	5.42854	1.00000
9.50000	36.73799	.40610	-1.96223	9.38707	1.00000
10.00000	36.64755	-.37360	N.A.	N.A.	1.00000

X=156.175 INCHES

DATE: 3-15-78
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L.O.V. MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S. ²)	S_U	F_U	Z_U
.01000	-1.59200	2.53023	-.35407	4.01074	.13761
.01500	-1.97300	4.14770	-.36456	3.85285	.15891
.02000	-2.52000	5.70947	-.34521	3.61187	.12429
.02500	-2.74100	7.08356	-.14499	3.49910	.13882
.03000	-3.23600	10.43529	-.10748	3.35927	.13271
.03500	-3.95800	12.54739	.11314	3.16713	.13231
.04000	-4.07900	13.91929	.16421	3.01987	.12646
.04500	-4.65900	13.14947	.11657	3.02987	.09733
.05000	-4.44300	14.45266	.22912	2.90726	.11452
.05500	-5.09300	14.58623	.21967	2.97264	.10998
.06000	-4.69400	16.37505	.29050	3.01753	.12632

Y (INS.)	V (F.P.S.)	V^2 (F.P.S. ²)	S_V	F_V	Z_V
.01000	-.19300	.035477	-.17005	6.48295	N.A.
.01500	-.04500	.00170	N.A.	N.A.	.48532
.02000	-.15200	.14490	N.A.	6.54024	.29034
.02500	.06800	.22434	N.A.	5.29766	.55712
.03000	-.00500	.37821	-.12749	4.87853	.50634
.03500	.10200	.78393	-.03754	N.A.	.55505
.04000	.06300	1.43734	-.13527	4.08780	.53012
.04500	.02700	2.06545	-.26715	4.08702	.48853
.05000	.79200	2.50351	-.23145	4.09902	.56615
.05500	.10900	3.50790	-.28789	3.82019	.52156
.06000	.09200	4.74303	-.47357	4.02660	.53486

Y (INS.)	U-V (F.P.S.)	$-\overline{UV}$ (F.P.S. ²)	S_{U-V}	F_{U-V}	Z_{U-V}
.01000	-1.70128	.39170	N.A.	5.61944	.12235
.01500	-2.05625	.19590	-.37003	4.03401	.14422
.02000	-2.22737	.36370	-.41267	4.37825	.17247
.02500	-2.58799	-.07550	-.22596	3.71280	.13574
.03000	-3.25123	-.19000	.00446	3.44881	.16329
.03500	-3.74753	-.15190	.06819	3.37321	.17259
.04000	-4.36139	.04230	.09431	3.60285	.12206
.04500	-4.47735	.35550	.13535	3.35841	.12774
.05000	-4.97374	.45710	.25261	3.24665	.11217
.05500	-4.72903	.72940	.37034	3.35909	.14412
.06000	-5.41073	1.00920	.39183	3.33892	.13045

1-170.874 INCHES

DATE: 2-20-78
AT 170A

L.D.V. MEASUREMENTS

V (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	$\frac{U^2}{V}$
.00000	-7.26000	5.27124	.16781
.00000	-4.86000	23.61600	.15441
.10000	-5.71100	32.62541	.06794
.32000	-4.29000	18.40810	.05265
.44000	-4.27500	18.27563	.07407
1.00000	-4.27400	18.26816	.06888
1.50000	-5.00000	25.00000	.13116
2.00000	-5.00000	25.00000	.15082
2.50000	-3.94000	15.52360	.19853
3.00000	-3.54100	12.53841	.30144
3.50000	-1.00000	1.00000	.29649
4.00000	.40000	0.16000	.45873
4.50000	2.53100	6.40616	.67793
5.00000	4.76000	22.65760	.73049
5.50000	7.19000	51.69610	.80392
6.00000	10.75000	115.50625	.83642
6.50000	12.46000	155.29160	.90848
7.00000	16.65000	277.22250	.95096
7.50000	16.36500	267.83625	.96784
8.00000	22.02700	485.19089	.99237
8.50000	24.25200	588.16032	.99657
9.00000	26.97400	728.60876	.99839
9.50000	31.15000	969.32250	1.00000
10.00000	31.62000	1000.00000	1.00000
10.50000	36.75000	1350.06250	1.00000

V (INS.)	V (F.P.S.)	V^3 (F.P.S.) ³	$\frac{V^3}{V}$
.02000	.20600	.00838	.05760
.04000	.11100	.00133	.06672
.10000	-.07000	-.00034	.02283
.37000	.06900	.00033	.02560
.44000	-.17500	-.00534	.09299
1.00000	.33300	.03693	.04465
1.50000	.43000	.07950	.05369
2.00000	.57400	.19000	.08270
2.50000	.64000	.26210	.06161
3.00000	.93200	.81200	.02665
3.50000	1.00000	1.00000	.00717
4.00000	.98400	.09520	.00640
4.50000	1.36000	2.51700	.01336
5.00000	1.72000	5.08800	.05337
5.50000	1.41600	2.83000	.01280
6.00000	1.92000	7.08000	.05054
6.50000	1.72000	5.08800	.02140
7.00000	2.41700	35.60000	.06033
7.50000	3.20500	32.80000	.02264
8.00000	2.26700	46.40000	.06524
8.50000	3.75700	52.20000	.07400
9.00000	4.27300	78.00000	.09272
9.50000	4.77700	108.00000	.08694
10.00000	4.39900	84.00000	.07420
10.50000	6.26300	246.00000	.04125

Y (N.S.)	U-V (F.S.S.)	γ_{u-v}
.03000	-3.20539	.05549
.04000	-4.00000	.09470
.05000	-4.68000	.09257
.06000	-5.25000	.07337
.07000	-5.70000	.07000
.08000	-6.00000	.09204
.09000	-6.127	.13497
1.00000	-5.73170	.14879
1.50000	-5.14200	.22940
2.00000	-4.37554	.31398
3.00000	-3.17430	.39040
4.00000	-1.67700	.45071
5.00000	.24407	.50729
6.00000	1.52300	.62890
7.00000	2.57050	.67435
8.00000	3.74392	.72355
9.00000	5.20111	.79717
10.00000	6.47700	.83935
11.00000	11.34413	.83022
12.00000	12.64573	.87648
13.00000	14.65535	.87324
14.00000	15.95500	.97231
15.00000	21.75534	.97362
16.00000	N.A.	.98211
17.00000	25.31953	.98223
18.00000	N.A.	

W 31.600 INCHES

DATE: 7-6-78

HOT-WIRE (X-WIRE) MEASUREMENTS

V (INS.)	U (F.P.S.)	V (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²	UV (F.P.S.) ²	S_V
.05000	44.11500	N.A.	23.09764	6.98016	4.86200	N.A.	N.A.
.06000	44.81700	N.A.	20.80272	5.34997	4.83200	4.77100	N.A.
.07500	46.46200	N.A.	19.44810	5.01312	4.60300	3.24600	N.A.
.09500	47.91900	N.A.	18.09652	4.63110	4.66900	2.43500	N.A.
.12000	49.07100	1.73900	16.44627	4.19981	4.20100	1.47400	.71970
.15000	51.29300	1.93800	15.00013	3.92040	3.10450	.71610	.82920
.19000	53.36400	1.97500	12.98492	3.45216	2.66700	-.04730	.86360
.25000	55.43400	2.04500	9.87716	2.79693	1.92750	-.58020	.94630
.29000	57.04400	2.12200	8.17355	2.35000	1.50400	-.91490	1.09170
.33000	58.15100	2.17200	6.83300	1.88235	1.16150	-.67640	1.22410
.39000	59.17000	2.16500	5.12117	1.43042	.75650	-.68950	1.39940
.43000	59.43900	2.04300	3.56454	.97632	.28140	-.72250	1.62420
.48100	60.50400	2.03900	2.49440	.59195	-.00519	-.87760	1.85280
.53000	61.00200	2.04400	1.52029	.25231	-.22530	-.98900	1.63460
.62000	61.78300	2.04900	.68459	.09333	-.11210	-1.36900	N.A.
.73000	62.18300	2.01900	.39665	.03063	.00430	-1.53500	N.A.

V = 54.100 INCHES

DATE: 6-31-78

HOT-WIRE (X-WIRE) MEASUREMENTS

V (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²
.05000	43.84500	30.27200	7.00661	8.14200
.06200	44.78500	32.00165	7.59003	7.35000
.08300	46.36900	31.78704	7.30621	7.56200
.09500	47.67700	31.23892	7.34952	7.36700
.12100	50.04500	30.70254	7.43653	7.29100
.17000	51.81400	29.46315	7.35494	7.20200
.19000	53.44400	29.09524	7.54601	6.94000
.20000	54.16000	26.47103	7.20923	6.57400
.27000	59.22700	23.45465	6.56897	5.49000
.35000	62.19400	19.87375	5.57432	4.59400
.48000	65.43400	15.17103	4.15752	3.44500
.52500	67.17900	11.47177	2.75692	2.59400
.75000	70.54500	5.04544	.98206	1.09200
.87400	71.32400	3.66340	.17550	.51000
.90000	72.10100	2.40250	.07840	.20000
1.00000	73.39000	1.88234	.06250	.00500

V = 84.500 INCHES

DATE: 7-11-78

HOT-WIRE (X-WIRE) MEASUREMENTS

V (INS.)	U (F.P.S.)	V (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²	UV (F.P.S.) ²	S_V
.03700	34.88200	1.02500	30.12012	7.15028	5.91100	13.90500	.52780
.04450	35.92000	1.10400	25.91213	6.91690	5.87100	14.53100	.53670
.06750	36.36000	1.25500	28.70672	6.74174	5.87000	12.47500	.50280
.08750	36.08000	1.33100	26.72960	6.80166	5.99500	10.50900	.35050
.09750	36.11000	1.34800	28.17486	7.14493	6.08600	9.10800	.22250
.09750	40.61000	1.45900	27.34476	7.21997	6.24300	9.03200	.14600
.12300	42.07000	1.53100	27.17537	7.50712	6.32600	N.A.	.14820
.15300	43.65500	1.59000	27.25884	7.66398	6.43300	N.A.	.41610
.20200	45.71000	1.66900	26.24513	7.52423	6.18900	N.A.	.40310
.27200	48.91000	1.77800	24.63079	7.57364	6.29800	10.95300	.43530
.35400	50.87000	1.85200	22.87709	7.62321	5.79400	9.61100	.42400
.47200	53.66000	2.01700	20.26900	7.20386	5.34200	7.14500	.47520
.60200	57.44000	2.22800	16.01400	5.86549	4.04100	4.54900	.55760
.80200	61.76000	2.49000	6.97796	3.87696	2.50100	3.53200	.76170
1.00700	64.98000	2.72300	4.23125	1.72134	1.06700	1.40700	.93950
1.22300	68.47000	2.92400	.86806	.93702	.02260	1.56200	N.A.
1.40200	66.71000	3.09200	.57973	.59444	.34350	1.07000	N.A.

1105.250 INCHES

DATE: 7-8-78

HOT-WIRE (X-WIRE) MEASUREMENTS

V (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²	S_V
.05900	27.54900	24.29504	4.23944	4.28000	.61300
.06900	27.38100	24.29504	4.43944	4.39900	.52700
.08300	26.53500	24.53721	4.78297	4.27300	.45070
.10100	25.49700	24.25544	5.30842	4.69500	.36250
.12400	24.72500	24.43137	5.81292	5.12600	.34530
.14100	27.59700	25.33109	6.57410	5.62300	.32170
.20100	29.42800	25.84705	7.24146	5.83800	.34190
.25100	31.16100	26.69789	7.74409	6.09800	.34930
.32100	33.14300	26.46074	8.30016	6.55670	.36800
.40100	34.16100	27.51003	8.55535	6.35000	.39370
.50700	36.37800	29.27441	8.80010	6.27200	.40000
.62100	39.97400	29.63397	8.45646	6.42800	.42650
.74100	42.71600	23.12548	8.03156	5.89200	.44570
.87100	45.55000	19.26332	7.06496	5.04900	.47640
1.01100	48.55400	15.95204	5.36199	4.32500	.55330
1.32100	51.44200	11.62126	4.26010	2.94000	.72840
1.53100	54.04100	7.03310	2.30224	1.67300	.86200
1.72100	56.34900	3.10112	1.56250	.72740	1.28390
1.92100	57.30500	.76580	.66374	.19240	N.A.
2.12100	57.55700	.19862	.21650	.02540	1.56070 (F.S.)

V=111.250 INCHES

DATE: 8-16-78

HOT-WIRE (X-WIRE) MEASUREMENTS

V (INS.)	U (F.P.S.)	V (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²
.07500	27.74900	.13700	19.74914	3.93376	3.06200
.09500	21.79400	.22910	21.22445	4.56250	3.01200
.12000	22.76700	.24910	20.46658	5.09405	3.46000
.14000	22.66500	.34440	22.74336	5.63113	3.44200
.22000	23.67200	.39300	23.01121	6.37563	4.53800
.27000	25.73100	.08150	24.81036	7.24635	5.26000
.35000	27.33100	.07490	24.26548	7.85120	5.33800
.45000	29.59300	.18720	25.84706	8.36366	5.77800
.60000	32.38900	.35170	25.86740	8.86253	6.04900
.80000	36.26100	.60450	24.71084	8.75568	5.73700
1.00000	40.24900	.91950	21.30745	9.16816	5.48300
1.20000	43.44200	1.20300	19.76692	7.14493	4.34700
1.40000	46.97700	1.59100	15.50794	5.55013	3.62800
1.60000	49.83100	1.96300	11.50566	4.25597	2.35300
1.80000	52.79900	2.33100	6.58949	2.86964	1.39500
2.00000	54.80400	2.73900	1.65123	1.14276	.24050
2.40000	55.13800	3.03600	.26194	.30349	.03400

V=117.625 INCHES

DATE: 7-24-78

HOT-WIRE (X-WIRE) MEASUREMENTS

V (INS.)	U (F.P.S.)	V (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²	$U^2 V$ (F.P.S.) ³	S_V
.90100	28.14100	2.02300	29.48490	8.97003	4.07600	N.A.	N.A.
1.10100	31.52700	2.42800	27.94180	8.94010	4.36000	11.48500	.11303
1.35000	35.41500	2.96900	26.13254	8.53772	4.11300	9.56900	.10290
1.60000	39.82600	3.50700	22.17448	7.54601	3.57500	10.61000	.16650
1.85000	43.14700	4.02300	18.14760	5.92436	2.89800	9.09400	.24230
2.10200	46.47100	4.49700	12.25000	4.36810	1.72900	7.61200	.31810
2.35000	49.33000	5.04500	6.36553	2.81233	.89770	4.39300	.36520
2.60100	51.77900	5.39800	2.40870	1.61848	.27530	N.A.	.14770
2.85000	51.71200	5.62300	.52944	.62442	.05396	N.A.	N.A.
3.10100	51.85700	5.74200	.17144	.22555	-.01690	N.A.	N.A. (F.S.)

X=126.780 INCHES

DATE: 7-22-78

HJT-WIRE (X-WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	V (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²	U^2V (F.P.S.) ³	S_V
2.37000	36.90700	3.92000	29.31140	9.35136	-4.02200	12.71900	.17320
2.57000	36.34500	4.37000	26.33742	9.36368	-3.70500	16.59800	.35210
2.87000	40.70500	5.04400	19.98878	6.36048	-3.18400	14.70200	.47570
3.17000	44.23800	5.69700	13.63086	4.57960	-1.81400	11.75900	.49310
3.47000	46.81100	6.21900	6.25000	2.77866	-.79730	6.41600	.76280
3.62000	49.01100	6.49200	2.91385	1.74504	-.45810	2.20600	.82550
3.82000	49.34900	6.70400	1.02010	1.37744	-.18930	.60200	.96360
4.17000	48.94300	6.74100	.31697	.44766	-.02529	.02900	.50440 (F.S.)

X=131.000 INCHES

DATE: 7-27-78

HJT-WIRE (X-WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	V (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²	U^2V (F.P.S.) ³	S_V
3.00000	17.18400	4.59000	25.08006	7.86803	-3.43800	13.37800	.21240
3.20000	19.53000	5.19900	21.78089	6.55872	-2.62600	13.76200	.26490
3.40000	41.63100	5.58300	16.98264	5.54323	-2.00000	10.78600	.35110
3.70000	44.00900	6.25700	12.22804	3.73649	-1.32700	7.90600	.47600
4.10000	47.31700	7.22700	2.43738	1.85777	-.54070	1.74400	.65730
4.50000	47.96400	7.51400	.53319	.68096	-.07710	.09090	N.A.
5.00000	47.42500	7.54200	.19740	.25817	-.00078	.04090	.72610
5.50000	47.33400	7.60500	.11560	.14394	-.00191	.00668	.28630
6.30000	46.98200	7.30900	.06625	.07464	-.00722	.00297	.29840 (F.S.)

X=139.000 INCHES

DATE: 7-20-78

HJT-WIRE (X-WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	V (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²	U^2V (F.P.S.) ³	S_V
4.00000	35.12000	4.97700	34.40996	10.51056	N.A.		
4.12000	36.29000	5.24400	32.46720	9.59141	N.A.		
4.37000	38.18000	5.77200	26.41960	8.30902	-3.17700		
4.52000	40.81000	6.40500	20.46658	6.56897	-1.46300		
4.82000	42.04000	6.91400	17.18932	5.56960	-1.68000		
5.12000	45.04000	7.52300	7.79526	3.74810	-1.30200		
5.67000	46.51000	8.02200	1.80634	1.71348	-.11220		
5.12000	46.82000	8.20000	.57199	.69389	-.03350		
6.47000	44.85000	9.25200	.33617	.35284	-.00252		
7.12000	46.78000	9.05200	.20921	.22848	-.02760		(F.S.)

X=144.000 INCHES

DATE: 7-26-78

HJT-WIRE (X-WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	V (F.P.S.)	U^2 (F.P.S.) ²	V^2 (F.P.S.) ²	$-UV$ (F.P.S.) ²	U^2V (F.P.S.) ³	S_V
5.50000	42.00900	8.90400	25.05003	7.77852	N.A.	11.23500	.20180
5.75000	43.74000	9.67200	18.11354	6.25500	N.A.	9.67100	.39630
5.90000	45.34300	10.17900	10.91542	4.94969	-.64070	5.44900	.42510
6.57000	48.05000	10.75000	2.97906	2.29825	-.27940	2.67400	.85980
7.07000	47.06400	10.97710	.89170	1.12148	-.00372	.49770	1.04500
8.00000	46.64300	10.95400	.30008	.37626	-.04610	-.00954	.07610
9.00000	45.74500	11.09200	.16794	.20258	-.03670	-.03963	-.47610
11.00000	46.40000	11.35300	.07706	.06724	-.02530	-.05738	N.A. (F.S.)

V=156.375 INCHES

DATE: 7-21-78

HOT-WIRE (X-WIRE) MEASUREMENTS

y (INS.)	U (F.P.S.)	V (F.P.S.)	u^2 (F.P.S.) ²	v^2 (F.P.S.) ²	$-uv$ (F.P.S.) ²	u^2v (F.P.S.) ³	S_v
8.50100	43.54800	7.63400	15.26465	5.56488	1.96900	14.26800	.74210
9.00000	44.46000	8.19500	5.09350	4.38065	.78080	6.96500	.85060
9.50000	44.90300	8.37700	1.86050	2.12576	.07710	1.21800	1.34700
10.00000	45.30300	8.50200	1.24546	1.50063	-.03206	.53500	.82980
11.00000	45.24300	8.60200	.60752	.68558	-.04032	.21870	.73080
12.00000	45.12500	8.82500	.38254	.34129	-.05164	.02300	.34260
13.00000	45.13500	8.97000	.25452	.21326	-.05720	-.00196	.11140 (F.S.)

V=149.750 INCHES

DATE: 7-25-78

HOT-WIRE (X-WIRE) MEASUREMENTS

y (INS.)	U (F.P.S.)	V (F.P.S.)	u^2 (F.P.S.) ²	v^2 (F.P.S.) ²
11.50000	42.01700	10.67000	36.38502	8.63184
12.50000	44.05400	11.45700	14.50086	4.72628
13.50000	44.24800	11.77900	3.76748	2.82240
14.50000	44.16800	12.04200	.66012	.92795
17.50000	44.15400	12.25000	.32036	.42942 (F.S.)

Y= 11.375 INCHES DATE: 10-11-77

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S. ²)
.00200	6.51700	4.24729
.00300	7.76300	6.04729
.00400	8.98300	8.06949
.00500	9.72400	9.45536
.00600	11.37100	12.73061
.00700	12.62900	15.93561
.00800	14.23500	20.26801
.00900	14.48500	20.98625
.01000	16.70000	27.89000
.01100	14.17400	20.23156
.01200	16.85800	28.42064
.01300	19.07300	36.37829
.01400	21.14500	44.71025
.01500	23.64600	55.89536
.01600	24.19300	58.53825
.01700	26.66200	71.47524
.01800	27.08300	73.55809
.01900	29.55200	87.32544
.02000	30.44100	92.67281
.02100	32.91000	108.32810
.02200	34.71600	120.50016
.02300	37.12400	137.79056
.02400	39.62700	157.00449
.02500	41.09000	168.86100
.02600	42.34000	179.31600
.02700	44.61900	199.61441
.02800	46.81900	219.10081
.02900	48.61900	236.35841
.03000	51.03300	260.35281
.03100	53.79000	289.36801
.03200	54.52000	297.23200
.03300	54.52000	297.23200

(F.S.)

X= 31.250 INCHES DATE: 1-26-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S. ²)
.00350	14.65100	214.53121
.00400	17.09300	292.17049
.00450	19.12000	365.56000
.00500	20.71400	429.08756
.00550	22.70400	515.28336
.00600	24.85300	617.27409
.00650	26.56500	707.15225
.00700	27.30400	745.91856
.00750	29.37500	862.90625
.00800	29.69300	881.60481
.00850	30.35800	921.80841
.00900	32.09400	1030.05156
.00950	32.11300	1031.24369
.01000	34.04500	1159.10025
.01050	35.75300	1277.97809
.01100	36.75200	1349.42881
.01150	38.74100	1500.10810
.01200	39.53400	1562.75556
.01250	40.92100	1674.58401
.01300	42.10700	1773.18841
.01350	43.04400	1852.75536
.01400	44.36200	1967.68841
.01450	45.42500	2063.25625
.01500	46.72900	2181.70801
.01550	47.90700	2286.66081
.01600	49.43200	2443.54241
.01650	51.61900	2664.58801
.01700	53.35600	2846.75361
.01750	55.37100	3066.60810
.01800	57.81800	3339.85241
.01850	59.89300	3587.18801
.01900	61.89900	3811.36801
.01950	63.76800	4047.32641
.02000	63.75200	4066.27041

(F.S.)

Y= 21.750 INCHES DATE: 10-13-77

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S. ²)
.00150	4.44400	19.74916
.00200	5.25500	27.61525
.00250	7.52200	56.58044
.00300	8.82200	77.83084
.00350	10.32700	106.65829
.00400	13.20700	173.43281
.00450	13.80900	190.68421
.00500	15.41000	237.46810
.00550	17.03100	289.85441
.00600	17.84400	318.40956
.00650	19.27600	371.57776
.00700	20.23300	409.36689
.00750	22.60500	510.86025
.00800	26.78300	726.31081
.00850	29.85500	891.12025
.00900	31.06000	964.72000
.00950	33.44400	1119.35536
.01000	35.64300	1269.95281
.01050	36.85900	1357.58801
.01100	37.85900	1427.50801
.01150	39.56500	1565.35025
.01200	39.84200	1587.40081
.01250	41.31800	1706.99241
.01300	42.47700	1804.75081
.01350	43.99100	1935.78801
.01400	45.44400	2065.05441
.01450	46.76300	2185.18801
.01500	48.47800	2350.10801
.01550	51.40300	2642.25601
.01600	53.95500	2911.35025
.01650	55.74100	3106.05801
.01700	57.71000	3326.40100
.01750	58.97500	3477.80061
.01800	59.09600	3491.25456
.01850	59.15200	3498.75281

(F.S.)

Y= 44.000 INCHES DATE: 1-24-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S. ²)
.00300	12.46800	155.47184
.00350	14.15900	200.47681
.00400	16.70000	278.89000
.00450	19.21500	369.31625
.00500	19.07300	363.78009
.00550	20.97700	439.99329
.00600	22.53900	507.94821
.00650	25.45100	647.85401
.00700	30.82500	950.16561
.00750	34.99100	1224.38981
.00800	36.93100	1363.83481
.00850	39.28600	1543.28841
.00900	40.97500	1679.00625
.00950	42.18500	1780.02250
.01000	43.15500	1862.40250
.01050	44.80100	2006.29601
.01100	46.10300	2125.06090
.01150	47.73300	2278.77281
.01200	49.44400	2444.75536
.01250	50.45500	2545.75025
.01300	52.43200	2749.25441
.01350	54.17900	2934.75601
.01400	55.99100	3124.25801
.01450	58.27400	3395.18761
.01500	60.89700	3708.35081
.01550	63.13700	3986.25681
.01600	65.71400	4318.35561
.01650	67.91300	4611.85801
.01700	68.04700	4630.45081
.01750	69.10100	4773.98001
.01800	69.25500	4797.75025
.01850	69.36300	4811.05801

(F.S.)

X= 52.500 INCHES DATE: 1-31-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

V (INS.)	U (F.P.S.)	U ² (F.P.S.) ²
.00300	14.49000	21.33115
.00350	17.19000	29.24354
.00400	19.17200	36.75354
.00450	20.56400	42.28560
.00500	22.43400	50.31220
.00550	24.38700	59.48272
.00600	26.79200	71.73776
.00650	28.77500	82.85126
.00700	30.79200	94.71276
.00750	32.76000	107.00140
.00800	34.70000	120.59328
.00850	36.61000	134.49540
.00900	38.49000	148.60280
.00950	40.34000	162.91160
.01000	42.16000	177.41760
.01050	43.95000	192.11700
.01100	45.71000	207.00500
.01150	47.44000	222.07680
.01200	49.14000	237.32760
.01250	50.81000	252.75360
.01300	52.45000	268.35000
.01350	54.06000	284.11200
.01400	55.64000	300.03440
.01450	57.19000	316.11240
.01500	58.71000	332.34100
.01550	60.20000	348.71560
.01600	61.66000	365.23160
.01650	63.09000	381.88440
.01700	64.49000	398.66960
.01750	65.86000	415.58240
.01800	67.20000	432.61800
.01850	68.51000	449.77080
.01900	69.79000	467.03600
.01950	71.04000	484.40800
.02000	72.26000	501.88200
.02050	73.45000	519.45360
.02100	74.61000	537.11840
.02150	75.74000	554.87200
.02200	76.84000	572.71000
.02250	77.91000	590.62800
.02300	78.95000	608.62160
.02350	80.00000	626.69600
.02400	81.00000	644.84640
.02450	82.00000	663.06800
.02500	83.00000	681.35600
.02550	84.00000	699.70400
.02600	85.00000	718.11600
.02650	86.00000	736.58640
.02700	87.00000	755.10800
.02750	88.00000	773.68400
.02800	89.00000	792.30800
.02850	90.00000	810.98400
.02900	91.00000	829.70600
.02950	92.00000	848.46800
.03000	93.00000	867.26400
.03050	94.00000	886.09800
.03100	95.00000	904.97600
.03150	96.00000	923.89200
.03200	97.00000	942.84000
.03250	98.00000	961.82400
.03300	99.00000	980.83800
.03350	100.00000	1000.00000
.03400	101.00000	1019.21600
.03450	102.00000	1038.47600
.03500	103.00000	1057.77600
.03550	104.00000	1077.11200
.03600	105.00000	1096.48800
.03650	106.00000	1115.90000
.03700	107.00000	1135.34400
.03750	108.00000	1154.82400
.03800	109.00000	1174.33600
.03850	110.00000	1193.88400
.03900	111.00000	1213.46400
.03950	112.00000	1233.07200
.04000	113.00000	1252.70400
.04050	114.00000	1272.36400
.04100	115.00000	1292.04800
.04150	116.00000	1311.75200
.04200	117.00000	1331.48000
.04250	118.00000	1351.22800
.04300	119.00000	1370.99200
.04350	120.00000	1390.77600
.04400	121.00000	1410.58400
.04450	122.00000	1430.41200
.04500	123.00000	1450.26400
.04550	124.00000	1470.13600
.04600	125.00000	1490.02400
.04650	126.00000	1509.93200
.04700	127.00000	1529.85600
.04750	128.00000	1549.79200
.04800	129.00000	1569.74400
.04850	130.00000	1589.70800
.04900	131.00000	1609.68800
.04950	132.00000	1629.68800
.05000	133.00000	1649.70400
.05050	134.00000	1669.73200
.05100	135.00000	1689.77600
.05150	136.00000	1709.83200
.05200	137.00000	1729.90400
.05250	138.00000	1749.98800
.05300	139.00000	1769.98800
.05350	140.00000	1789.99600
.05400	141.00000	1809.91600
.05450	142.00000	1829.84400
.05500	143.00000	1849.78400
.05550	144.00000	1869.73200
.05600	145.00000	1889.69200
.05650	146.00000	1909.66000
.05700	147.00000	1929.63600
.05750	148.00000	1949.62400
.05800	149.00000	1969.62400
.05850	150.00000	1989.63200
.05900	151.00000	2009.64800
.05950	152.00000	2029.67200
.06000	153.00000	2049.70800
.06050	154.00000	2069.75200
.06100	155.00000	2089.80400
.06150	156.00000	2109.86800
.06200	157.00000	2129.94400
.06250	158.00000	2149.93200
.06300	159.00000	2169.93600
.06350	160.00000	2189.95200
.06400	161.00000	2209.97600
.06450	162.00000	2229.91200
.06500	163.00000	2249.86400
.06550	164.00000	2269.82800
.06600	165.00000	2289.80800
.06650	166.00000	2309.79600
.06700	167.00000	2329.79600
.06750	168.00000	2349.80400
.06800	169.00000	2369.82400
.06850	170.00000	2389.85200
.06900	171.00000	2409.88800
.06950	172.00000	2429.93200
.07000	173.00000	2449.98400
.07050	174.00000	2469.94800
.07100	175.00000	2489.92400
.07150	176.00000	2509.90800
.07200	177.00000	2529.90000
.07250	178.00000	2549.89600
.07300	179.00000	2569.89600
.07350	180.00000	2589.90400
.07400	181.00000	2609.91600
.07450	182.00000	2629.93600
.07500	183.00000	2649.96000
.07550	184.00000	2669.98800
.07600	185.00000	2689.92400
.07650	186.00000	2709.86800
.07700	187.00000	2729.82400
.07750	188.00000	2749.78800
.07800	189.00000	2769.76400
.07850	190.00000	2789.74800
.07900	191.00000	2809.74000
.07950	192.00000	2829.73600
.08000	193.00000	2849.73600
.08050	194.00000	2869.74400
.08100	195.00000	2889.75600
.08150	196.00000	2909.77200
.08200	197.00000	2929.79200
.08250	198.00000	2949.81600
.08300	199.00000	2969.84400
.08350	200.00000	2989.87600
.08400	201.00000	3009.91200
.08450	202.00000	3029.95200
.08500	203.00000	3049.99600
.08550	204.00000	3069.94800
.08600	205.00000	3089.90400
.08650	206.00000	3109.86800
.08700	207.00000	3129.83600
.08750	208.00000	3149.80800
.08800	209.00000	3169.78400
.08850	210.00000	3189.76400
.08900	211.00000	3209.74800
.08950	212.00000	3229.73600
.09000	213.00000	3249.72800
.09050	214.00000	3269.72400
.09100	215.00000	3289.72400
.09150	216.00000	3309.72800
.09200	217.00000	3329.73600
.09250	218.00000	3349.74800
.09300	219.00000	3369.76400
.09350	220.00000	3389.78400
.09400	221.00000	3409.80800
.09450	222.00000	3429.83600
.09500	223.00000	3449.86800
.09550	224.00000	3469.90400
.09600	225.00000	3489.94400
.09650	226.00000	3509.98800
.09700	227.00000	3529.93600
.09750	228.00000	3549.88800
.09800	229.00000	3569.84400
.09850	230.00000	3589.80400
.09900	231.00000	3609.76800
.09950	232.00000	3629.73600
.10000	233.00000	3649.70800
.10050	234.00000	3669.68400
.10100	235.00000	3689.66400
.10150	236.00000	3709.64800
.10200	237.00000	3729.63600
.10250	238.00000	3749.62800
.10300	239.00000	3769.62400
.10350	240.00000	3789.62400
.10400	241.00000	3809.62800
.10450	242.00000	3829.63600
.10500	243.00000	3849.64800
.10550	244.00000	3869.66400
.10600	245.00000	3889.68400
.10650	246.00000	3909.70800
.10700	247.00000	3929.73600
.10750	248.00000	3949.76800
.10800	249.00000	3969.80400
.10850	250.00000	3989.84400
.10900	251.00000	4009.88800
.10950	252.00000	4029.93600
.11000	253.00000	4049.98800
.11050	254.00000	4069.94400
.11100	255.00000	4089.90400
.11150	256.00000	4109.86800
.11200	257.00000	4129.83600
.11250	258.00000	4149.80800
.11300	259.00000	4169.78400
.11350	260.00000	4189.76400
.11400	261.00000	4209.74800
.11450	262.00000	4229.73600
.11500	263.00000	4249.72800
.11550	264.00000	4269.72400
.11600	265.00000	4289.72400
.11650	266.00000	4309.72800
.11700	267.00000	4329.73600
.11750	268.00000	4349.74800
.11800	269.00000	4369.76400
.11850	270.00000	4389.78400
.11900	271.00000	4409.80800
.11950	272.00000	4429.83600
.12000	273.00000	4449.86800
.12050	274.00000	4469.90400
.12100	275.00000	4489.94400
.12150	276.00000	4509.98800
.12200	277.00000	4529.93600
.12250	278.00000	4549.88800
.12300	279.00000	4569.84400
.12350	280.00000	4589.80400
.12400	281.00000	4609.76800
.12450	282.00000	4629.73600
.12500	283.00000	4649.70800
.12550	284.00000	4669.68400
.12600	285.00000	4689.66400
.12650	286.00000	4709.64800
.12700	287.00000	4729.63600
.12750	288.00000	4749.62800
.12800	289.00000	4769.62400
.12850	290.00000	4789.62400
.12900	291.00000	4809.62800
.12950	292.00000	4829.63600
.13000	293.00000	4849.64800
.13050	294.00000	4869.66400
.13100	295.00000	4889.68400
.13150	296.00000	4909.70800
.13200	297.00000	4929.73600
.13250	298.00000	4949.76800
.13300	299.00000	4969.80400
.13350	300.00000	4989.84400
.13400	301.00000	5009.88800
.13450	302.00000	5029.93600
.13500	303.00000	5049.98800
.13550	304.00000	5069.94400
.13600	305.00000	5089.90400
.13650	306.00000	5109.86800
.13700	307.00000	5129.83600
.13750	308.00000	5149.80800
.13800	309.00000	5169.78400
.13850	310.00000	5189.76400
.13900	311.00000	5209.74800
.13950	312.00000	5229.73600
.14000	313.00000	5249.72800
.14050	314.00000	5269.72400
.14100	315.00000	5289.72400
.14150	316.00000	5309.72800
.14200	317.00000	5329.73600
.14250	318.00000	5349.74800

X=124.310 INCHES DATE: 6-10-77

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
.00450	9.90000	12.44162
.00700	10.44000	13.49443
.00750	11.02000	14.96467
.00900	11.96000	17.06001
.00950	12.47000	17.97787
.00960	13.44000	19.61501
.01150	15.39000	22.00399
.01350	16.79000	22.35553
.01550	17.90000	23.33114
.01550	19.38000	23.15139
.02150	20.04000	23.27931
.02550	20.98000	23.22050
.03050	22.06000	22.52136
.03750	23.11200	22.00399
.04550	24.04000	21.54913
.05550	24.44000	21.37979
.06750	25.70000	21.71914
.08250	26.50000	22.06117
.10250	27.40000	22.40587
.12550	28.18000	23.27931
.16050	29.51000	23.69263
.20050	30.77000	24.33234
.25050	31.99000	25.62942
.32050	33.79000	26.37394
.40050	35.74000	26.49923
.50050	37.99000	26.63772
.62050	40.67000	26.94009
.75050	43.45000	26.75370
.92050	47.25000	25.13735
1.13050	51.00000	26.59835
1.38050	54.52000	14.72994
1.53250	57.48000	6.94711
1.70050	59.62000	3.99271
1.90050	61.65000	1.18912
2.13050	60.95000	.45726
2.30050	60.92000	.31412 (F.S.)

X=114.500 INCHES DATE: 8-10-77

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
.00800	4.35000	4.81950
.01000	5.01000	5.55935
.01200	5.77000	9.53633
.01400	6.59000	10.29750
.01600	7.39000	11.94266
.01800	8.73000	13.70909
.02200	9.40000	14.49832
.02500	9.70000	15.02319
.03000	10.42000	15.47437
.03700	11.23000	15.64310
.04500	11.84000	16.05826
.05500	12.58000	16.55734
.07000	13.74000	16.10038
.09000	13.86000	16.43194
.11500	14.95000	18.14225
.14500	15.16000	16.35544
.18000	15.96000	19.55371
.22000	16.45000	20.40075
.26000	17.49000	21.40924
.30000	18.89000	23.50114
.40000	20.50000	25.26232
.50000	22.72000	26.55364
.70000	24.79000	28.31053
.90000	27.49000	30.00659
1.10000	31.03000	29.83432
1.35000	35.29000	28.08224
1.60000	39.73000	25.42095
1.85000	43.33000	21.30655
2.10000	47.04000	16.78140
2.35000	50.25000	9.69971
2.60000	52.15000	3.87993
2.85000	52.30000	N.A.
3.10000	52.52000	N.A. (F.S.)

X=122.625 INCHES DATE: 2-16-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
.47000	19.47280	17.65445
.60000	20.14990	20.50039
.80000	22.92110	22.83270
1.10000	27.47300	23.79344
1.40000	31.20980	22.64435
1.80000	37.77400	18.41434
2.00000	40.49960	15.92490
2.20000	43.33470	12.33320
2.40000	45.91340	9.77872
2.60000	48.00070	6.25599
3.20000	51.66870	.23512
3.70000	51.92400	.05200
4.50000	51.93770	.00566 (F.S.)

X=127.130 INCHES DATE: 9-10-77

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
1.12000	17.46000	28.82572
1.42000	21.50000	31.32515
1.82000	27.40000	32.10619
2.32000	34.37000	27.77202
3.12000	45.29000	12.32370
3.62000	48.44000	2.63713
3.82000	49.25000	1.02093
4.12000	49.44000	.54454
4.62000	49.53000	.34740 (F.S.)

X=131.975 INCHES DATE: 2-16-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
2.00000	24.59540	29.95754
2.20000	26.54180	29.75336
2.40000	29.51740	25.79004
2.60000	32.01460	25.84053
3.20000	39.16420	17.54710
3.70000	44.75740	6.82954
4.50000	49.34420	.41049
5.80000	49.69070	.01422
6.30000	49.67130	.00484 (F.S.)

X=139.750 INCHES DATE: 2-16-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
4.12000	38.05740	21.48387
4.62000	43.47530	11.24385
5.12000	47.01220	3.40376
5.42000	48.75210	.56094
5.12000	48.95160	.15508
5.62000	48.86100	.07249
7.12000	48.95740	.03106
7.62000	49.70060	.01330 (F.S.)

X=144.975 INCHES DATE: 2- 7-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
4.50000	27.06490	48.43735
5.00000	33.27940	38.67601
5.50000	39.49290	23.51563
6.00000	42.92390	9.97559
6.50000	45.63270	2.56851
7.00000	46.58430	.92090
7.50000	46.55720	.45253
8.00000	46.57250	.35001
8.50000	46.58130	.23422
9.00000	46.55900	.16315
9.50000	46.70320	.12534
10.00000	44.43380	.03742
10.50000	44.20050	.08613
11.00000	44.91670	.07534
11.50000	46.51550	.05096
12.00000	46.47900	.05883
12.50000	46.01510	.05644
13.00000	46.48530	.05425
13.50000	46.91790	.04794
14.00000	46.94180	0.00000 (F.S.)

X=153.250 INCHES DATE: 2- 9-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
8.00000	37.74400	57.44721
8.50000	31.10000	45.72009
9.00000	34.31700	33.06315
9.50000	38.03600	28.15446
10.00000	41.41100	11.37065
10.50000	42.25400	5.84582
11.00000	43.72900	2.04150
11.50000	43.96400	1.47236
12.00000	43.56100	.96259
12.50000	43.59900	.57131
13.00000	44.16700	.37384
13.50000	44.47900	.34190
14.00000	44.25000	.24650
14.50000	43.29700	.20505
15.00000	42.49900	.13965
15.50000	44.45700	.12063
16.00000	44.12400	.09471
16.50000	44.57500	.03419
17.00000	44.05100	.07571
17.50000	43.77000	.04332 (F.S.)

X=151.000 INCHES DATE: 2-14-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
5.00000	24.31000	85.50569
5.50000	27.03330	58.90092
6.00000	36.14450	47.34486
6.50000	46.66740	17.14713
7.00000	49.28720	6.41247
7.50000	50.56810	1.63293
8.00000	51.72900	.75096
8.50000	51.89110	.42073
9.00000	51.83600	.16382
9.50000	51.43420	.12520
10.00000	51.57300	.03444
10.50000	51.28100	.03383
11.00000	51.47770	.02265
11.50000	51.55760	.01077
12.00000	51.84450	.00455
12.50000	51.94990	.00455
13.00000	51.95360	0.00000
13.50000	51.98090	0.00000
14.00000	52.75310	0.00000 (F.S.)

X=170.975 INCHES DATE: 2- 2-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
9.50000	29.03900	53.20794
10.50000	35.03500	40.65521
11.50000	39.60300	16.61597
12.50000	41.81000	3.14035
13.50000	42.55100	1.52709
14.50000	42.79300	.72910
15.50000	42.28800	.37649
16.50000	42.89300	.13045
17.50000	43.47900	.14583
18.50000	43.22100	.05774 (F.S.)

X=154.325 INCHES DATE: 2- 7-78

HOT-WIRE (SINGLE WIRE) MEASUREMENTS

Y (INS.)	U (F.P.S.)	U^2 (F.P.S.) ²
6.50000	27.98640	54.91307
7.00000	33.21560	47.25773
7.50000	37.35750	37.30191
8.00000	41.78960	17.24989
8.50000	43.73260	7.32930
9.00000	44.14250	3.11434
9.50000	44.09340	1.20499
10.00000	44.74430	.73340
10.50000	44.19910	.51278
11.00000	45.69390	.34969
11.50000	44.44350	.23432
12.00000	45.75370	.15421
12.50000	45.84250	.11059
13.00000	46.74430	.03742
13.50000	45.92630	.05771
14.00000	45.59070	.04715
14.50000	44.94490	.03553
15.00000	45.90560	.02467
15.50000	46.00510	.02031 (F.S.)

