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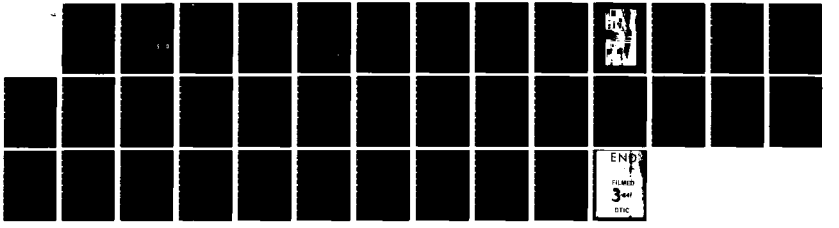

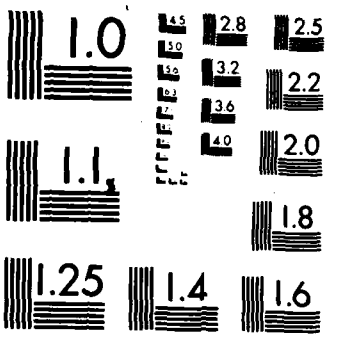

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Grumman Research and Development Center Report RE- 667

AN INVESTIGATION OF TURBULENCE MECHANISMS IN V/STOL UPWASH FLOW FIELDS

by

Barry L. Gilbert
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submitted to

Dr. James D. Wilson
External Aerodynamics and Fluid Mechanics
Office of Scientific Research
U. S. Air Force

First Annual Report on Contract F49620-82-C-0025

May 1983

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The results of the first year of an experimental investigation of the abnormally high turbulence level and mixing layer growth rate characteristics found in the upwash regions of V/STOL flows in ground effect are presented. The overall objectives of this program were to examine the origin of the increased fluctuations, to systematically characterize the development and structure of the upwash, and to determine the parameters that influence these characterisicts. The approach adopted was to investigate the fundamental turbulent V/STOL upwash mechanisms in increasingly more complex flow

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A unique set of velocity profiles were obtained at six locations in the upwash. Two components of the velocity were found simultaneously using an ~~X-probe anemometer~~. This baseline set of two component velocity profiles has never been reported before. While the turbulence levels and mixing layer growth rates were larger than those found in a free two-dimensional jet, these values were less than those reported by previous investigators.

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Richard A. Schleuing
Director, R&D Center

ABSTRACT

The results of the first year of an experimental investigation of the abnormally high turbulence level and mixing layer growth rate characteristics found in the upwash regions of V/STOL flows in ground effect are presented. The overall objectives of this program were to examine the origin of the increased fluctuations, to systematically characterize the development and structure of the upwash, and to determine the parameters that influence these characteristics. The approach adopted was to investigate the fundamental turbulent V/STOL upwash mechanisms in increasingly more complex flow configurations. In the first year's effort, a two-dimensional upwash was formed by the collision of opposed two-dimensional wall jets. Extensive measurements were made in the two-dimensional wall jet to establish the starting conditions of the upwash. Evaluation of these measurements have shown classical wall jet behavior, and by the time the wall jet reaches the collision zone, both the mean and turbulence profiles are fully developed.

A unique set of velocity profiles were obtained at six locations in the upwash. Two components of the velocity were found simultaneously using an X-probe anemometer. This baseline set of two component velocity profiles has never been reported before. While the turbulence levels and mixing layer growth rates were larger than those found in a free two-dimensional jet, these values were less than those reported by previous investigators.

RESEARCH OBJECTIVES

The development of aircraft with vertical/short take-off and landing (V/STOL) capability has led to a requirement for understanding the unique turbulence phenomena encountered in the interaction of lift jets with the ground. When a V/STOL aircraft is in ground effect (IGE), the exhaust from the aircraft lift jets interacts with the ground, producing an upwash flow directed towards the underside of the aircraft. Two characteristics of the upwash flow that make its behavior very difficult to analyze are an abnormally high turbulence level and a much greater mixing layer (fan width) growth rate compared to other types of turbulent flows (Ref. 1,2).

Although a number of investigations of overall flow in ground effect

have been carried out, measurements in these highly unsteady flows are very difficult, and interpretations of these measurements vary widely (Ref. 3-7). The problem is made computationally difficult, by the intrinsic three-dimensionality of the upwash. However, even when these difficulties are overcome, the numerical codes require better definition of the turbulent structure in order to make reliable predictions of the fountain flow and later, the fountain/ aircraft interaction.

Previous investigations have attempted to study the full V/STOL flow field with its full geometric complexity. Some of these have even made measurements with an aircraft planform. These are configuration specific studies that necessarily miss the fundamental flow characteristics. Our approach was to employ a simple two-dimensional flow configuration. In this configuration, the complex V/STOL upwash flow geometry was simplified. The lifting jet impingement region with the ground has been eliminated. The radially spreading wall jets were replaced by the much simpler two-dimensional wall jets. This part of the study had the goal of producing a baseline data set showing the high turbulence level and the increased mixing rate. In addition, during this part of the study, the upwash turbulence structure was examined in finer detail than ever reported before.

The first major research objective for the first year's effort was the design and construction of the experimental apparatus used to produce the two-dimensional upwash. After the facility was running and sufficient measurements were obtained to assure two dimensionality and uniformity of the exit profiles, detailed measurements of the wall jet profiles were to be obtained. These measurements are very important since these two-dimensional wall jets represent the initial flow conditions into the formation region of the upwash. Finally, a single wire anemometer was to be used to measure one component mean and turbulence profiles at six locations in the upwash. These would form a comparison set of data to the relatively small sample of upwash measurements that exist in the current literature. This data set would then be repeated using an X-probe anemometer to measure two component velocities, resulting in new measurements never before appearing in the literature.

SIGNIFICANT ACCOMPLISHMENTS

In this section the significant accomplishments and progress made during the first year's research effort will be described. In summary, the test facility is functioning well and a basic set of calibration exit profile data have been taken. Wall jet profiles were obtained at 20 locations from the jet exit to the facility centerline. These surveys showed the rapid development of the mean and turbulence similarity profiles. They also exhibited the well established mixing layer growth rate and mean velocity decay rate that characterize wall jets. Careful measurements were made at six heights in the upwash using both a single hot film probe and an X-hot film probe The expected abnormally high mixing layer growth rate was found in the two-dimensional upwash flow. However, the turbulent intensity was of the same order as is found in ordinary two-dimensional free jets. There is basic agreement between our data and prior studies. Although there is some disagreement in specific details such as spread rate, our values are in the range of those of others. Our set of carefully generated data from a well defined two-dimensional source shows symmetry of the turbulence energy profiles in the upwash, data not given by others. This baseline upwash data show mean velocity decay and spread rate trends required by conservation considerations. These trends have eluded some earlier investigators. Data interpretation difficulties due to directional ambiguity of the hot film sensor were somewhat resolved when the profile measurements were repeated using an X-probe. These X-probe measurements have shown, for the first time, the cross component mean velocity in the upwash. In addition, the turbulence profiles for both components were obtained. Finally, one component of the Reynolds stress was measured as a sign of the accuracy of the measurement technique, these cross component data show remarkable symmetry. In the remainder of this section, these accomplishments will be detailed.

The wind tunnel facility designed and constructed for the first year's effort is diagrammed in Fig. 1, and the test section is shown in Fig. 2. Each of two independent fans drives the flow through identical, 90 cm long, 26.5^{o} half angle, subdivided diffusers. The plenum chamber has honeycomb, three sets of 16 mesh/inch screens and a gentle balsa contraction. The nozzle section employs a symmetric ASME long nozzle contraction to 10 cm height followed by an asymmetric lemniscate curve contraction to a 1 cm high exit.

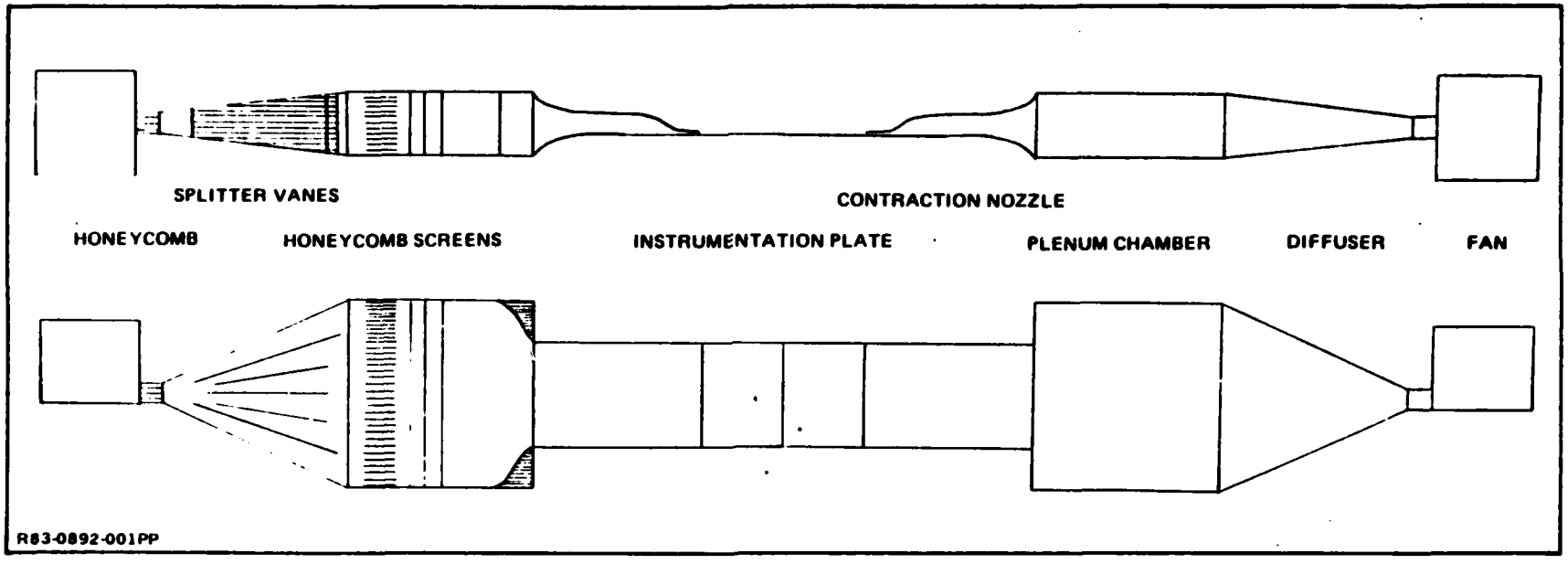


Fig. 1 Diagram of Two-dimensional Jet Upwash Facility

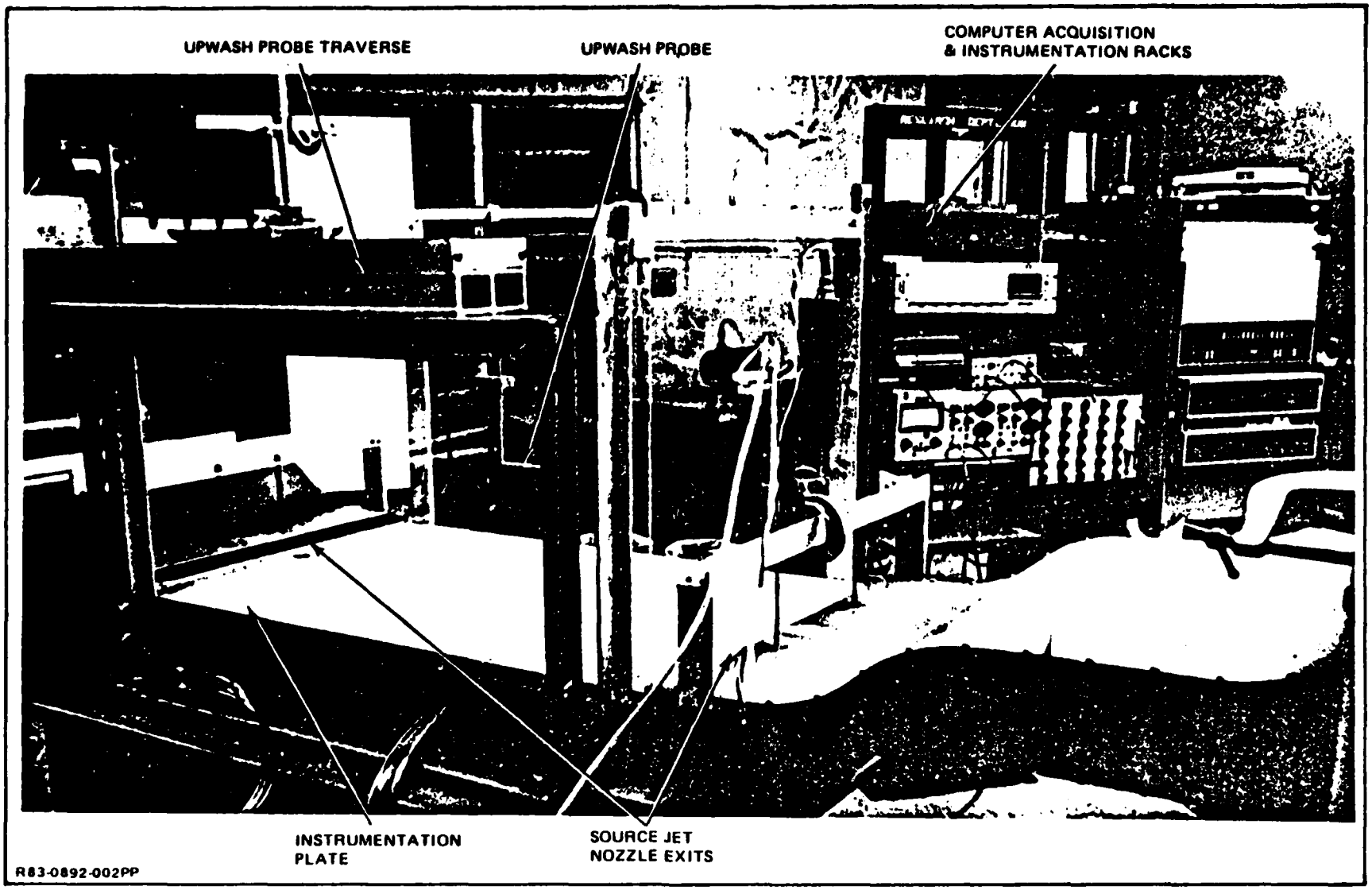


Fig. 2 Photograph of Two-dimensional Jet Upwash Facility

This nozzle geometry was carefully chosen to minimize the interference to the entrainment flow over the top of the nozzle. The success of this design can be seen in the nozzle exit profiles later. The exit aspect ratio is 50:1. The test section has plexiglass side walls to aid in maintaining the two dimensionality of the flow. The ground plane is instrumented with static pressure taps connected to pressure transducers capable of high frequency response. To facilitate the ease in understanding and in comparing the data, a coordinate system was chosen that allows the X direction to be the mean direction of the largest velocity component. That is, X tracks some centerline streamline and Y is always perpendicular to it. This results in a 90^{0} rotation of X from the wall jet to the upwash as shown in Fig. 3. Therefore, for clarity, wall jet parameters are subscribed with w. U and u' are the mean and fluctuation components in the X direction. V and v' are the components in the Y direction.

The facility has the capability of producing two independently controlled wall jets with flow rates that may be balanced up to an exit velocity of 67 m/s. Figure 4 shows hot film anemometry measurements of a typical exit plane velocity profile taken vertically across the nozzle exit and includes the entrained flow velocity over the top of the nozzle. There was negligible variation in these exit profiles taken at various locations across both nozzles. This flow is uniform to 0.5% across the 50 cm long dimension excluding the regions near the ends of the nozzle. Disregarding the boundary layer, the mean velocity is uniform to 0.75% with turbulent intensities u'/U of about 0.6%. The single jet external entrainment velocity increases from about 6.6% of the mean exit velocity to 9.7% when both wall jets are used to form an upwash. The instrumentation plate is 84 cm long (nozzle to nozzle).

The first curve in Fig. 5 shows the mean velocity decay from a single nozzle to a position past the plate centerline. This trace was taken at a single height (Y_w/exit height D = 0.5), and so although it is not a local maximum decay profile, it is similar to it, and certainly the qualitative information is correct. The second curve shows the mean velocity at the same height using both jets. There is a definite problem with data interpretation of velocity direction in the interference zone. Since these data were obtained with a single wire constant temperature anemometer, with the sensor perpendicular to the page, it measures the velocity component normal to its

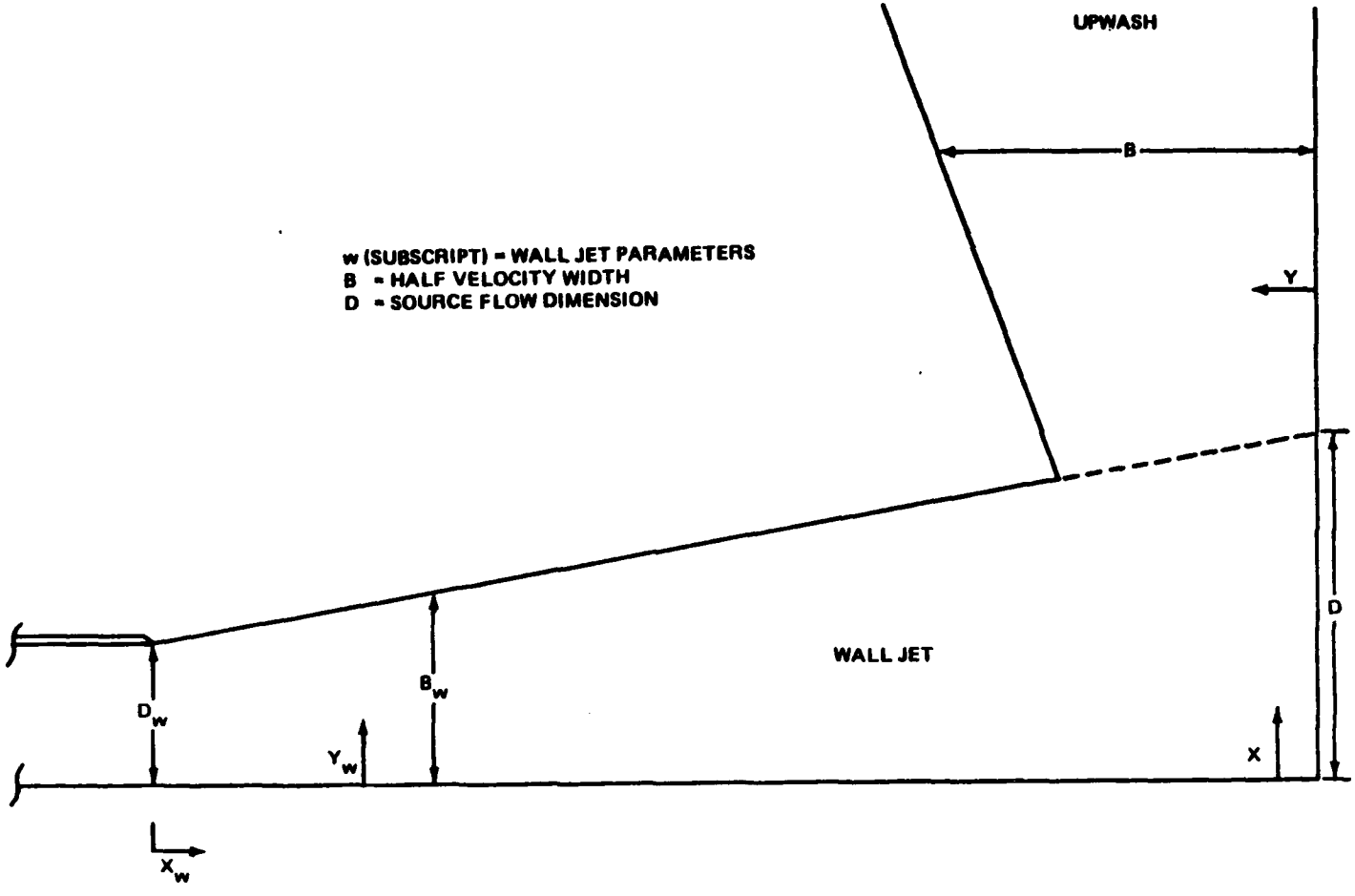
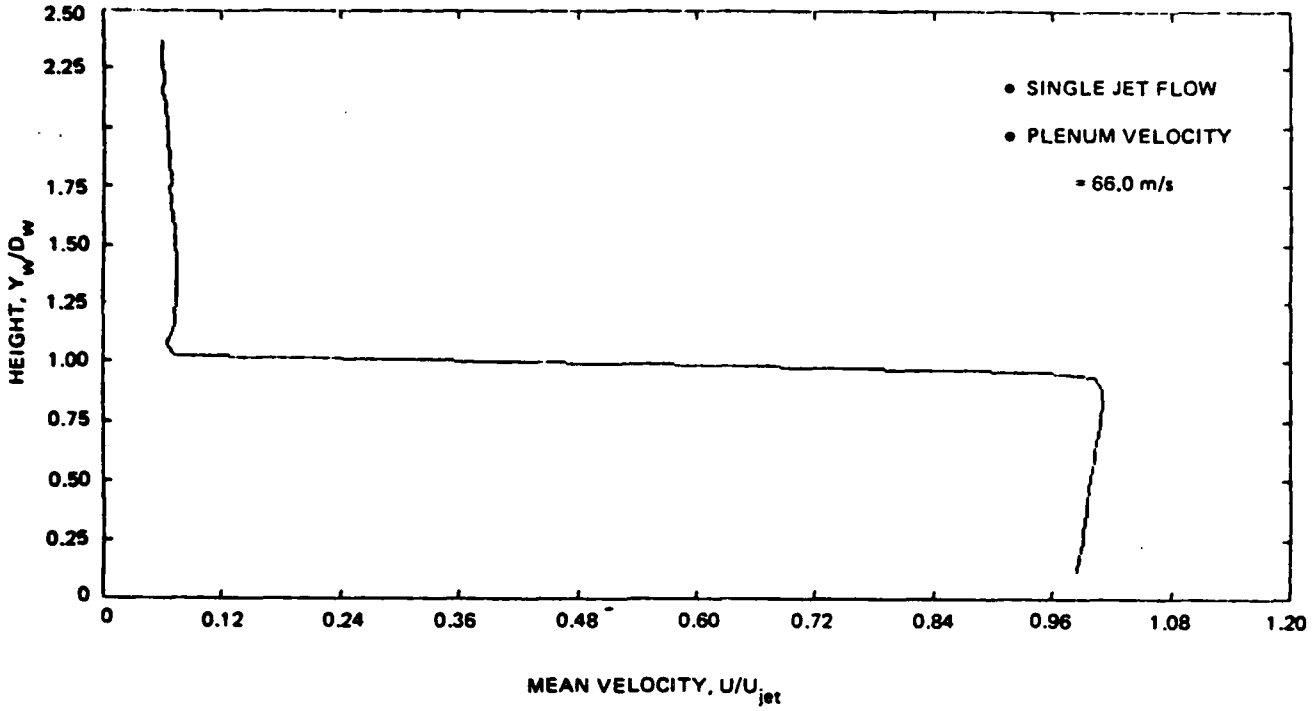


Fig. 3 Coordinate System Nomenclature Conversion



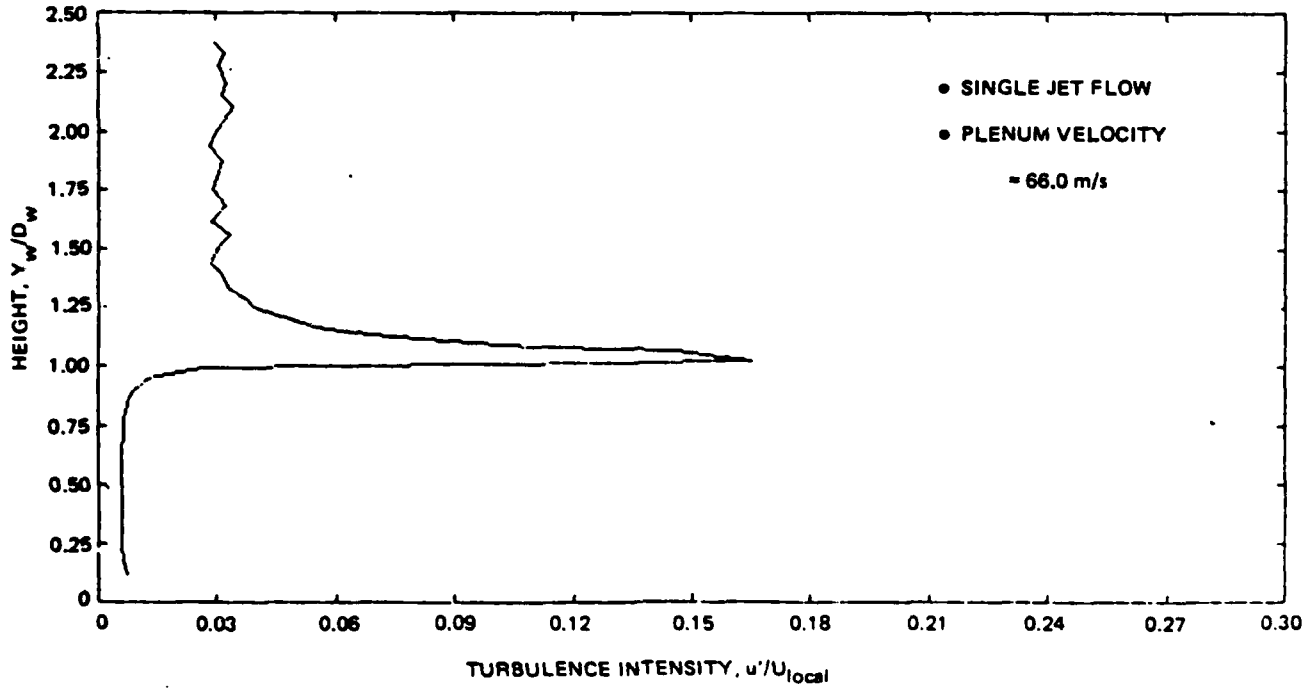


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Fig. 4 Typical Jet Exit Velocity Profiles

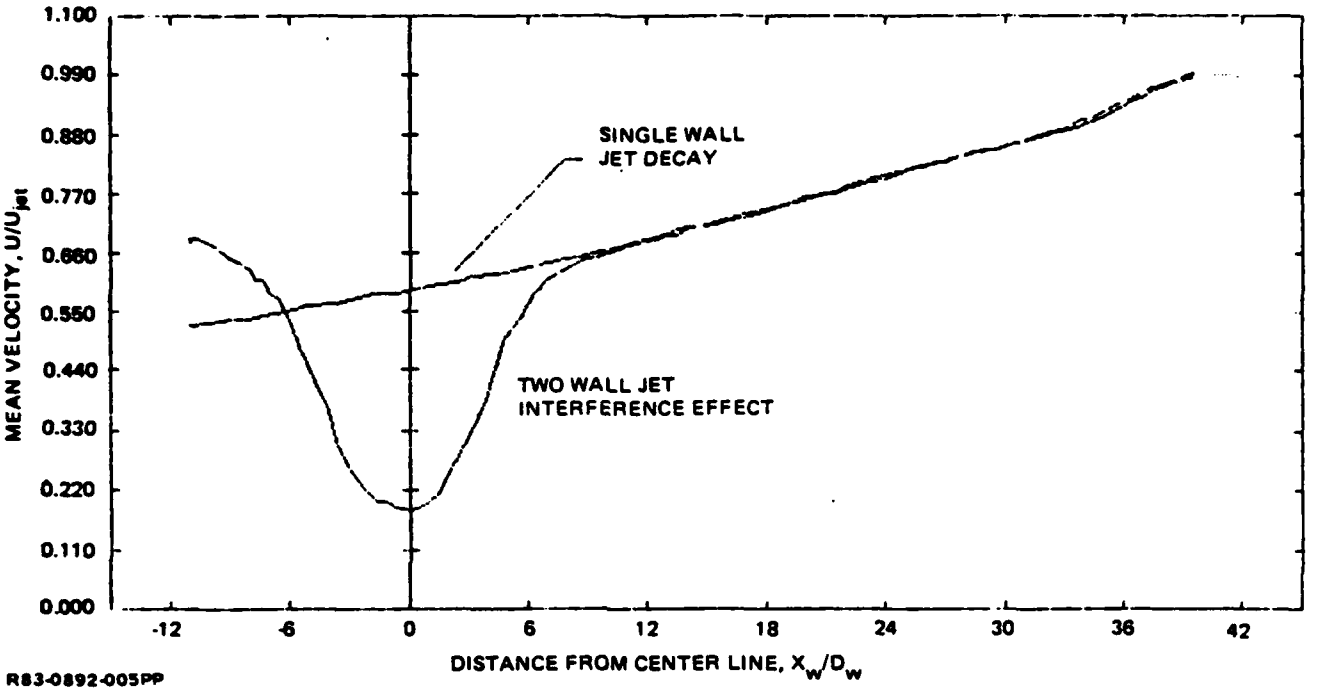

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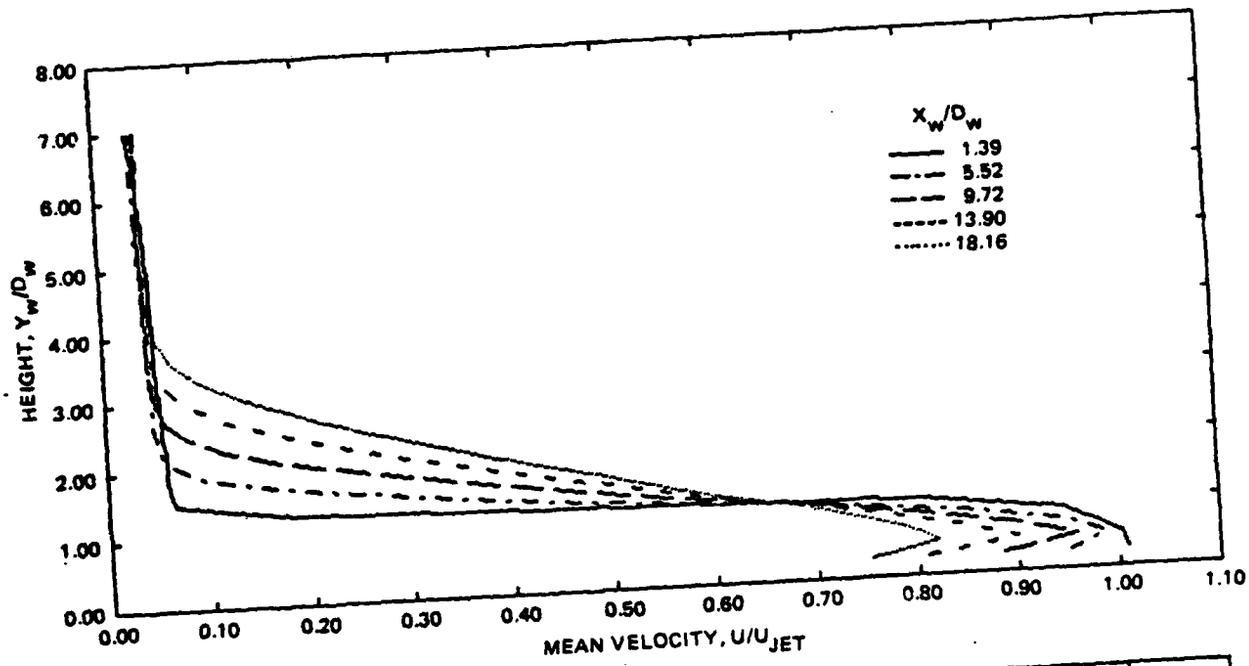
Fig. 5 Mean Velocity Decay Trace at $Y_w/D_w = 0.5$ with a Single Wall Jet and with Colliding Wall Jets

axis, that is, the component in the plane of the page composed of the vector sum of U + V. There are two features of these curves that are important. First, the effect of the second jet is confined to the collision zone as shown by the unaffected decay tract from the jet exit to the zone. Second, as will be shown in the next set of plots, the wall jet layer would be of the order of four nozzle heights at the centerline if the second jet was not running. One would expect the collision zone to be twice this wide (consistent with Kind & Suthanthiran (Ref. 3)). Figure 5 shows the collison zone to be of that order.

Wall jet mean and turbulence profiles were taken at 20 locations from the jet exit nozzle to the instrumentation plate centerline. These profiles were made at equal distances along the plate in increments of approximately two nozzle heights. Each profile contains 24 data points. The measured variation in probe position above the plate from the first to the last profile position was less than 0.005 in. The data acquisition and positioning of the single element hot film probe were accomplished under the total control of the automatic digital data system.

Figure 6 shows only the 10 alternate mean velocity profiles. The data are normalized by the source jet velocity and the initial nozzle height D_w. From these data, using the maximum velocity, the wall jet "half velocity heights," B_w, were obtained by linear interpolation. The half velocity height is the usual length scale used to characterize wall jets. It is the height (above the maximum velocity point) where the mean velocity is half the maximum velocity.

A plot of the wall jet growth rate as characterized by the half velocity height vs the distance downstream is given in Fig. 7a. A linear least squares curve fit of the data from station 6 through 20 ($X_w/D_w > 10$) gives a growth rate of 0.0728. This is exactly the growth rate established as the "correct" value for self-preserved two-dimensional wall jets on plane surfaces at the 1980-81 AFOSR-HTTM Stanford conference (Ref. 8) of 0.073 ± .002. The first five stations were eliminated from the curve fit because they appeared to be in the development region. Figure 7b shows the linear decay of the maximum velocity squared vs distance. This relationship is required by conservation of momentum considerations. Normalizing the data on Fig. 6 by the characteristic half height dimension and replotting this as Fig. 8 shows that the mean velocity similarity exists as early as $X_w/D_w = 10$, much sooner than



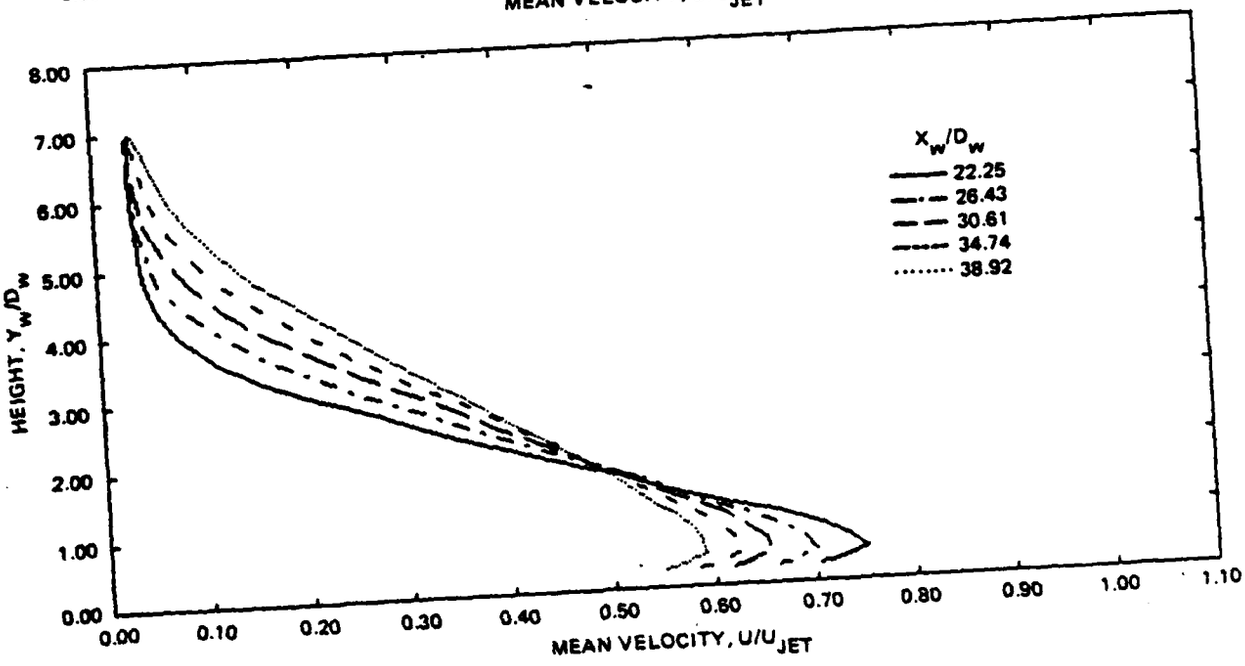


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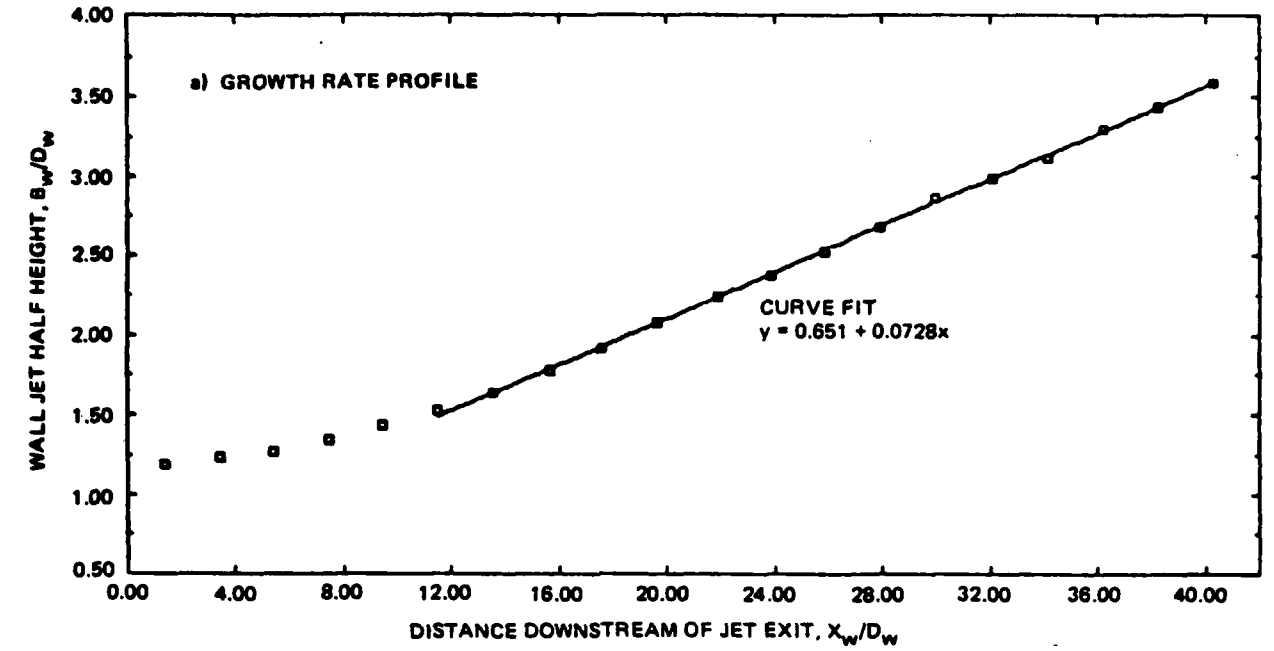
Fig. 6 Wall Jet Mean Velocity Profiles



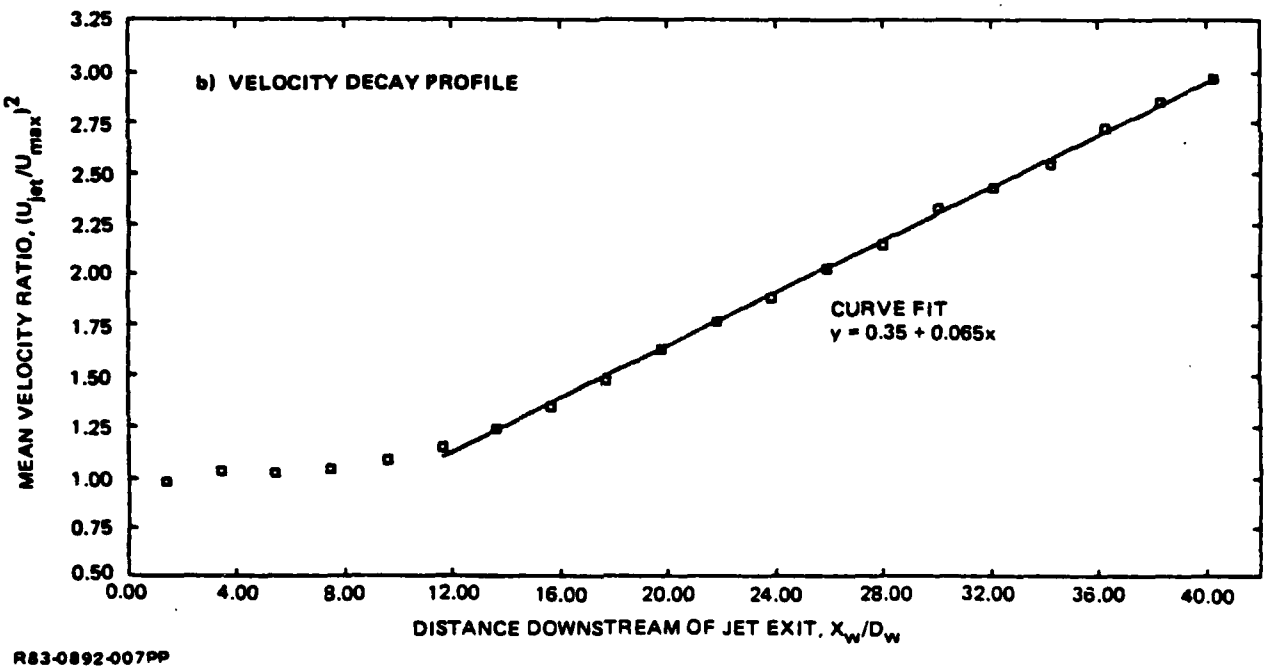


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Fig. 7 Two-dimensional Wall Jet Characteristics

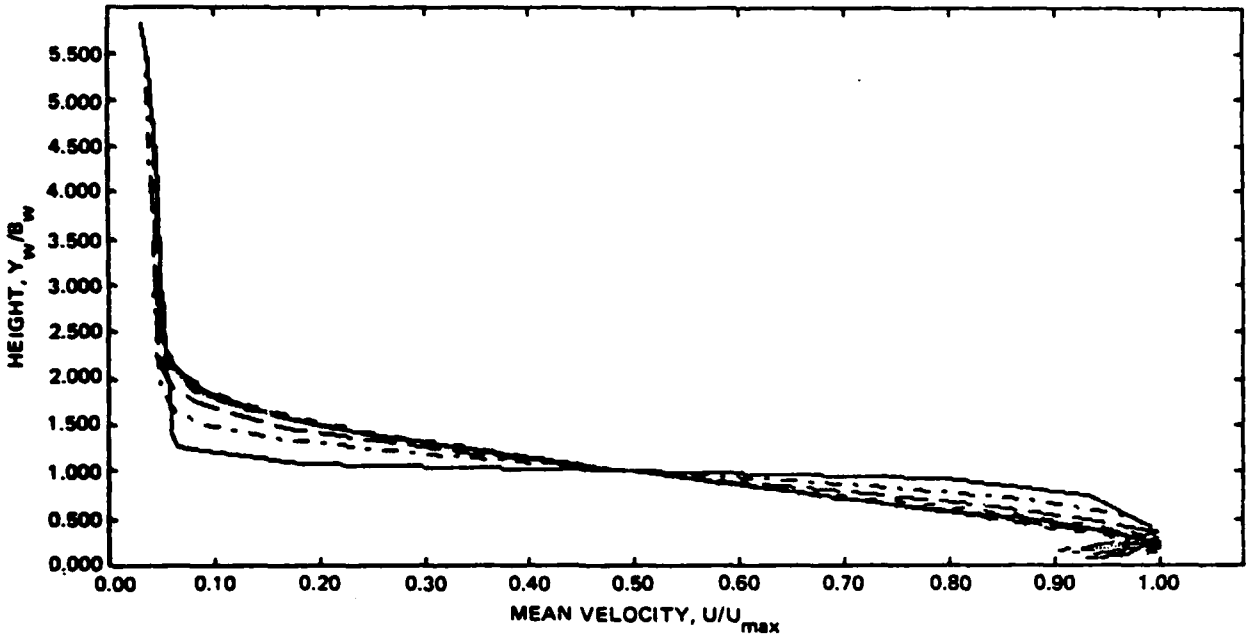

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Fig. 8 Wall Jet Mean Velocity Profiles in Similarity Form (See Fig. 6 For Symbol Key)

the 50 slot heights quoted at Stanford.

The one-component turbulent intensity data are shown on Fig. 9 at the same 10 locations and normalized the same way as in Fig. 6. Figure 10 shows the same turbulence profiles normalized by the half velocity width. These show similarity at X_w/D_w about 20.

Using the results shown on Fig. 6 through 10, the wall jet characteristics at the centerline of the collision zone may be determined. From Fig. 5 it was noted that the collision process is a very local phenomenon. The wall jet parameters when no collision occurs should be used to normalize upwash data in a manner similar to using the wall jet nozzle height as an initial characteristic dimension. At the centerline, the wall jet half height is $B_w/D_w = 3.702 = D$ for the upwash. Further, U_{max}/U jet = 0.571 at the centerline.

The next set of figures (Fig. 11) shows velocity profiles in the upwash at six heights from 1.35 D to 8.10 D in 1.35 D increments. These data were obtained by positioning the single element hot film probe at a point and waiting five integration periods before taking the measurement. Each measurement is the average of 10 statistically independent samples, each having been analog filtered with a time constant sufficient to assure reproducibility. Each profile is composed of 150 positions with a maximum spacing of 5 mm in the tails and a minimum of about 1 mm near the center of the upwash. The full trace is about 50 cm long. The profiles have been shifted somewhat arbitrarily to an estimated symmetry point, and profile half widths were determined crudely by finding the positions of half maximum velocity.

There is a great deal of information that can be obtained from these data. The residual velocities in the tails are similar to other studies (Refs 3-7). This flow in the tails is the entrainment flow towards the center, perpendicular to the upwash direction. This has been verified by smoke flow visualization studies. Of course, a single wire perpendicular to the page cannot distinguish these velocity components. The mean velocity profiles are symmetric, and beyond H/D = 2.70, the turbulence profiles have symmetric peaks. Kotansky does not give these turbulent profile data (Ref. 5); Witze (Ref. 4) and Foley (Ref. 6) show only one-sided turbulence measurements, that is, they do not show the symmetric data; only Kind and Suthanthiran (Ref. 3)

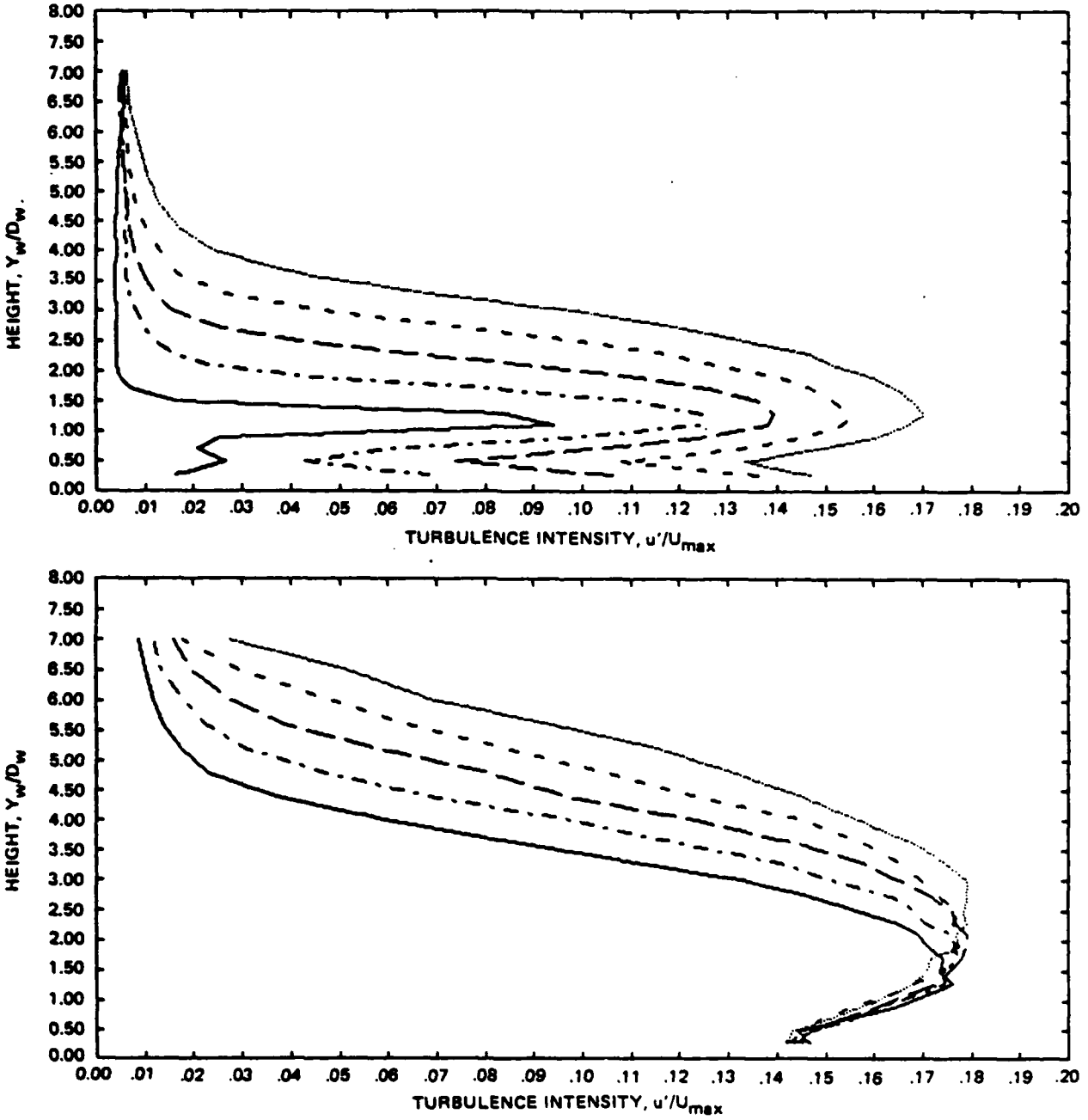

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Fig. 9 Wall Jet Turbulence Intensity Profiles (See Fig. 6 for Symbol Key)

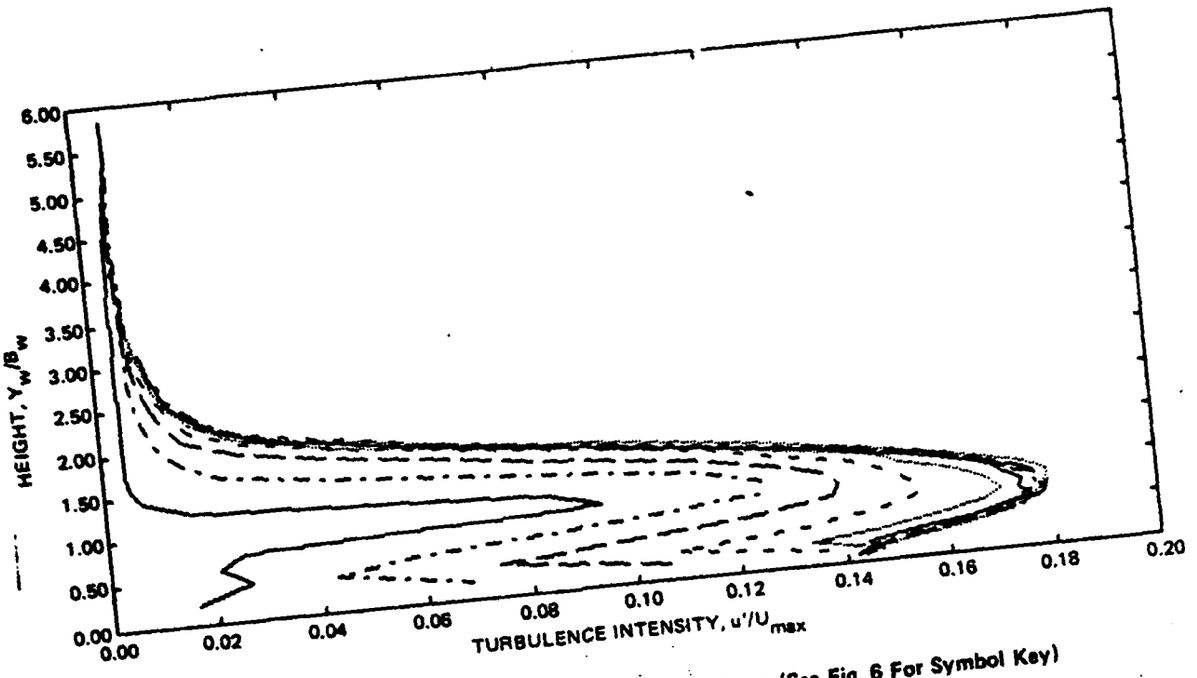

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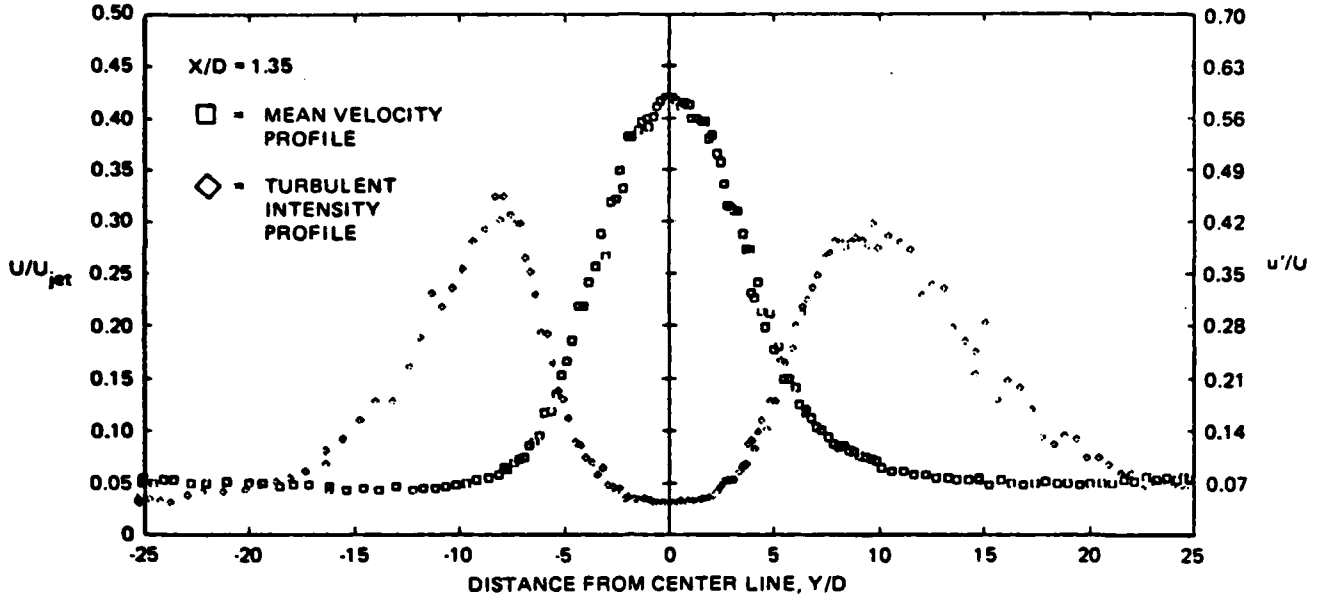
Fig. 10 Wall Jet Turbulence Intensity Profiles in Similar Form (See Fig. 6 For Symbol Key)



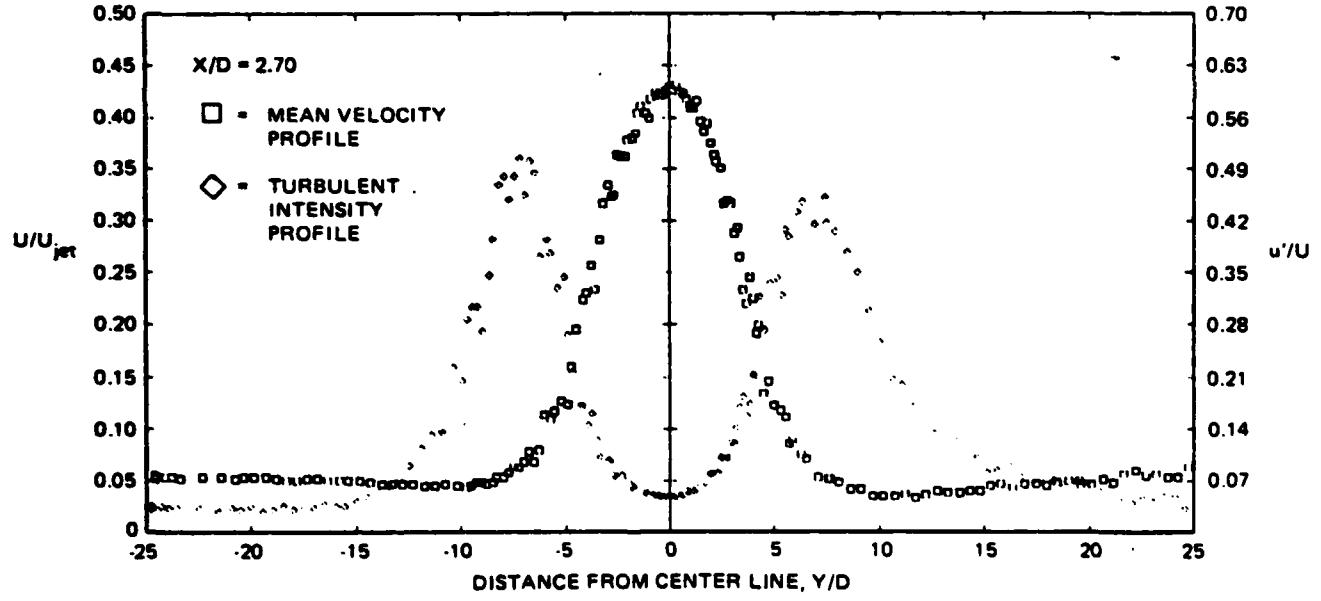


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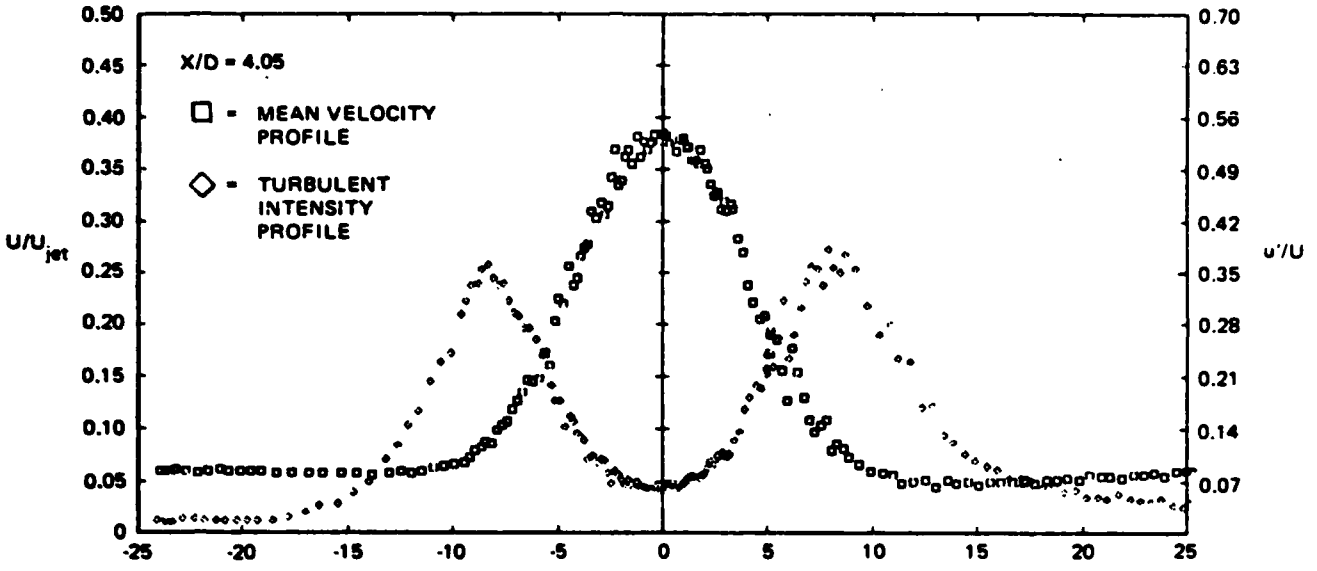
Fig. 11 Mean and Turbulent Intensity Profiles in the Upwash (U_{jet} = 67.0 m/s) (Sheet 1 of 3)



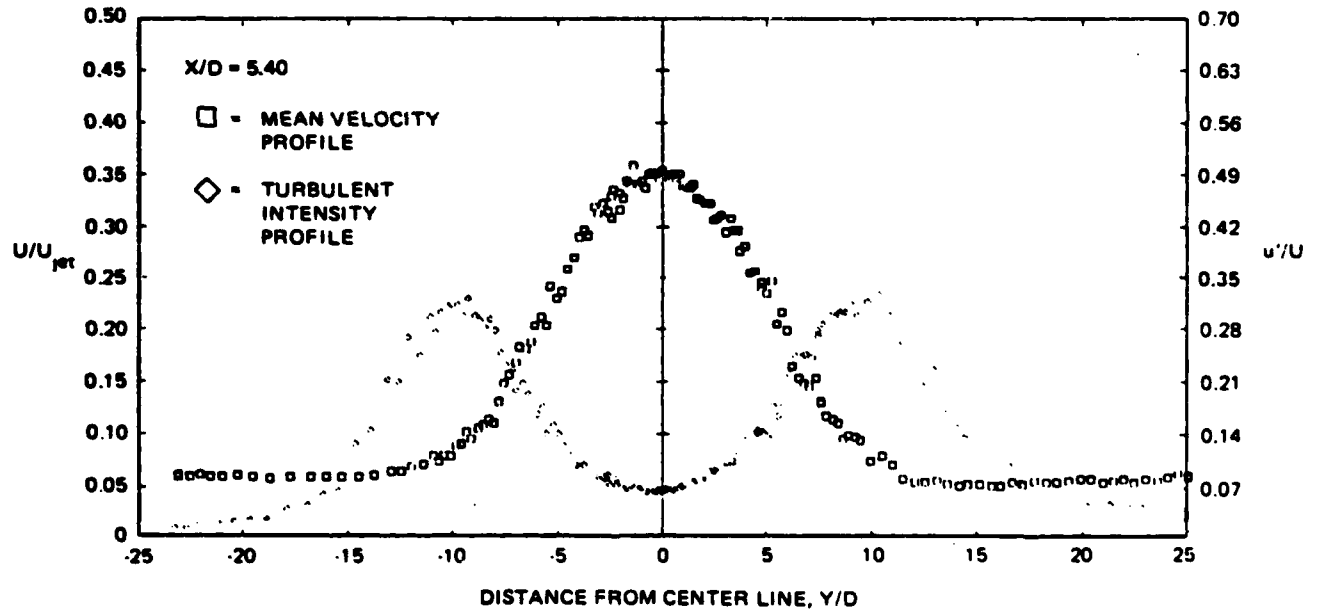


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Fig. 11 Mean and Turbulent Intensity Profiles in the Upwash (U_{jet} = 67.0 m/s) (Sheet 2 of 3)

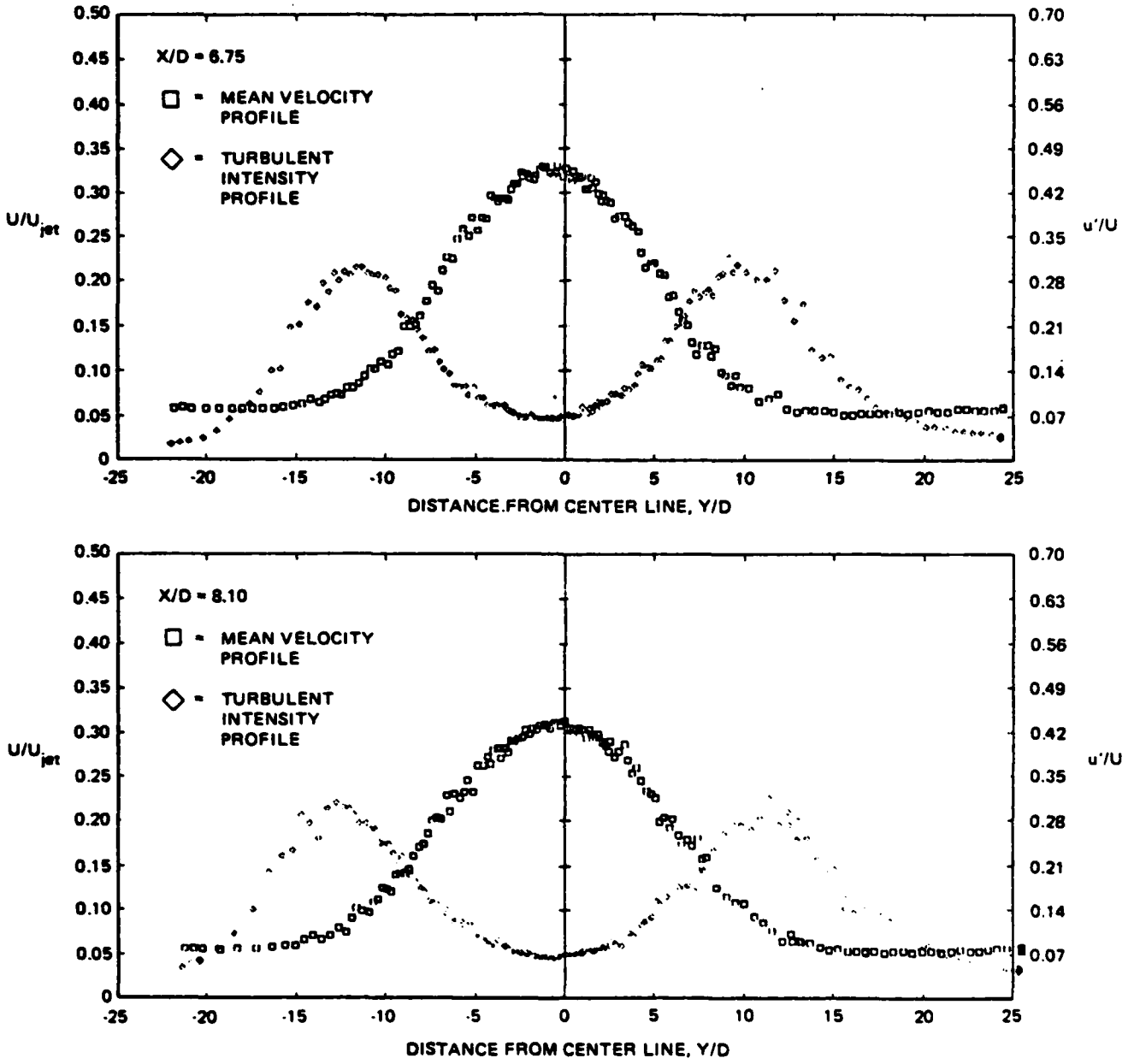

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Fig. 11 Mean and Turbulent Intensity Profiles in the Upwash (U_{jet} = 67.0 m/s) (Sheet 3 of 3)

show the complete profiles and their data are not symmetric.

Figure 12 shows the spread rate and maximum velocity decay. The rate is about 0.20, which doesn't agree with previously reported results. However, a closer look at these other data show inconsistency and, in some cases, plotted data disagree with written statements. We believe our data are correct. This is further supported by X-probe measurements shown next. The proper mean velocity decay characteristic is shown for X/D greater than 2.70. This is the form for the mean velocity decay required by conservation of axial momentum in the upwash, a characteristic not usually found by others. Between X/D = 1.35 and 2.70, the mean velocity actually increases and the mixing width decreases correspondingly. This is a strong indication that the extent of the collision zone is between 1.35 D and 2.70 D consistent with decay trace shown in Fig. 5.

The upwash profiles were repeated using an X-probe hot film anemometer. This measurement technique is able, with proper electronic manipulation, to sense two perpendicular instantaneous velocity components. Using this technique, two component mean velocity profiles at the same six heights as previously described were obtained by an automatic data acquisition process. These were mean velocity profiles in the direction of the upwash (X) and also the mean component into the upwash (Y) as entrainment or as spreading. These data were obtained by digitizing 4000 data pairs in 1.5 sec from each wire of the X-probe. In addition to the mean (average) value from the new time series, the turbulent intensity (deviation) in each direction and one component of the Reynolds stress (cross product) were also obtained.

The mean velocity components in the upwash direction are shown in Fig. 13. As was shown by the single element probe data, at the first height, X/D = 1.35, the data do not follow the trend of the data at the other five locations. This trend will be very obvious in successive plots.

Figure 14 shows the cross-stream mean velocity component. Looking at the data at higher stations shows the mean speading velocity to the right on the right hand side and the symmetric mean spreading velocity (negative values) to the left, left of the center. These profiles are symmetric about the upwash velocity maximum. At X/D = 1.35, these trends are reversed. That is, for example, there is an inflow from the right of center. Remember that X= D would be by definition the position where the wall jet velocity is half the local wall jet maximum. For X slightly larger than D, the wall jet still has

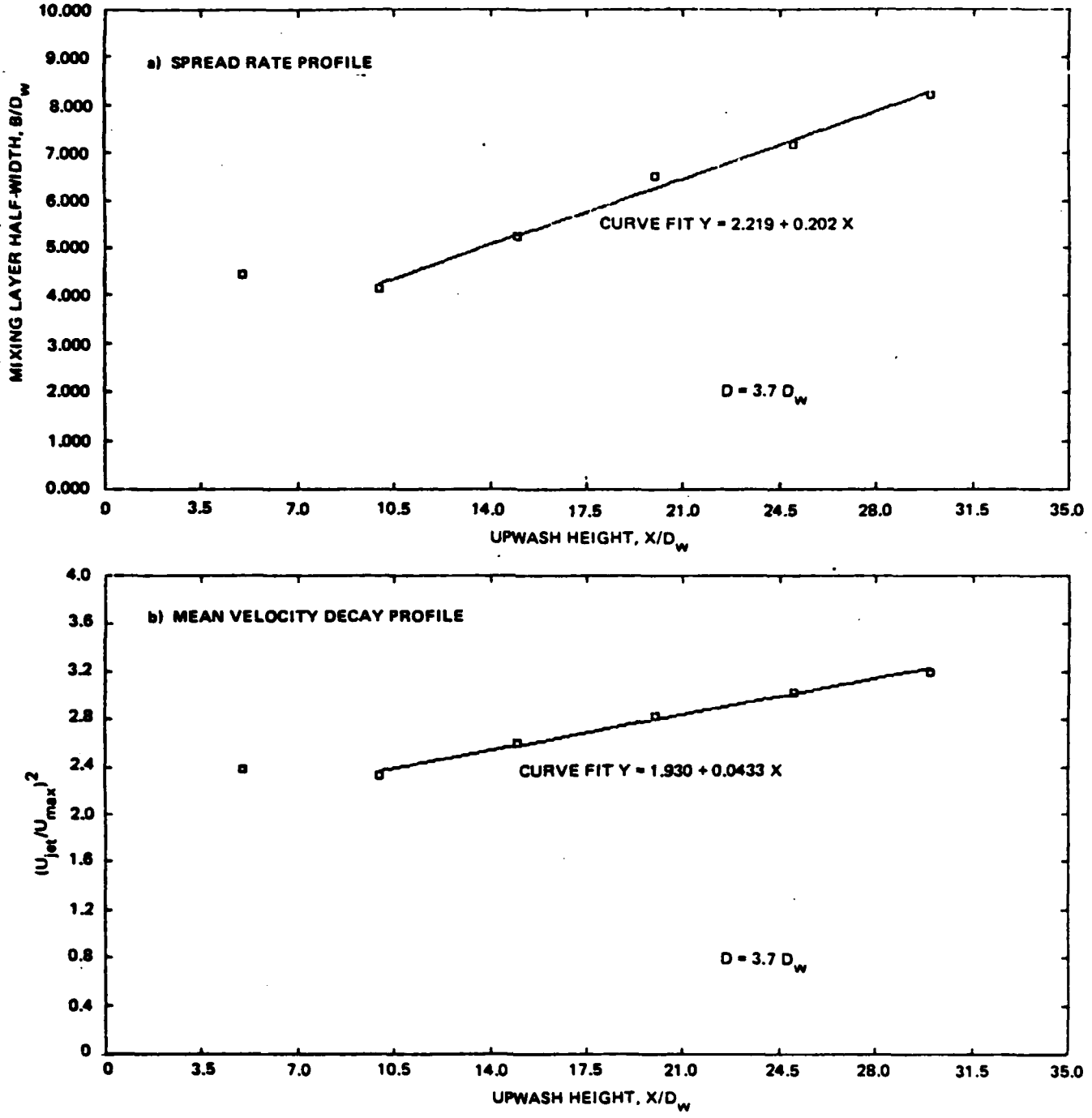
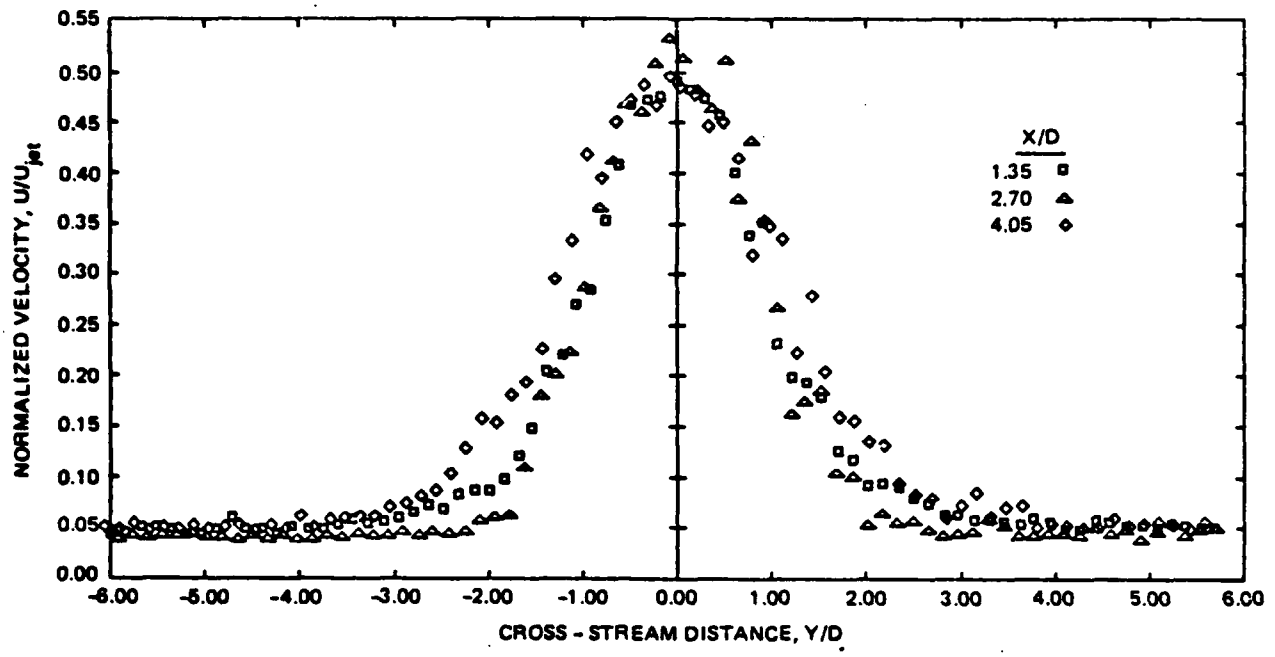


Fig. 12 Two-Dimensional Upwash Characteristics



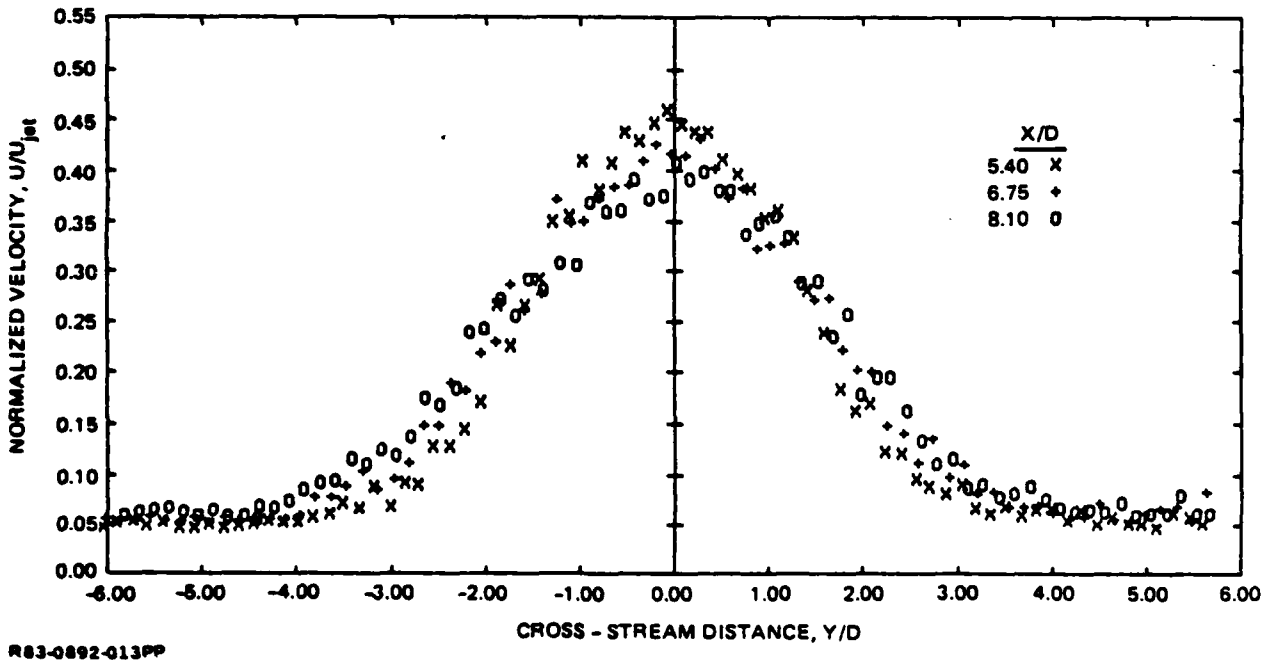


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Fig. 13 Upwash Mean Velocity Profiles

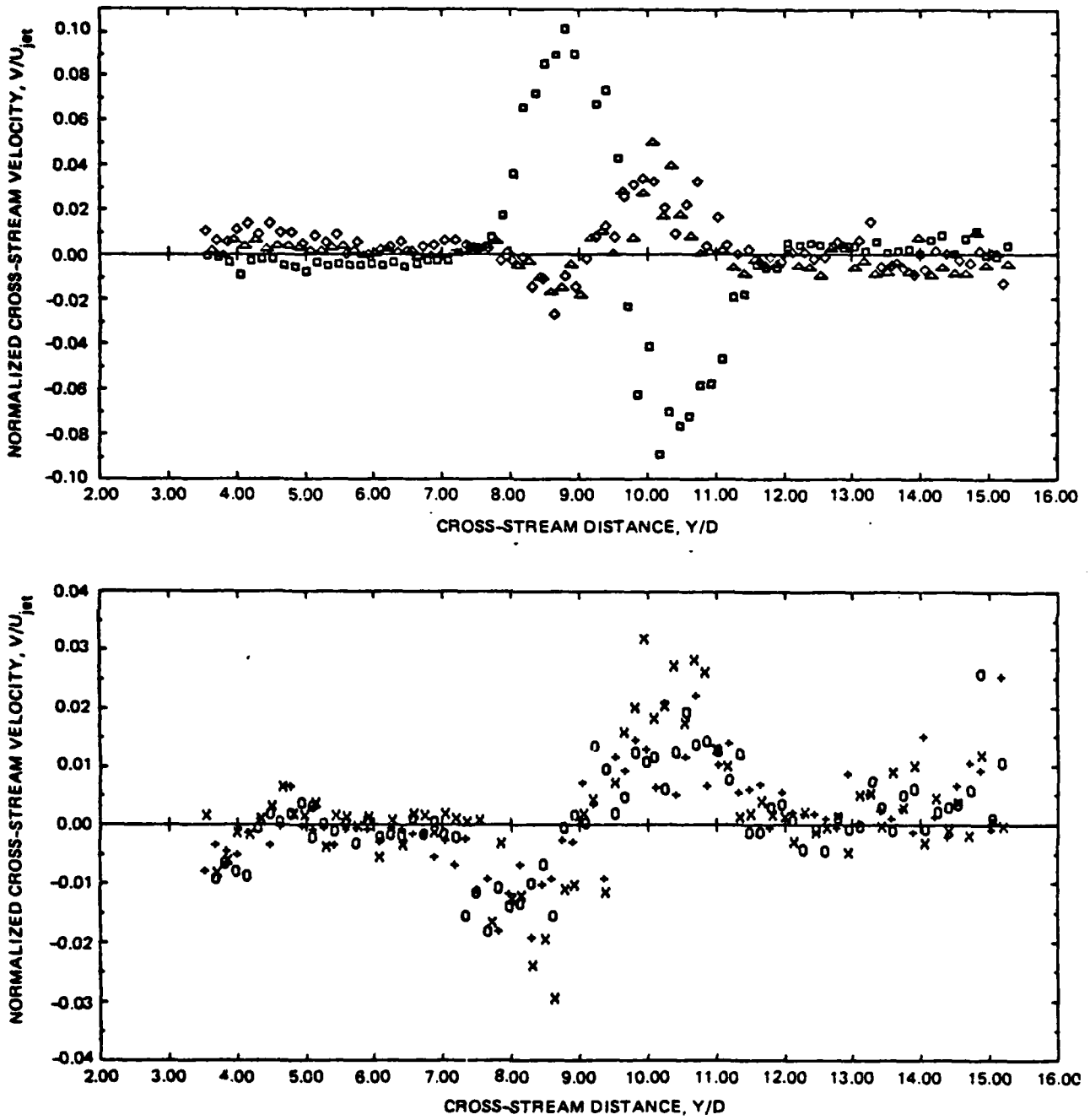

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Fig. 14 Upwash Cross-Stream Mean Velocity Profiles (See Fig. 13 for Symbol Key)

a velocity component towards the centerline, which appears as a cross upwash direction component. This is a direct indication that X/D = 1.35 is still in the interference collision zone.

Figures 15 and 16 show the component turbulent energy in the upwash and relative turbulence energy in the cross-stream direction repectively. The forms of these profiles are similar to those expected for two-dimensional free jet flows.

Preliminary evaluation of the turbulence levels found in the upwash shows these values to be the same as those found in ordinary two-dimensional free jet flows. This is contrary to statements made by Foley (Ref. 6) and Witze (Ref. 4) that the turbulence intensity is a factor of three greater than the free jet case. However, examination of their data indicates ordinary levels. Only Kind and Suthanthiran (Ref. 3) show factors of three. Kotansky (Ref. 5) shows no turbulence data at all. Local values of turbulence intensities, that is, the rms of the fluctuations normalized by the local mean, are on the order of 60%. This is well in excess of the range of application of the small perturbation approximation used to evaluation turbulence properties in thermo-anemometry. In addition, 4000 data pairs are probably not a long enough sample for fully converged quantities. These experiments will be repeated after some digital analysis shows a proper sample length. With this in mind, these data may still be used.

Figure 17 shows one component of the Reynolds stress, uv. Again looking to the higher stations first, across the center region the Reynolds stress profiles are anti-symmetric about the centerline and the same magnitude on either side. Since Reynolds stress measurements are particularly sensitive to measurement techniques, these plots are also a good indication of the precision of the entire experiment. Plotted as a correlation coefficient normalized by the rms values, the scatter in the tails is due to normalizing by successively smaller values. Again, at X/D = 1.35, the entire profile is reversed.

The mean velocity profiles in the upwash direction were curve fit with a least square curve of the form $U = A + C \exp(-(y - y_0)^2/2S^2)$. This curve fit gives the symmetry coordinate y_0, the maximum velocity (A+C), and the standard deviation S. Using the generally accepted definition of half velocity width, $B(U = U_{max}/2) = 1.177\ S$. It should be emphasized that this technique is far

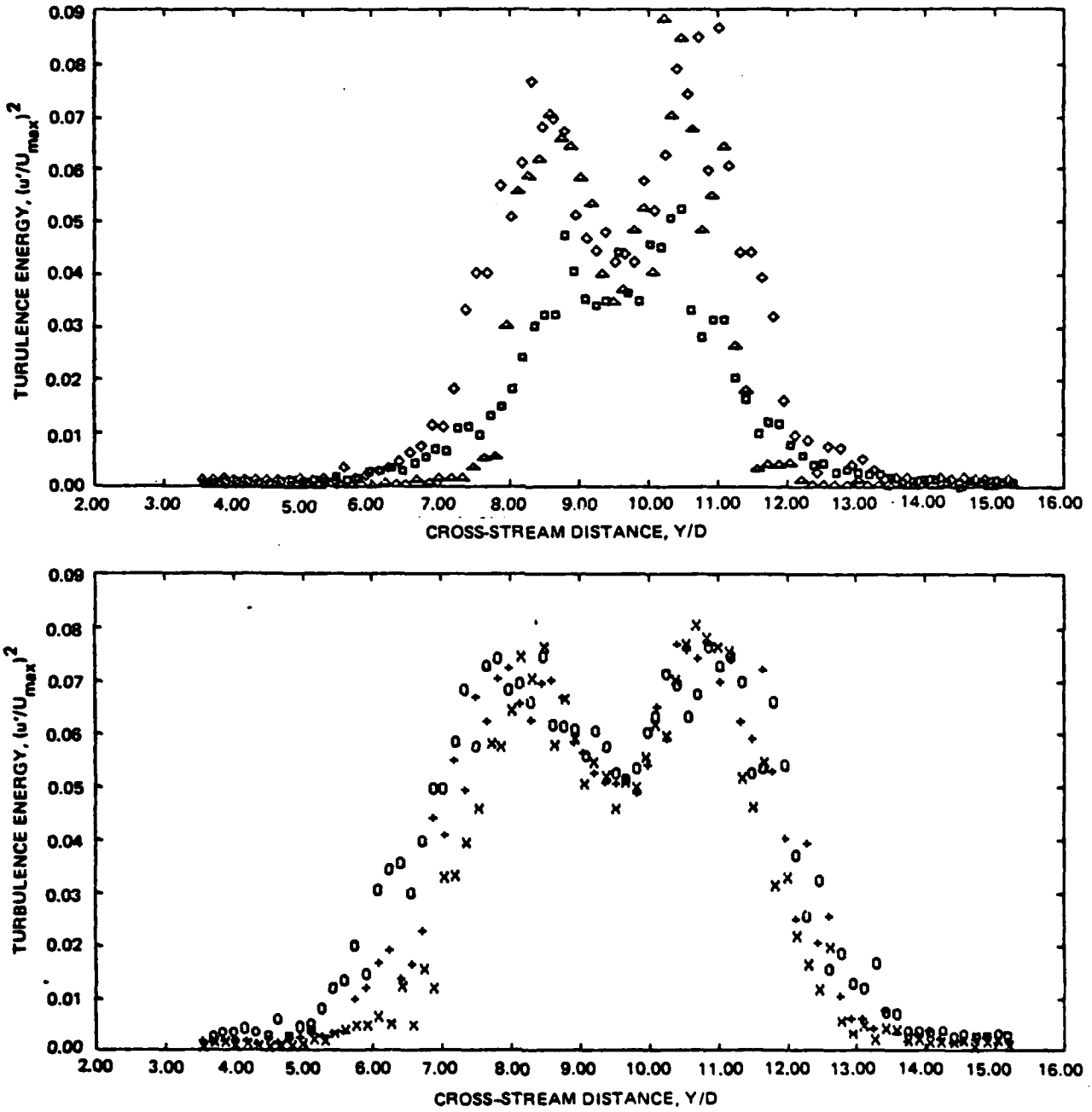

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Fig. 15 Upwash Mean Direction Turbulence Energy Profiles (See Fig. 13 For Symbol Key)

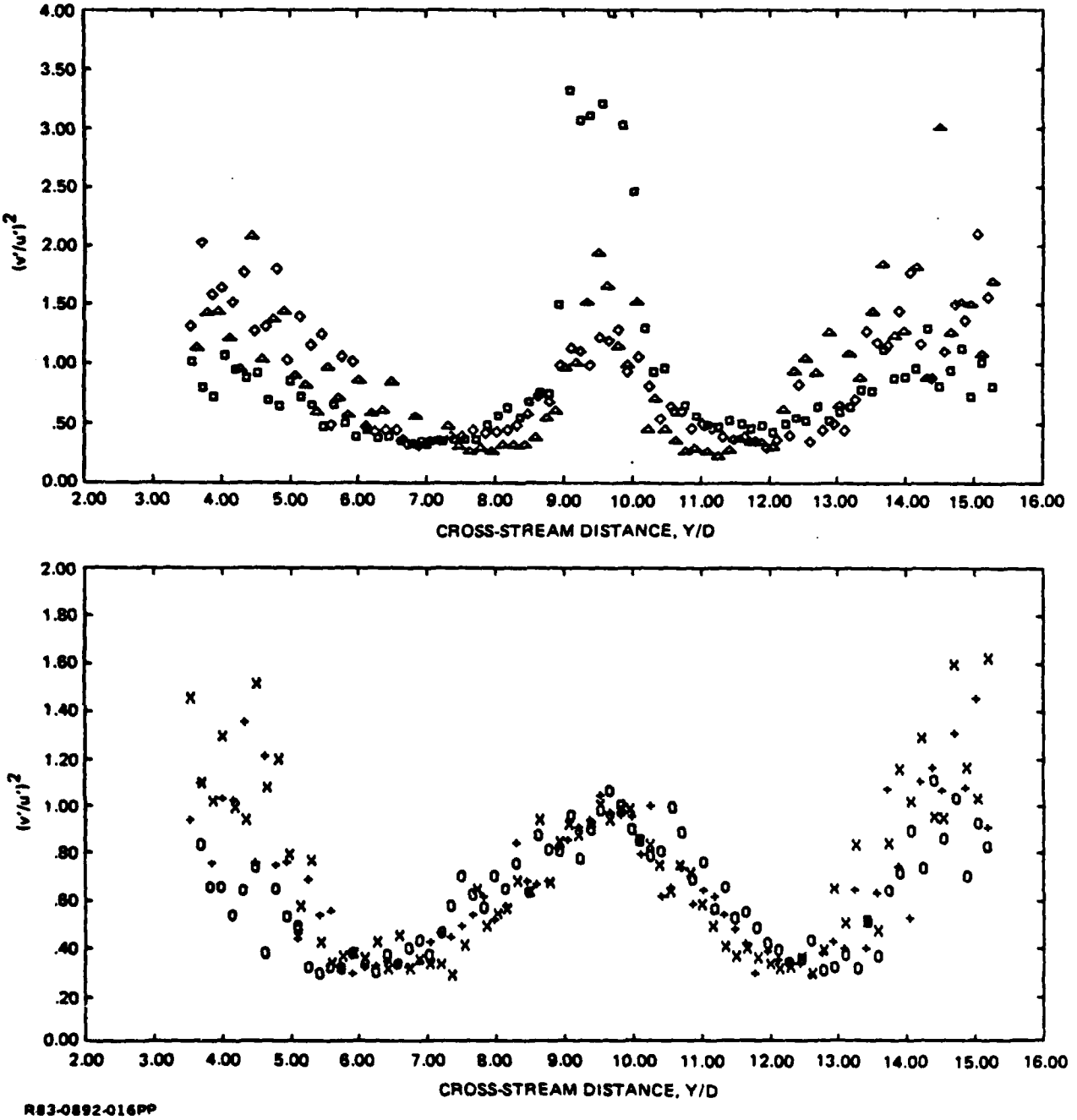


Fig. 16 Upwash Relative Turbulence Energy Profiles (See Fig. 13 for Symbol Key)

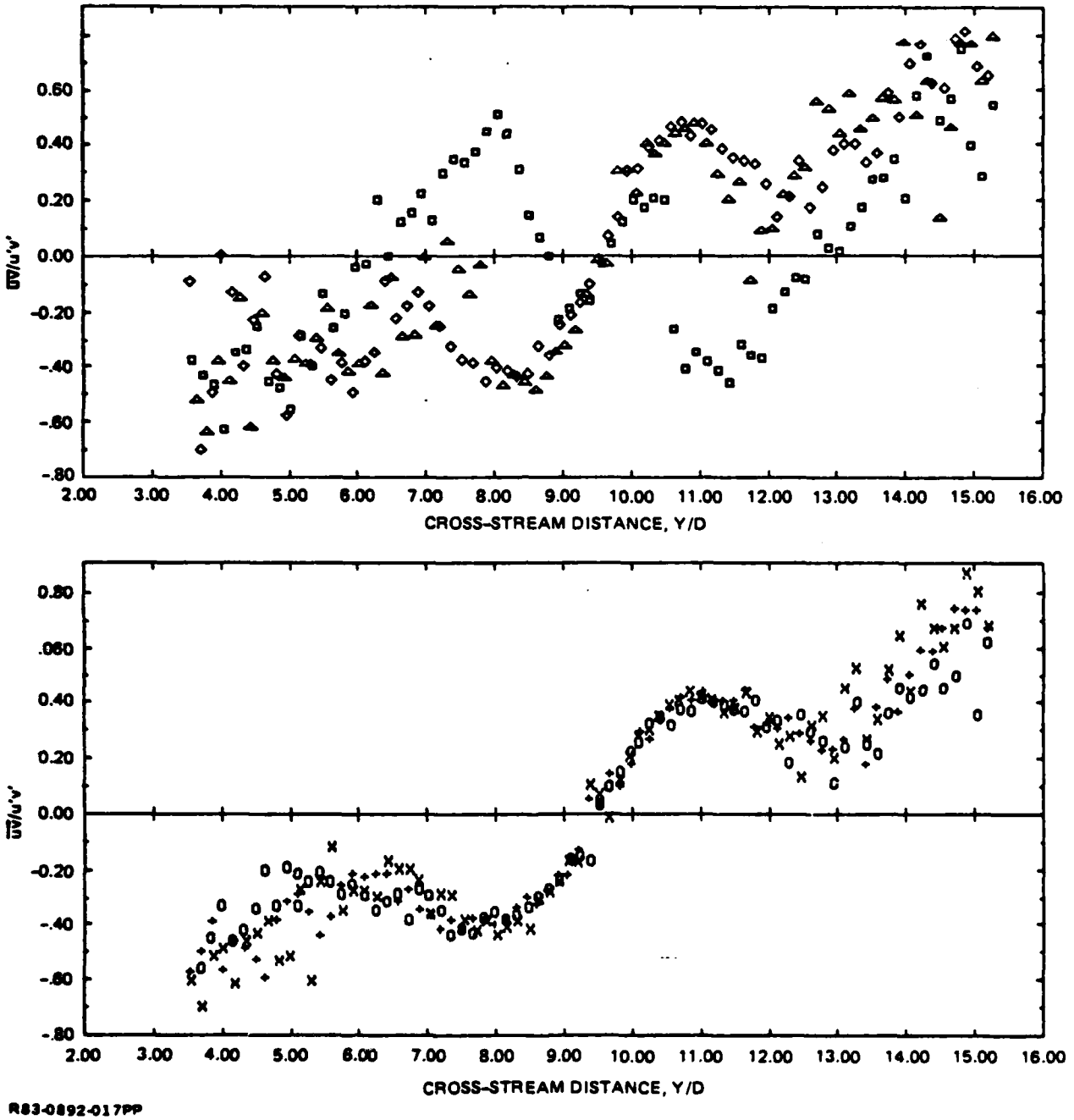
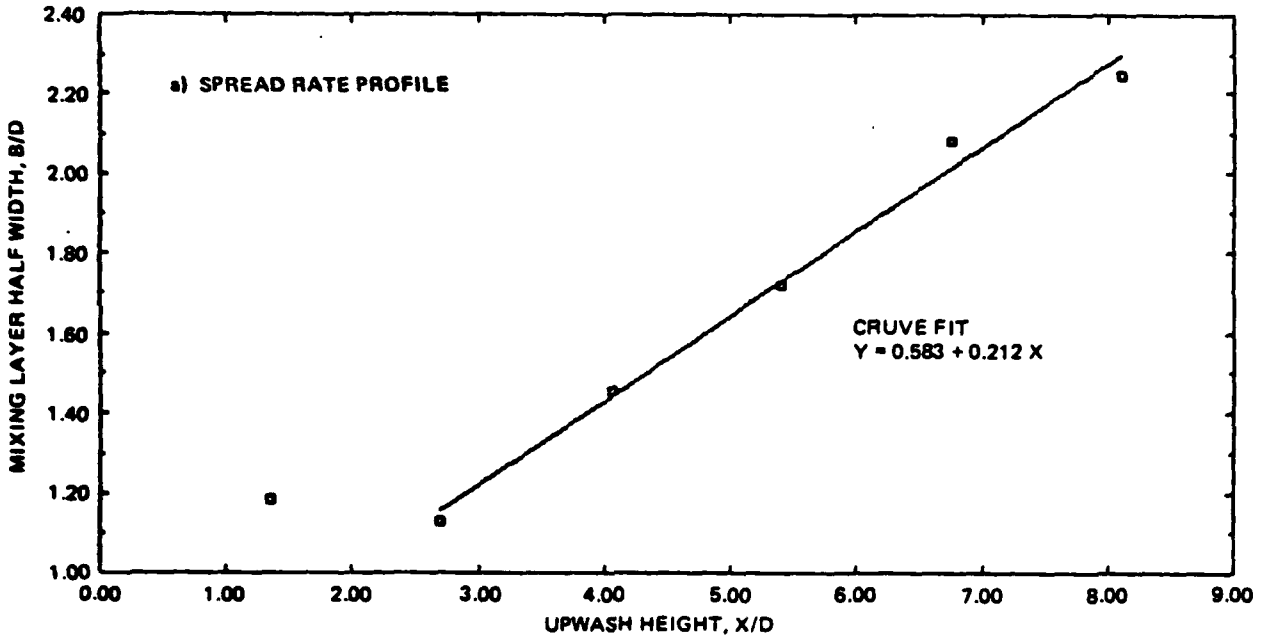


Fig. 17 Upwash Reynolds Stress Profiles (See Fig. 13 for Symbol Key)



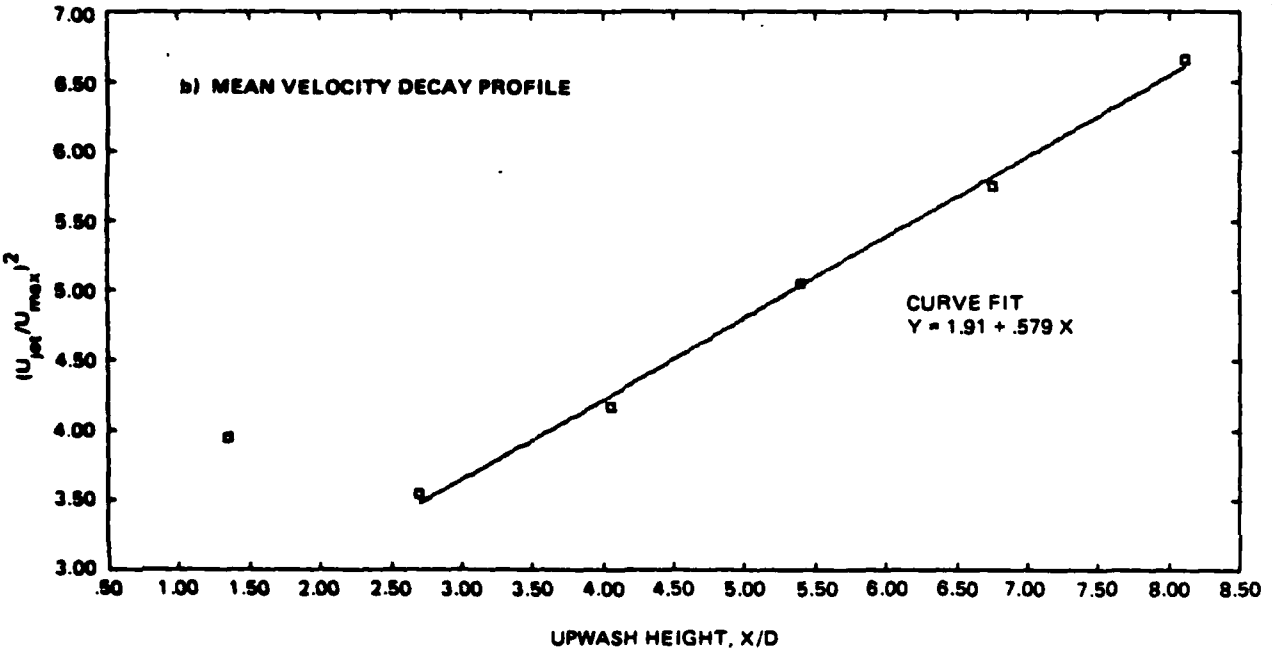


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Fig. 18 Two-dimensional Upwash Characteristics

superior to the usual determination of half width. That procedure usually entails finding U_{max} and interpolating between data points to determine B. The method suffers severely from scatter in the data at both U_{max} and particularly at the half velocity point. Also, it rarely gives symmetric half velocity positions. A least squares curve fit avoids these problems.

The results of the half velocity growth rate so derived are shown on Fig. 18a. As with the earlier one element probe data (Fig. 12), the upwash growth rate is about 0.21 compared to values of about 0.37 reported by Witze, for example. However, this value is still more than twice the free jet values. Note, that the X/D = 1.35 data were not used in the curve fit. Finally, Fig. 18b shows the mean velocity decay relationship required by conservation considerations.

One hypothesized mechanism to explain the large mixing layer growth rate found in an upwash, is that a simple free jet is waving (Ref. 9). Our turbulence measurements would tend to support this mechanism. A remaining task is to try to detect this waving phenomenon by carefully tracking the upwash boundary. This will be accomplished using two, two-component probes at various locations in the upwash and measuring correlations. Probes on the same side of the upwash should show consistent in-phase correlation, and probes on either side should show consistent out-of-phase correlations.

In the event that the waving structure does not exist, the increased mixing and turbulence must be due to a structure formed by the collision process (Ref. 10). This process will be carefully investigated by controlling the flow regime of the wall jets forming the upwash. In a laminar flow, there is no turbulent structure, therefore any structure found in the upwash must originate in the collision process itself.

Another task will be an investigation of the effects of the wall jet initial conditions, particularly along the stagnation line, on the upwash turbulence characteristics (Refs 6, 11, 12). The location of a small object on the stagnation line may serve to stabilize the upwash waving if that is a mechanism. Alternatively, the object will isolate the turbulent structures in each wall jet from each other during the critical turning phase. These experiments will employ a single wall jet flowing into "symmetry" planes of various heights. After a baseline set of data is obtained, a second wall jet will be added and the height of the dividing "symmetry" plane will be successively shortened until the real two jet upwash jet flow is simulated.

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Publications from this contract

"Detailed Turbulence Measurements in a Two Dimensional Upwash," to be presented at the AIAA 16th Fluid & Plasma Dynamics Conf, Danvers, MA, 12-14 July, 1983.

PERSONNEL

The research conducted during the first year has been carried out by the staff of the Grumman Aerospace Corporation R&D Center. Dr. Barry Gilbert has been the Principal Investigator, reporting to Mr. Vincent Calia, Head of the Experimental Fluid Dynamics Laboratory, and Dr. Richard Oman, Director of Aerosciences. Dr. Gilbert devoted approximately 80% of his time to this contract. Some additional research support was provided by Mr. Richard C. Jenkins, Senior Research Scientist.

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