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Sandia Laboratories Low-Speed Wind Tunnel for Research in Atmospheric Flows and Incompressible Fluid Mechanics

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Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Energy Research and Development Administration under Contract AT(29-11-789

Printed April 1975

Sandia Laboratories

SF 2900 Q(7-73)

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SANDIA LABORATORIES LOW-SPEED WIND TUNNEL FOR RESEARCH IN ATMOSPHERIC FLOWS AND INCOMPRESSIBLE FLUID MECHANICS

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ABSTRACT

A twelve-foot-long wind tunnel with a 9 x 16-inch test section has been constructed at Sandia Laboratories to provide a low-speed, controlled test environment for the study of atmospheric flows and other fundamental problems in incompressible fluid mechanics. The facility is distinguished from other low-speed wind tunnels by its simplicity of design and flexibility of operation. Experiments involving the test section wall boundary layers, particulate matter in the flow, or models mounted in the center of the test section are easily accommodated by simple modifications to the interchangeable tunnel walls and air intake sections. Complimenting this versatile facility are sophisticated hot-wire and laser velocimeter instrumentation which provide measurements of mean-flow and turbulent fluctuating velocities in low-speed flows of practical interest. This report describes the low-speed wind tunnel and its instrumentation in detail.

ACKNOWLEDGMENTS

The authors wish to thank E. A. Koenig, D. A. Powers, and D. R. MacKenzie, 5645, for their help in setting up the wind tunnel and its instrumentation. The efforts of D. K. Werling, 5642, who contributed to the interfacing of the laser velocimeter instrumentation to the data acquisition and control system, are also gratefully acknowledged.

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I. Introduction

Since its beginnings a century ago, the field of fluid mechanics has been preoccupied with problems in low-speed airflows. Current emphasis in this area centers upon atmospheric winds and their interactions with surface objects, particulate matter, thermal layers, moisture, and chemicals. The extreme complexity of the interactions makes it impossible to model the wind flows mathematically without experimental guidance. Experiments conducted in the atmosphere suffer from the fact that the winds are not steady in either speed or direction. When unsteadiness is not germain to the experiment, it is desirable to perform these studies in a low-speed wind tunnel, where the essential features of the atmospheric winds can be reproduced in a controlled, repeatable environment. The current interest in atmospheric fluid mechanics, coupled with the serious lack of carefully-defined experimental data to guide analyses, resulted in the construction of the Sandia Laboratories Low-Speed Wind Tunnel described in this report. Subsequent sections outline the physical characteristics of the facility, its performance, and the instrumentation for making flow measurements.

II. Description of the Low-Speed Wind Tunnel

A planform view of Sandia's Low-Speed Wind Tunnel is shown in Figure 1. The test section is supported by a steel frame above the fan, mufflers, filter, and air velocity damper sections. It is 12-feet (3.66 m) long, 9-inches (0.23 m) high, and 16-inches (0.41 m) wide. Eight windows are positioned on both sides of the test section to provide complete visual coverage of the entire test section, including the top and bottom wall surfaces. The inner surfaces of the windows are mounted flush with the side walls so that flow disturbances in the test section are minimized. Nine survey port stations are located in the test section ceiling along the centerline of the tunnel, and off-centerline ports are also available at several of these stations. These ports accommodate flow-field instrumentation, such as hot-wire probes, and they may also be used as anchor points for models to be mounted in the tunnel.

The airflow in the test section is generated by a fan driven by a two-speed, 3 HP electric motor located in the return section of the tunnel. The air velocity is controlled

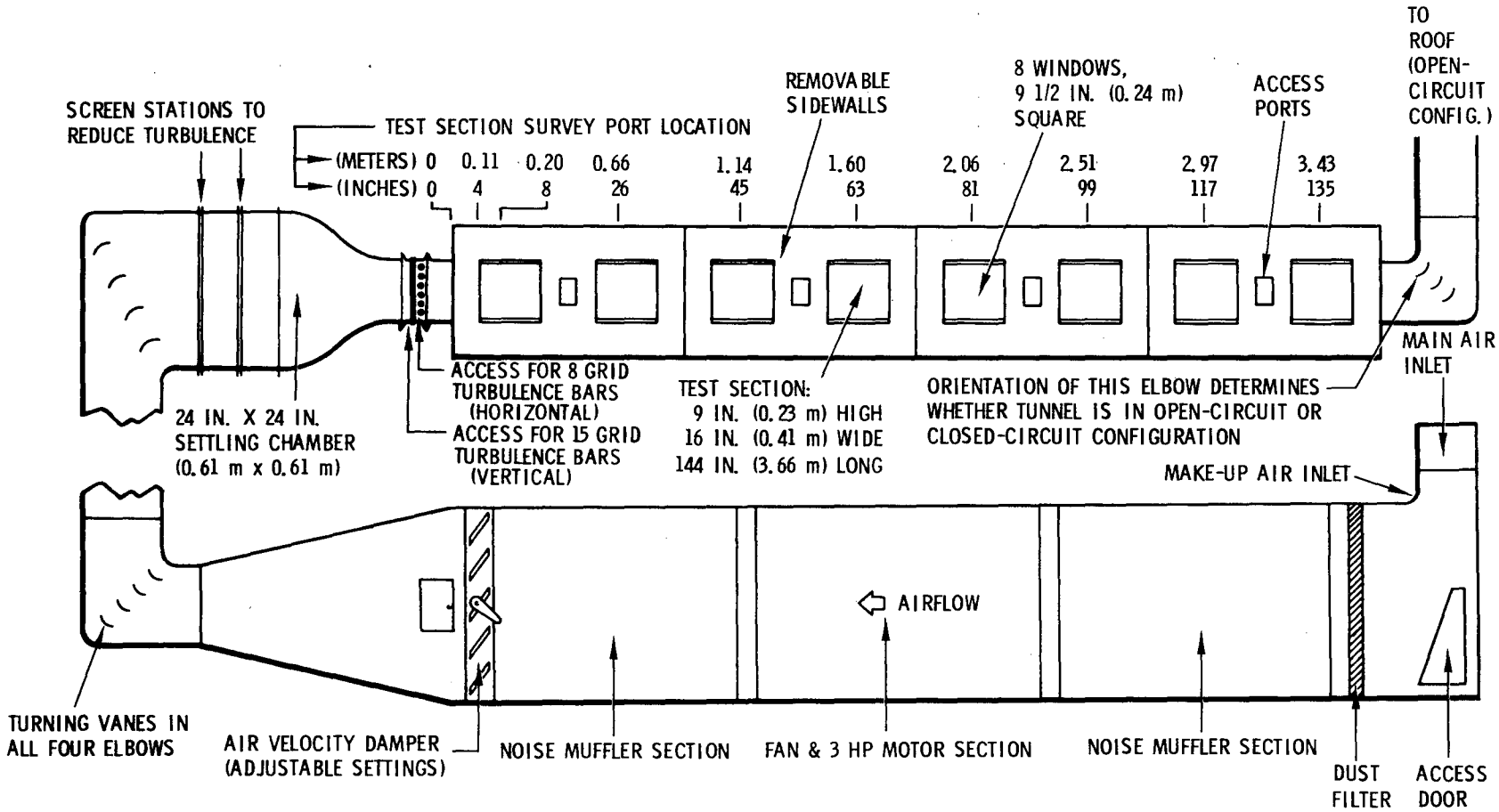


Figure 1. Planform View of the Low-Speed Wind Tunnel

by both the motor speed and the setting of a damper located downstream of the fan. Two sections of mufflers reduce the noise level in the airflow. The turbulence level is reduced in the settling chamber by two stations of fine-mesh screens. However, some experiments may require that the turbulence level be varied independently of the mean flow velocity. To accommodate this requirement, a special section at the entrance to the test section can be fitted with horizontal and vertical turbulence grid bars. A second section can be modified to accept turbulence generators of different shapes. This capability is particularly important in the study of atmospheric flows, where both the mean velocity and turbulent structure must be properly simulated in order to obtain meaningful results.

The construction of the entire tunnel, particularly the test section, is modular to permit easy access and to encourage the replacement of any standard component with a specialized component needed for specific experiments. For example, the facility can quickly be converted from an open-circuit configuration (as shown in Fig. 1) to a closed-circuit configuration simply by inverting the elbow at the downstream end of the test section. As a second example, the side walls of the test section have been divided into four sections, each of which can be replaced by special units for supporting models, injecting particulate matter into the flow, or mounting additional instrumentation. The top and bottom walls are constructed to give a smooth surface for wall boundary layer studies, but roughness elements can easily be fastened to these walls to simulate the earth's surface or to thicken the boundary layer if better resolution of measurements is needed. The standard walls can also be replaced with others which generate thermal gradients, represent clusters of buildings, or provide a liquid surface instead of a solid boundary. Particulate matter can be introduced in the test section, through the turbulence grid bars, or at several locations in the return section. The simplicity of the tunnel design makes it possible for such modifications to be made at low cost and with minimal effort. This versatility is the principle reason why the facility is a candidate to conduct a large number of low-speed experiments above and beyond the scope of work originally intended for this wind tunnel.

III. Standard Instrumentation for the Low-Speed Wind Tunnel

The versatility of the low-speed wind tunnel design has been matched by the wide range of flow-field measurements which can be made using instrumentation developed specifically for this facility. Many techniques, such as the measurement of temperature and pressure, are standard in their application and need not be described in this section. Of greater interest is the variety of information which can be obtained by the skillful application of hot-wire anemometer and laser velocimeter instrumentation.

A. Hot Wire Anemometry

The hot-wire probe is a small-diameter (0.004 mm) tungsten wire supported at its ends by slender prongs. The wire is maintained at a constant temperature (usually 100-200°C above ambient temperature) by an electronic feedback network. As the air velocity passing over the wire increases/decreases, the feedback network must operate at higher/lower power levels to keep the wire at a constant temperature. The relationship between flow velocity and power to the wire (or, more accurately, the relationship between wire Reynolds number and anemometer bridge voltage) is the basis for operation of this diagnostic technique. Because the wire is small, it can respond to fluctuations in velocity with frequencies up to 50 kHz. This makes the hot wire ideally suited for use in turbulent flows or measurements of laminar instabilities, where both mean flow velocities and fluctuating velocities are desired.

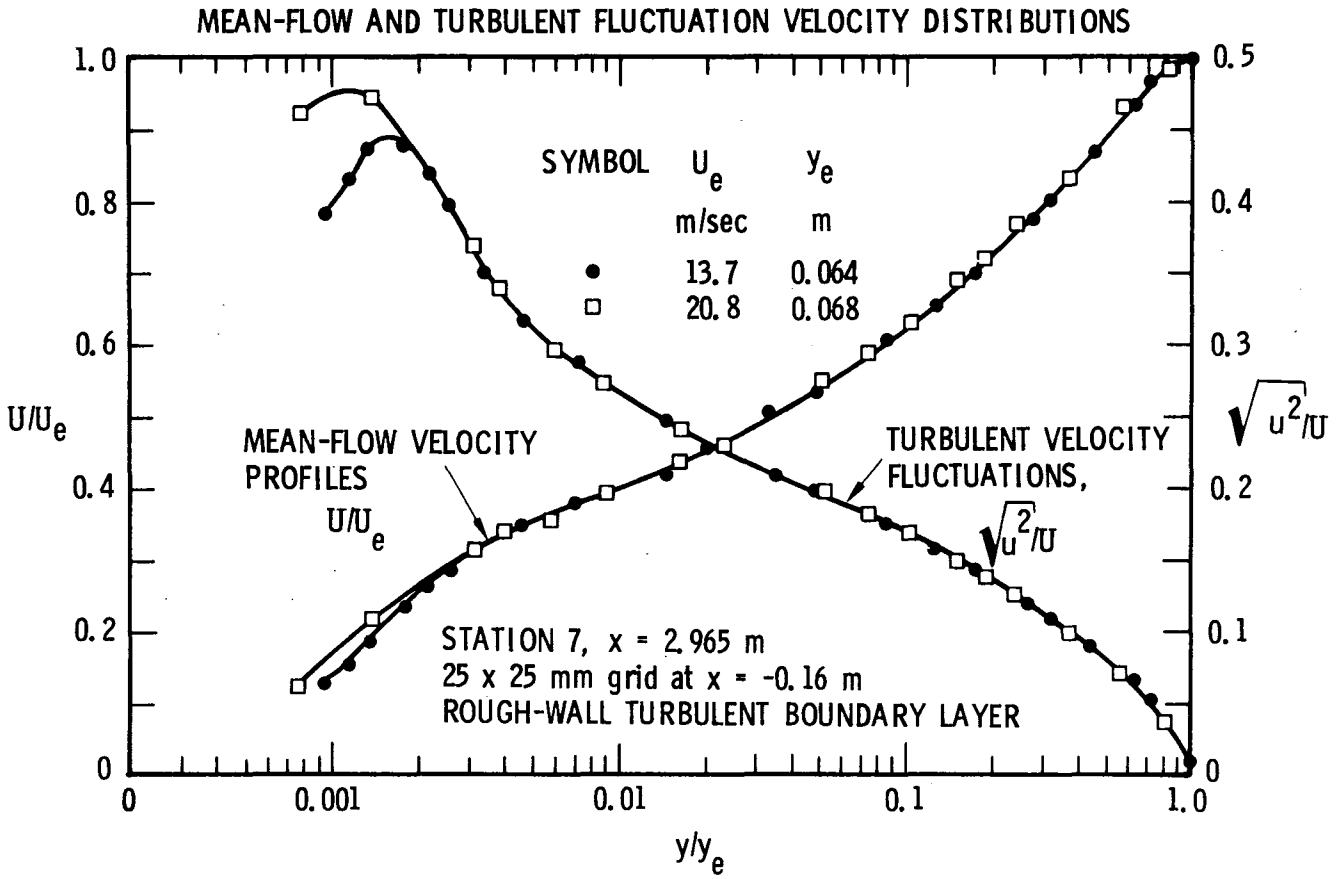
Measurements with a single hot-wire probe of mean-flow and fluctuating (rms) velocities in the direction parallel to the tunnel centerline can be performed routinely in the low-speed wind tunnel. Before a hot wire is used in the facility, it is calibrated in laminar flow over the full range of velocities that it will encounter during subsequent testing. Calibration points (wire Reynolds number vs bridge voltage) are fed into a computerized data reduction program where a curve is fitted to them. A cubic polynomial is used for the calibration curve (rather than the linear fits cited in the literature) to improve the accuracy of measurements made in highly turbulent flows and at very low velocities. Mean-flow velocities are obtained by using the calibration curve in conjunction with measured mean-flow anemometer voltages; the computer program performs these calculations and adds any necessary corrections for thermal losses to solid walls.

Fluctuating (rms) velocities are computed in a similar manner using rms voltage measurements. Additional information on turbulent velocities, such as frequency content or autocorrelation measurements, can be obtained using either analog instruments or computerized frequency analysis techniques developed at Sandia during the past year.[1] Figure 2 illustrates the variety of information which was obtained in the turbulent boundary layer flowing over roughness elements mounted on the floor of the low-speed wind tunnel.

B. The Laser Velocimeter

The laser velocimeter (LV) is an optical instrument which provides non-interfering measurements of particle mean and fluctuating velocities. The LV implemented at this facility utilizes two wavelengths emitted from a 4-watt argon-ion laser for the simultaneous measurement of orthogonal velocity components. A schematic diagram of the two-wavelength ("two-color") LV is shown in Fig. 3. The fringe-mode optical arrangement requires that each wavelength individually be split into two equally intense beams which are focused at the "point" of interest in the flow. Because the two beams are coherent, they will interfere constructively and destructively to form two sets of superimposed orthogonal fringe structures in the measurement volume. As small particles (submicron to micron in size) which are carried by the flow pass through the orthogonal fringe patterns, the scattered light will vary in intensity as the particle moves from the bright to dark portions of the fringe pattern. The two-wavelengths of this scattered light are then separated by an optical filter and focused on separate photomultiplier (PM) tubes. The frequency of the electronic signal from each PM tube is directly proportional to the corresponding velocity components of the particle. Successful measurements of particle mean-flow velocities have been made with this system in the low-speed wind tunnel.

It has been experimentally established that micron-sized (and smaller) particles will faithfully follow a low-speed flow of this type. Thus, it is possible to measure accurately all of the mean and fluctuating flow velocities, in addition to the particle velocities. This enables the LV system to be used as an alternative to the hot wire for acquiring all necessary flow field information in cases where the presence of the hot-wire probe may introduce errors in measured velocities.



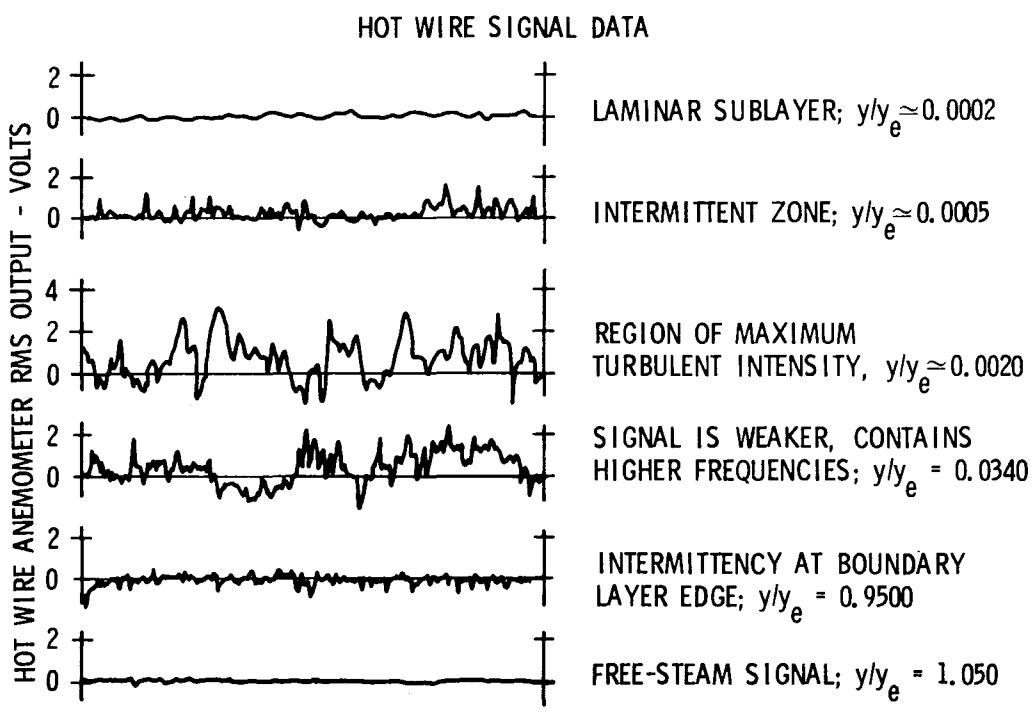


Figure 2. Hot-Wire Measurements in a Turbulent Boundary Layer.

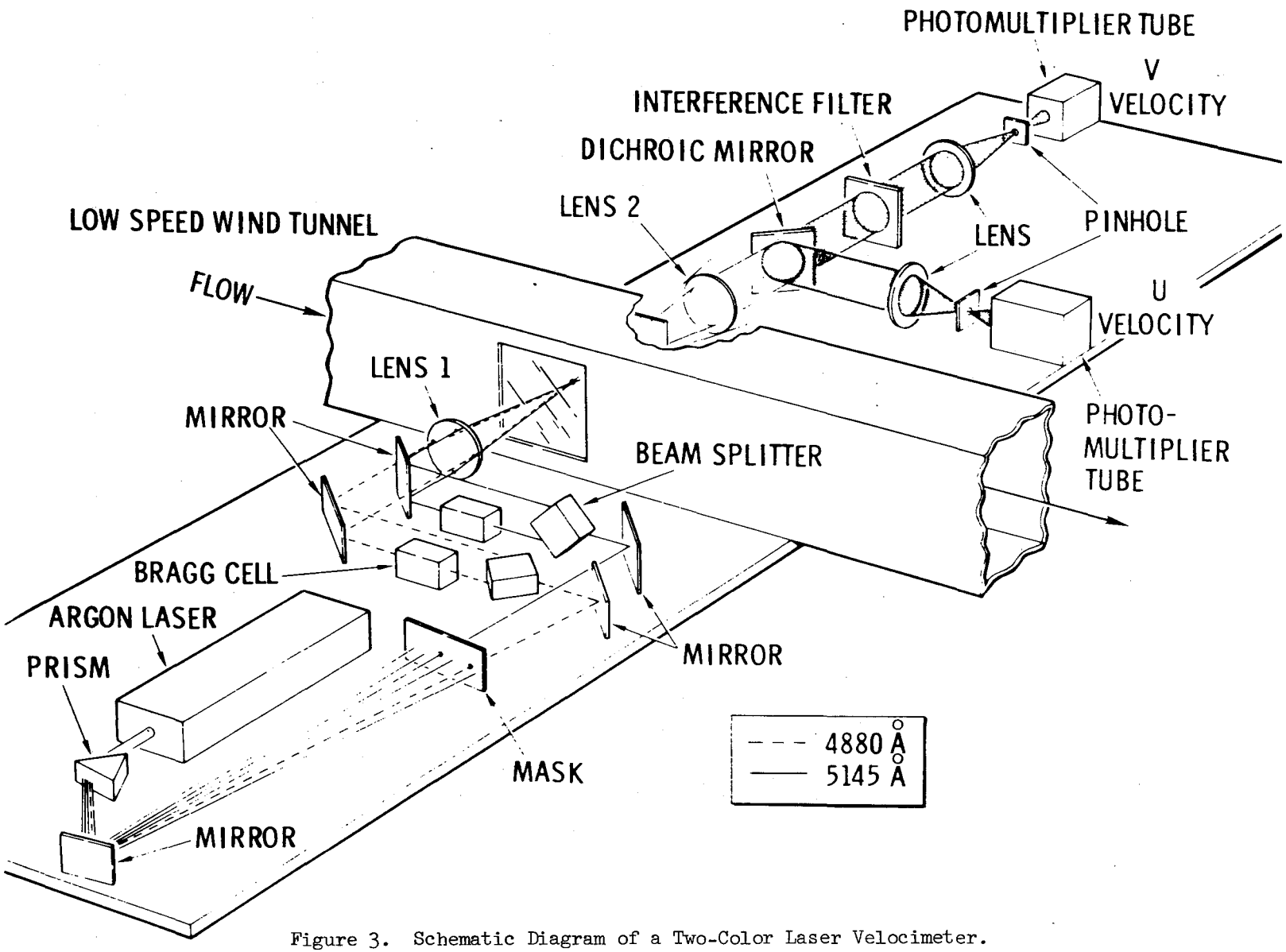


Figure 3. Schematic Diagram of a Two-Color Laser Velocimeter.

The random arrival time of a particle and the possible presence of several particles in the measuring volume requires sophisticated data validation and processing schemes. The electronic signals from the PM tubes are validated by a Thermo Systems Inc. Model 1094 Signal Processor which provides a digital output of the velocity. These digital data are then automatically recorded by the DACS to obtain the statistically significant number of measurements required for this technique.

IV. Demonstration of Facility Performance

The first flow-field measurements in the low-speed wind tunnel were made to determine the extent to which the facility fulfills the intended objective of providing a controlled, repeatable airflow for research in atmospheric flows and basic incompressible fluid mechanics. Such an investigation was made using the hot-wire anemometer, as described in Section III. Measurements of mean-velocity, flow uniformity and two-dimensionality, free-stream turbulence levels, and the effect of turbulence generators on the flow were carried out during this developmental phase of the low-speed wind tunnel.

By adjusting the fan motor speed and the setting of the damper mechanism, the mean-flow velocity in the test section can be varied nearly continuously from 0 to 50 mph (22 m/sec). Surveys indicate that the flow velocity is constant to within 1 percent both vertically and horizontally across the test section. None of the velocity settings impose undue stress on the motor or damper, so these velocities can be sustained indefinitely. Higher velocities are possible using test section geometries with smaller cross-section areas. With the damper wide open and only the motor speed control used to set the free-stream velocity, typical mean-flow velocities achieved in the test section are 31 and 50 mph (14 and 22 m/sec). At any velocity setting, the tunnel is allowed to run for approximately an hour before data are acquired so that the air temperature in the test section is stabilized.

The free-stream turbulence level, as indicated by rms measurements of the axial component of velocity fluctuations $\left(\sqrt{u^2}\right)$, was measured at several test section survey stations (x) with and without turbulence grid bars located 6 inches (0.16 m) in front of the entrance to the test section. With no grid bars, the measured rms velocity fluctuations were approximately 1 percent of the mean-flow velocity (U) for U = 14 m/sec and U = 22 m/sec.

This ratio was observed to be independent of the test section survey station, implying that the screens in the settling chamber are successful in eliminating most of the turbulence before the flow enters the test section. With the turbulence grid bars in position, the measured free-stream turbulence level near the entrance to the test section was much greater than the "no grid" turbulence level, but it decreased monotonically to the "no grid" turbulence level at a tunnel station of 81 inches (2.1 m). Downstream of this station, the grid bars had no effect upon the free-stream turbulence level. These results indicate that the mechanisms for generation, development, and decay of turbulence in an isotropic, homogeneous flow can be observed within the length of the test section of this wind tunnel.

Many experiments in atmospheric flows require that mean velocity profiles be "tailored" to give shear stress distributions that would not normally exist in a boundary layer growing on the smooth test section walls. In other instances, it is desirable to artificially thicken the wall boundary layer while preserving the non-dimensional velocity profiles and turbulent intensity distribution. Both objectives can usually be accomplished by placing a special grid at the entrance at the test section and iterating on its shape until the desired flow field is obtained in the test section. As an example of how this process works, an experiment was conducted in the low-speed wind tunnel to thicken a rough-wall boundary layer on the test section floor. Figure 4 shows the shape of the fins which were used as a "first guess" in the iteration process. The fins were installed immediately downstream of the turbulence grid bars at test section station 0.0 m. The plastic packing material, which was glued to the normal test section floor to serve as roughness elements, is also shown in the photograph. The roughness elements are in the shape of domed cylinders at right angles to the tunnel floor. They are 9 mm in diameter, 5 mm in height, and are surrounded by six other elements whose centers are separated by 11 mm. Single-wire measurements of mean-flow and fluctuating velocities were made at tunnel station 2.965 m (116.7 inches) at two free-stream velocities. Additional measurements were made to determine the two-dimensionality of the boundary layers, the effect of surveying in a "trough" between roughness elements rather than on a "peak", and the effect of the turbulence grid bars on the profiles. In the plots presenting the results of these sur-

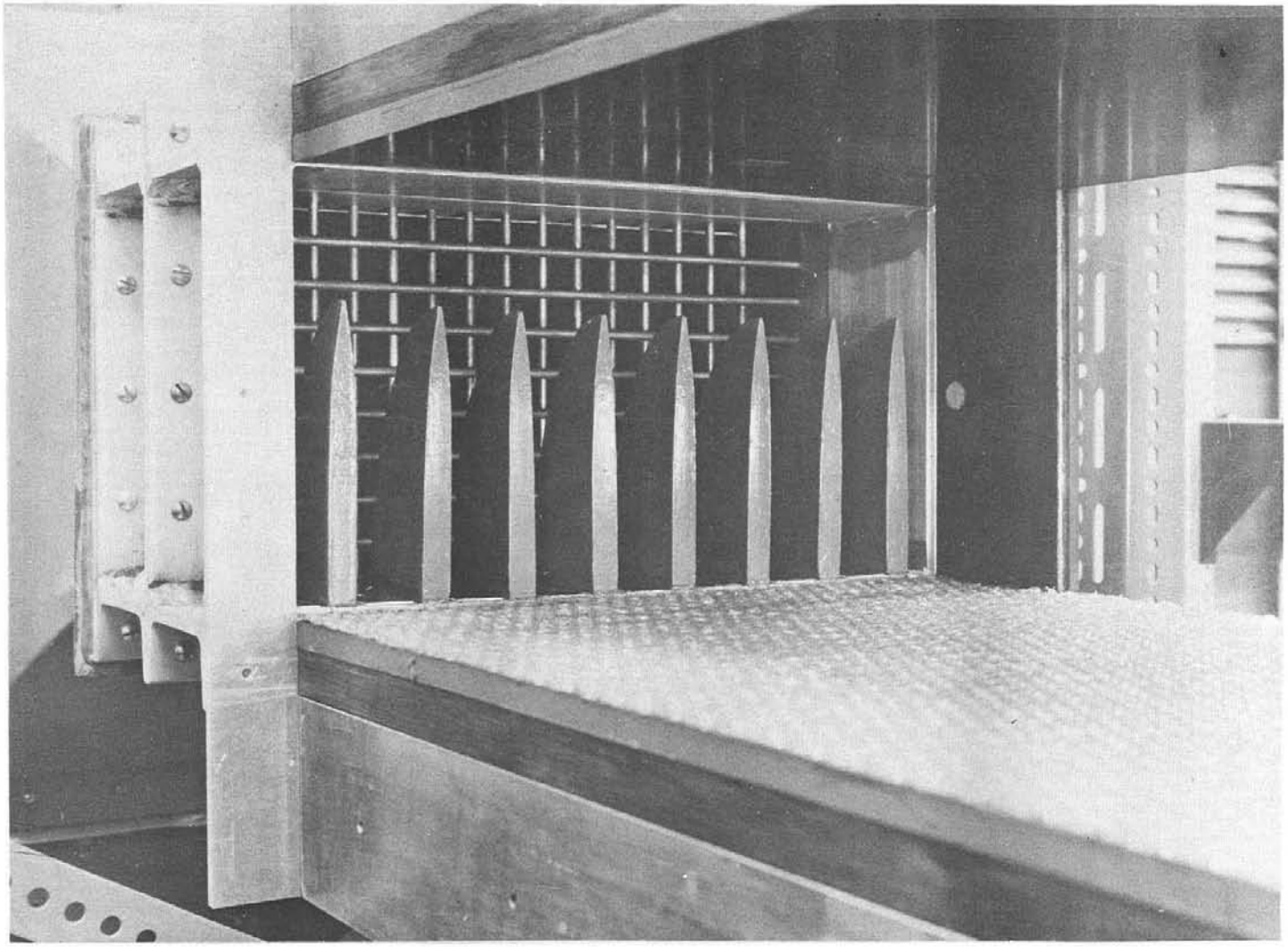


Figure 4. Fins Used to Thicken the Rough-Wall Test Section Floor Boundary Layer.

veys, the distance from the wall is represented by y and boundary layer edge values are denoted by the subscript e.

Mean-flow velocity surveys (Fig. 5) show that the fins are successful in doubling the thickness of the boundary layer without altering the non-dimensional velocity distribution appreciably. Hence, in experiments where only the local modeling of the mean velocity profile is required, this fin configuration is entirely adequate. However, the turbulent velocity distribution does not scale properly as the boundary layer is thickened by the fins. This is because most of the turbulence convected downstream from the fins has died out, leaving only the turbulence generated by shear stresses near the wall (as in the "no fins" configuration). In many instances, these differences in distribution of turbulence between the "fin" and "no fin" configurations are not critical, and this fin configuration can, therefore, be used without any changes in shape. If these differences are important, the fin geometry would have to be altered to produce a higher level of turbulence at boundary layer locations farther from the wall. Variable mesh screens, rough-wall fins, and air injection techniques can be used either singly or in combination to make any necessary adjustments in the flow.

Surveys at tunnel station 2.965 m showed that the turbulence grid bars have no effect on either the mean-flow velocity profile or the fluctuating velocity distribution. Figure 6 shows the results for a configuration without fins at low speed; these results are typical of the data obtained at high speeds and with or without fins. At x = 1.745 m (68.7 in), the grid had a negligible effect on mean-flow velocities and on fluctuating velocities when the fins were installed. Without the fins, the distribution of turbulent intensity did not depend upon the presence of grid bars in regions of the boundary layer where the generation of turbulence by shear stress is much stronger than the turbulence convected downstream from the grid bars. Near the edge of the boundary layer, the convected turbulence is stronger than the shear-induced turbulence, leading to small increases in turbulent intensity when the grid bars are installed. As was observed in the free-stream, the level of grid-induced turbulence at the boundary layer edge increases when surveys are made at locations nearer to the grid bars.

The results of hot-wire surveys at 0.05 m and 0.10 m (1.97 and 3.94 in.) off of the test section centerline are compared with centerline velocity data in Fig. 7. The mean

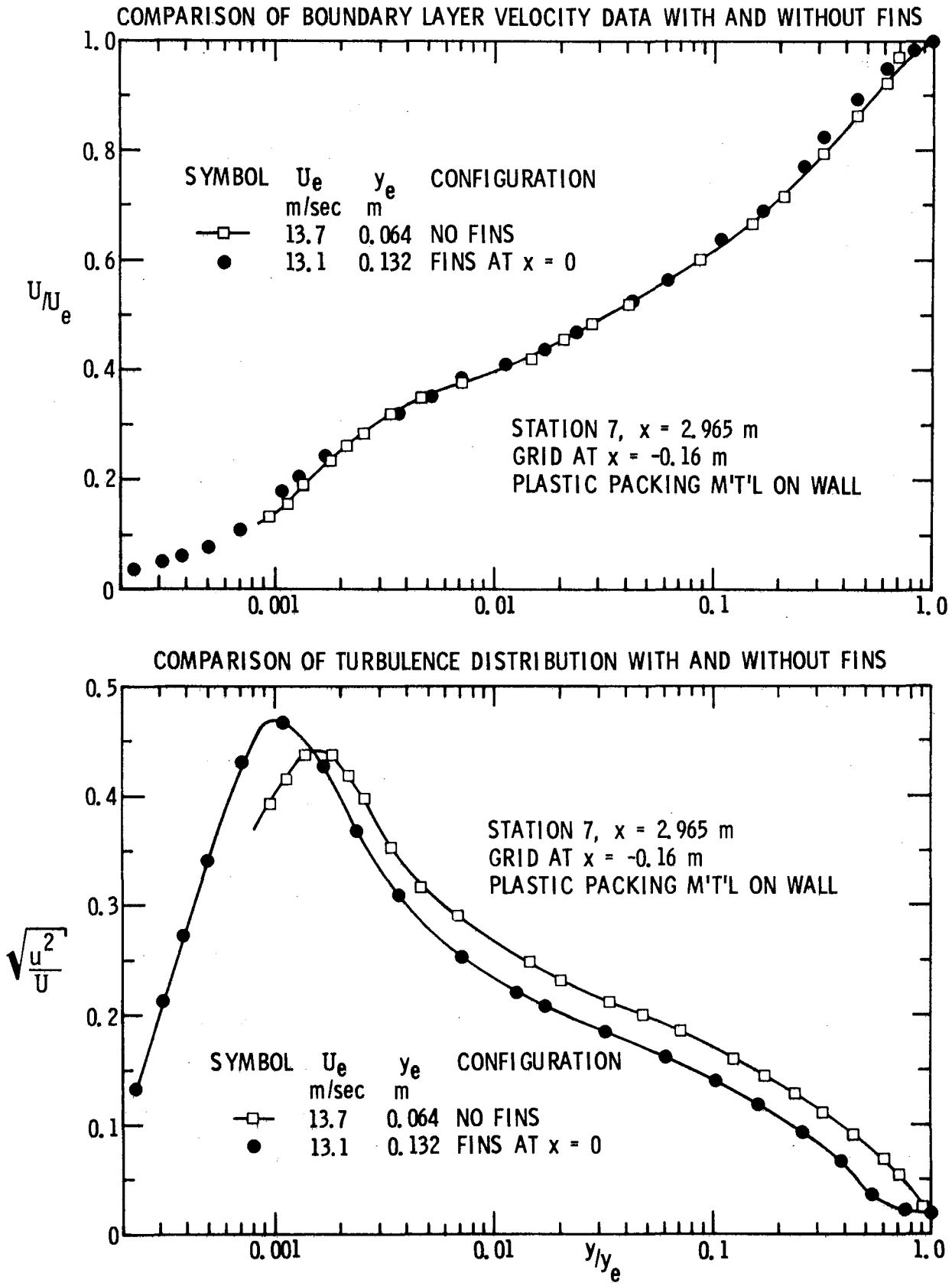


Figure 5. The Effect of Fins Upon Boundary Layer Profiles.

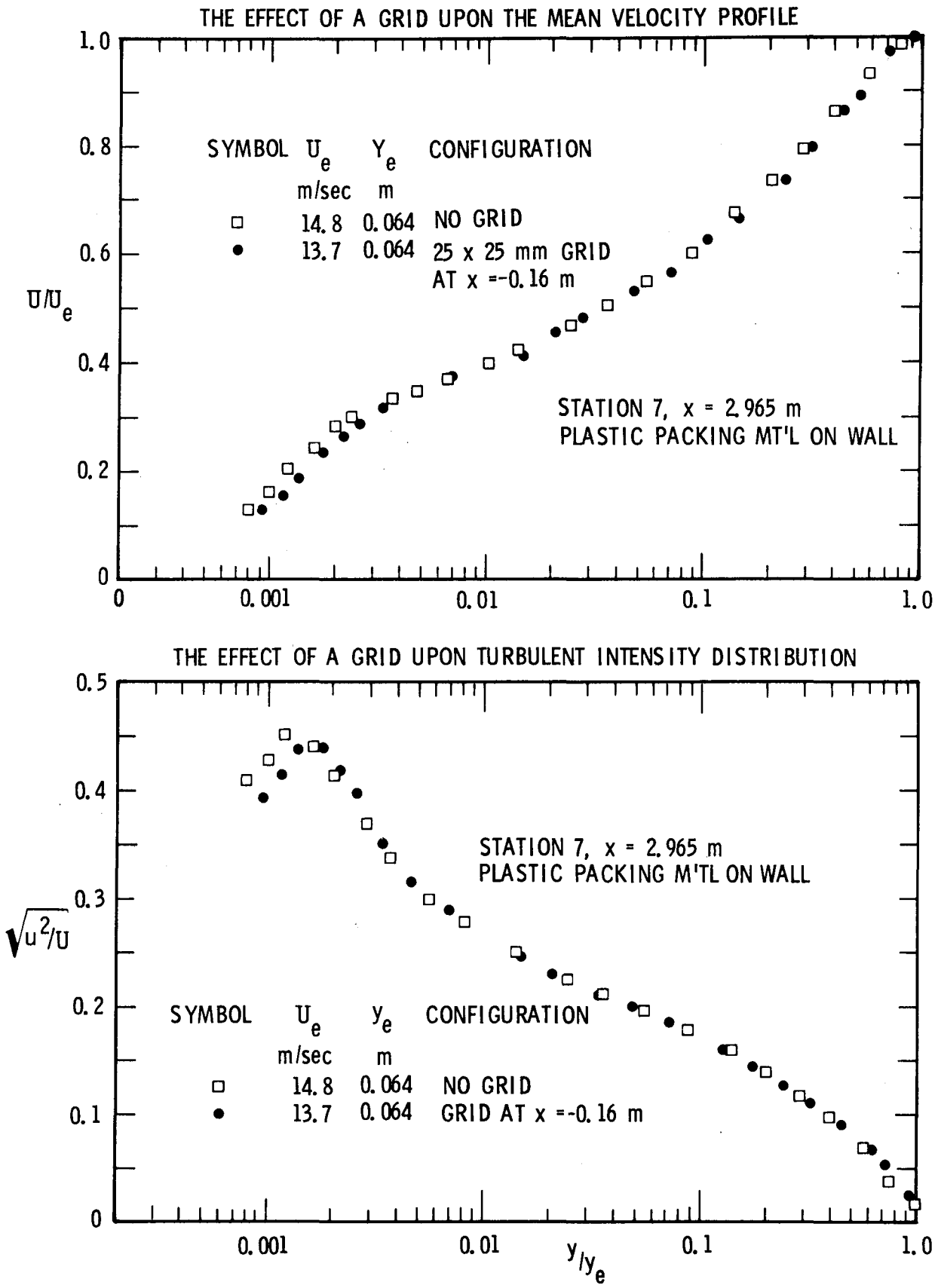


Figure 6. The Effect of Turbulence Grid Bars Upon Boundary Layer Profiles.

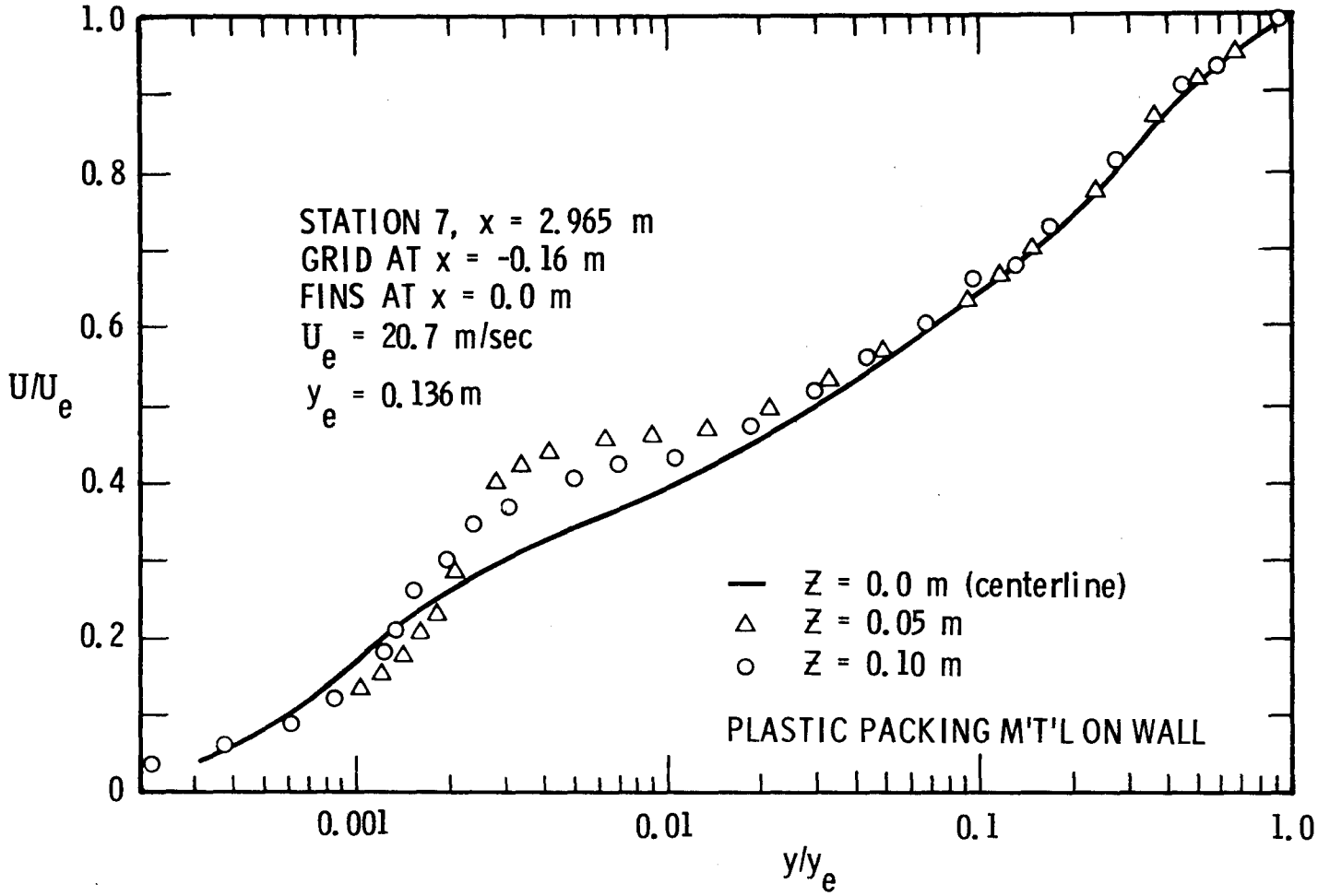


Figure 7. Two-Dimensionality of Mean Flow Boundary Layer Velocity Profiles.

velocity profiles are nearly identical across the outer 95 percent of the boundary layer, indicating that the flow can be considered two-dimensional at this survey station. However, large differences in profile shape are observed near the wall; these are due to differences in the position of the hot-wire sensor relative to individual roughness elements. Such irregularities are to be expected (due to the definition of a "rough" wall), and are of no concern in experiments investigating atmospheric flows.

V. Summary

A twelve-foot-long wind tunnel with a 9 x 16-inch test section has been constructed at Sandia Laboratories to provide a low-speed, controlled test environment for the study of atmospheric flows and other fundamental problems in incompressible fluid mechanics. The facility is distinguished from other low-speed wind tunnels by its simplicity of design and versatility of operation. It may be operated at any mean-flow air speeds between 0 and 50 mph (22 m/sec), and the capability exists for generating different turbulence levels and velocity distributions in the test section. Experiments to study fundamental problems in atmospheric fluid mechanics and boundary layers, wakes, and turbulent flows can be conducted with the tunnel in the closed-circuit configuration. The long test section is ideal for studying the thick boundary layers on the tunnel walls or the development and decay of turbulent eddy structure in a free shear layer. In the open-circuit configuration, the tunnel may be used to study the dispersal of small particles in the atmosphere. In either configuration, the test section walls may be modified to accommodate specific experimental requirements for surface roughness, temperature, particle injection, and model mounting.

Flow-field instrumentation for the low-speed wind tunnel includes sophisticated mean-flow and fluctuating velocity measurement techniques in addition to traditional pressure and temperature diagnostics. A single-channel hot-wire anemometer has been used successfully to record both time-averaged and turbulent velocities in the tunnel wall boundary layer, and development of a dual-channel system for measuring Reynolds stresses is underway. For measurements of particle velocities in atmospheric flows, a two-component laser velocimeter (LV) is available. Both the hot-wire anemometer and the LV can be interfaced to a mini-computer data acquisition system for rapid, accurate interpretation and

analysis of the data. The same mini-computer will be used to control the LV optical bench for automatic traversing of the flow in the test section.

After performing simple experiments to validate the laser velocimeter measurements, the low-speed wind tunnel will be used to study the deposition and resuspension of particulate matter in the earth's boundary layer. Particle deposition and resuspension may be important processes governing the dispersion of pollutants downwind of a pollution source. Unfortunately, most techniques[2-4] for predicting deposition and resuspension rates are empirical and are not based upon an understanding of the fundamental physical processes. The objectives of this work will be to observe the basic mechanisms for particle transport near the surface, and to correlate measured deposition and resuspension rates using parameters which characterize the transport mechanisms. At first, simple turbulent boundary layer flows will be used as the deposition/resuspension environment. Hot-wire surveys will define the flow field and LV measurements will define the particle motion. Once a model of particle deposition and resuspension is generated, the flow in the low-speed wind tunnel will be tailored to simulate the earth's boundary layer. The response of the particle motion to these additional flow field complexities will lead to improvements in the deposition/resuspension model.

The low-speed wind tunnel may also be used to examine fundamental problems in fluid mechanics, such as turbulent mixing in isotropic, homogeneous flows. Previous investigations of turbulent mixing were conducted using only the hot-wire anemometer. The mixing process could be observed by the hot wire only if different gases were used in the experiment. Difficulties were encountered in generating the same scale of turbulence in each gas while maintaining isotropy and inhomogeneity in the mixing region. However, experiments in the low-speed wind tunnel will use the laser velocimeter to circumvent this problem. With the LV, the same gas is used everywhere; the mixing process is studied by seeding part of the flow with particles and using the LV to observe the particles as they mix with regions where no particles were introduced.

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