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EFFECT OF TRANSIENT WINDS ON THE FLOW QUALITY OF AN OPEN-CIRCUIT WIND-TUNNEL MODEL

by Douglas C. Breunlin and Noel B. Sargent

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

The effect of a transient wind on the test-section flow quality of an open-circuit wind tunnel has been investigated experimentally. The investigation was restricted to transient wind effects associated with the inlet. A small open-circuit wind tunnel was placed outside in the real wind environment. Test-section speed and angularity as well as wind speed and direction were measured by high-response instrumentation. The inlet configuration was varied with a set of screens, a removable honeycomb, and a removable inlet lip. Acceptable flow was obtained at all wind angles and for wind- to test-section-velocity ratios up to 0.4 with an inlet configuration having five screens, a honeycomb, and a lip. With inlet configurations sensitive to winds, a transient wind parallel to the tunnel axis produced local fluctuations in test-section speed and angularity; however, oscillation of the average test-section speed was not evident. The effect of wind direction was negligible up to wind angles of 45° relative to the tunnel axis. At larger wind angles, flow distortions occurred primarily on the windward side of the test section.

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EFFECT OF TRANSIENT WINDS ON THE FLOW QUALITY OF AN OPEN-CIRCUIT WIND-TUNNEL MODEL

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SUMMARY

The effect of a transient wind on the test-section flow quality of an open-circuit wind tunnel has been investigated experimentally by placing a small open-circuit tunnel in the real wind environment. The investigation was restricted to correlation between test-section flow quality and wind effects associated with the inlet. Exit effects were minimized by employing high discharge velocities. The inlet configuration was varied with a set of screens, a removable honeycomb, and a removable inlet lip.

With an inlet configuration having five screens, a honeycomb, and an inlet lip, the test-section flow possessed a uniform profile and speed and angularity fluctuations less than 0.3 meter per second (1 ft/sec) and 0.25°, respectively, for all wind angles and for wind- to test-section-velocity ratios up to 0.4.

The test-section flow obtained with inlets sensitive to transient winds possessed unsteady speed and angularity fluctuations. For winds parallel to the tunnel axis these fluctuations appeared to be random in time and across the test section. No oscillation of the average test-section velocity was evident. For all inlet configurations, the flow quality was unchanged as the wind angle was varied from 0 to 45° relative to the tunnel axis. At large wind angles flow unsteadiness occurred primarily on the windward side of the test section.

INTRODUCTION

The need for modern and larger wind-tunnel facilities is being felt throughout the field of aerodynamics. This need is perhaps most pressing in the area of subsonic aerodynamics, where new concepts leading to the development of STOL and VTOL aircraft are being investigated (ref. 1). To meet these needs, the NASA is presently studying the feasibility of a full-scale subsonic wind tunnel (ref. 2). The enormous structural cost of such a tunnel has led investigators to consider strongly an open-circuit design. In addition to a significant cost reduction, the open-circuit design is also well suited for testing real propulsion systems as well as large wake-producing models.

The attainable flow quality in an open-circuit tunnel, however, remains an unresolved question. The exposed inlet and exit are subject to atmospheric disturbances, the most serious of which is the wind. Nonuniform velocity profiles, angularity, flow unsteadiness, and turbulence may occur in the test section unless these atmospheric disturbances are effectively attenuated at both inlet and exit. The design of the inlet and exit of an open-circuit tunnel, therefore, becomes a major item of concern.

A number of open-circuit tunnels have been constructed in Europe, but the flow qualities of these tunnels do not meet the requirements of the proposed NASA research facility (refs. 3 and 4). The definition of an acceptable flow quality is a subject of controversy; however, for versatile usage, it has been suggested that a wind tunnel should possess profile uniformity and steadiness to within 1 percent of the average velocity and angularity no greater than 0.25°. These requirements may be relaxed at very low tunnel speeds, less than 30 meters per second (100 ft/sec). In this low-speed range, velocity fluctuations and profile nonuniformity should not exceed 0.3 meter per second (1 ft/sec), and angularity should not exceed 1°.

Several experimental programs have been conducted in an effort to design effective inlet and exit configurations (refs. 5 and 6). These programs employed models of the proposed tunnel configurations. For certain tests, the external wind was simulated by a fan. In most tests, however, the models were placed in large existing tunnels, the airflows of which simulated the wind conditions. These approaches present the advantage of a controlled wind environment but are limited to uniform steady-state wind conditions.

The wind, in reality, is neither uniform nor steady. Rather, it is transient, possessing gusts as well as vertical and lateral nonuniformities in magnitude and direction which are unsteady in nature. This wind transience may adversely affect the test-section flow quality and thus compromise the data accuracy and validity.

A decision in favor of an open-circuit wind-tunnel design cannot be made until the transient wind problem is fully understood and solved. For this reason, an experimental program was conducted at the Lewis Research Center, the objective of which was to investigate the transient wind problem. The investigation was restricted to correlation between test-section flow quality and wind effects associated with the tunnel inlet. Exit effects were eliminated by employing high discharge velocities.

A small open-circuit wind tunnel was placed out of doors and in the real wind environment. The magnitude and direction of the external wind and the test-section flow speed and angularity were measured simultaneously by high-response instrumentation.

The effect of a transient wind on test-section flow quality was obtained for winds varying from 0 to 180° relative to the tunnel axis. Tunnel speeds ranged from 15 to

23 meters per second (50 to 75 ft/sec) and wind speeds from 3 to 9 meters per second (10 to 30 ft/sec). The inlet configuration was varied by employing a removable honeycomb, a removable inlet lip, and a set of inlet screens.

SYMBOLS

AZ	azimuth angle in test section, deg
C_D	screen loss coefficient, $\Delta P/q$, dimensionless
d	diameter of honeycomb
EL	elevation angle in test section, deg
l	length of honeycomb
P	total pressure, N/m^2; lbf/ft^2
q_o	dynamic pressure in test section, N/m^2; lbf/ft^2
$\Delta P/q_o$	inlet loss coefficient, dimensionless
V	velocity or speed, m/sec; ft/sec
t	time, sec
θ_W	wind angle (relative to tunnel axis), deg

Subscripts:

C	center of test section
P	port side of test section
S	starboard side of test section
T	test section
W	wind

EQUIPMENT AND PROCEDURE

Description of Model Tunnel

Figure 1 is a three-quarter view of the open-circuit tunnel used in the program. It consists of an inlet, a rectangular test section with a 0.5- by 0.75-meter (20- by 30-in.) cross section, a diffuser between the test section and drive section, and the drive section itself. The overall diffuser area ratio is small; consequently, the tunnel exit velocity is very high. The high discharge velocity makes the exit insensitive to wind effects. This was appropriate to the test program, which dealt only with wind effects associated with the inlet. The drive section consists of an 0.86-meter (34-in.) axial-flow fan which is powered by a two-speed electric motor. These two speeds provide velocities of 15 and 23 meters per second (50 and 75 ft/sec) in the test section. The fan design is consistent with conventional wind-tunnel fan design. The entire tunnel is mounted on castors to facilitate rotation.

The inlet is shown in more detail in figure 2 and consists of the following components:

(1) A rectangular contracting section having a 13:6:1 contraction ratio.

(2) A set of four 18-mesh screens having a $C_D \approx 1$ per screen. These screens mate directly to the front of the inlet, and their number can be varied.

(3) A honeycomb - settling-chamber combination which is 2.4 meters (8 ft) wide and 2.1 meters (7.08) high. It has 1.2 meters (4 ft) of honeycomb and a 1.2-meter (4-ft) settling chamber. The honeycomb has 0.15-meter (6-in.) cells and an $l/d = 8.0$. The honeycomb and settling chamber are mated into one component which is hereinafter simply referred to as the honeycomb.

(4) A 0.15-meter- (6-in.-) diameter metal lip mounted on an 18-mesh screen also having a $C_D \approx 1$. This lip mounts directly on the contracting section or on the front of the honeycomb. Hereinafter it is referred to simply as the lip.

The calculated loss coefficient $\Delta P/q_0$ for the complete inlet configuration is 0.025 to 0.030. Removal of one screen reduces this figure by a factor of 0.005.

Description of Instrumentation

All measurements were made with wind anemometers such as those shown mounted in the test section in figure 3. The wind-speed output is an analog voltage which is generated by a linear tachometer circuit. This circuit is driven by the pulse signal from the anemometer light chopper, which registers 50 pulses per revolution. Each anemometer propeller has a factory-calibrated pitch (number of feet of air producing one prop revolution). Wind speed was calibrated by measuring the number of revolutions per second and multiplying by the propeller pitch. The propellers have a starting threshold less than 0.3 meter per second (1 ft/sec) and are accurate to 0.3 meter per second (1 ft/sec). Wind speeds to 36 meters per second (120 ft/sec) can be handled.

The azimuth and elevation angles were measured by voltages produced by a potentiometer linearly proportional to tail vane deflection. Elevation angles can be measured from -60° to 60° and azimuth angles over 360°. The anemometers in the test section were capable of recording angularity fluctuations less than 0.25°.

Description of Test Setup and Procedure

The test-section speed and angularity were measured by three anemometers mounted spanwise in the test section as shown in figure 3. A fourth anemometer, mounted on a tripod, was positioned in front of the inlet to measure the magnitude and azimuthal direction of the wind. The wind and test-section parameters were recorded simultaneously with a 12-channel oscillograph. In this manner, the test-section flow quality could be related to wind magnitude and direction. It should be noted, however, that while the wind anemometer provided an accurate measurement of the wind speed and direction at its location, it did not fully define the wind entering the tunnel for several reasons. The wind anemometer did not reflect vertical or lateral nonuniformities in the wind. Also, tunnel blockage effects may have changed the magnitude and direction of the wind at the inlet.

Data were obtained for the nine inlet configurations listed in table I. The total number of screens listed in the table includes the screen mounted to the inlet lip when the lip was included in the configuration. Accordingly, a configuration designated four screens, honeycomb, and lip actually had three screens between the contraction and the honeycomb and one screen mounted to the lip.

The tunnel was located on the Lewis hangar apron, which is adjacent to the Cleveland Hopkins Airport. Winds coming across the airport were unobstructed. The only buildings obstructing the wind from other directions for which data were taken were 69 to 90 meters (75 to 100 yd) away. Comparison of unobstructed wind data with obstructed wind data for a given inlet configuration indicated that these buildings did not significantly alter the quality of the wind. Wind speeds varied from 3 to 9 meters per second (10 to 30 ft/sec). The wind direction was measured relative to the tunnel axis, $\theta_W = 0$ being parallel to this axis. The desired wind direction relative to the tunnel axis was obtained by rotating the tunnel on its support castors. The prevailing wind direction was seldom constant for long periods of time. Rather, changes of $\pm 20^{\circ}$ were frequently encountered during data acquisition. To ensure that data samples at the desired wind angles were obtained, 1 to 2 minutes of continuous data were taken for each test condition.

In order to obtain a desirable resolution of flow disturbances and to keep individual traces from crossing on the oscillograph output, it was necessary to record test-section velocities and angularities independently; consequently, the three test-section velocities appear on one output, while the three elevation angles and three azimuth angles appear together on another output. Data were obtained at both low and high tunnel speeds, 15 and 23 meters per second (50 and 75 ft/sec), respectively. Thus, each strip of oscillograph data presents a set of test-section parameters, a prevailing wind direction, and a test-section speed.

RESULTS AND DISCUSSION

Data Interpretation

Representative strips of the data, each spanning a time interval of approximately 13 seconds, were selected for each condition of interest. These data strips, arranged in groups to facilitate comparison, are presented in figures 4 to 8. The data strips contain either test-section speed traces or test-section angularity traces. The wind speed and direction appear at the bottom of the data strips with the exception of figure 4. From bottom to top, the test-section speed traces represent starboard, center, and port anemometer recordings. From bottom to top, the test-section angularity traces represent starboard, center, and port elevation angle and starboard, center, and port azimuth angle. The abscissa for each figure is time, which proceeds from right to left. A unit division of time, 1 second, is indicated in each figure. A unit division of angularity, 1°, is also shown in each figure.

The average steady location of each angularity trace is considered the zero reference for each of the six angularity parameters. Lack of an exact geometric reference in the test section made precise determination of a zero reference impossible. Also, the surface on which the tunnel was placed was not level; consequently, frequent tunnel rotations resulted in slight shifts in the relative location of zero angularity on the output. Such slight shifts in the angularity traces from strip to strip, therefore, do not indicate a relative angularity between the test conditions represented by the data strips. Actual changes in flow angularity were accompanied by large oscillations in the traces and are easily distinguished in the data. Positive (nose up) and negative elevation are recorded above and below the zero reference, respectively. An upward deflection of the azimuth trace represents a sidewash to the port side of the test section, while a downward deflection represents a sidewash toward the starboard side of the test section.

In figures 5 to 8, the wind conditions prevailing during data acquisition appear at the bottom of each data strip. The abscissa, time, is identical to that for the test-section parameters. The ordinates of the wind speed and direction appear at the left in each figure. For all strips of data appearing in figures 5 to 8 the wind direction is represented by the slightly unsteady horizontal trace. The wind speed appears as the more highly fluctuating trace. (The three horizontal lines at the bottom of the angularity strips are merely the zeroes for the test-section speed traces.)

Data were taken at two test-section speeds, 15 and 23 meters per second (50 and 75 ft/sec). The effect of external winds on the test-section flow quality is generally taken to be proportional to the wind- to test-section-velocity ratio V_W/V_T. This suggests that the lower test-section speed will be more sensitive to the wind; consequently, most of the data are presented for this test-section speed.

Since winds recorded during tests averaged 6 to 7 meters per second (20 to 25 ft/sec), the velocity ratio V_W/V_T commonly ranged from 0.4 to 0.5. These values represent the largest realistic figures expected during any open-circuit tunnel operation.

Reference Condition

The best test-section flow quality for both low- and high-speed operation is shown in figure 4. These results were obtained in the absence of an external wind and with an inlet configuration having five screens, the honeycomb, and the lip. These traces serve as a reference condition and indicate that the test-section flow in the absence of an external wind was steady, possessed negligible angularity, and had a uniform velocity profile at both low and high speeds. (Although the anemometers have an accuracy of 0.3 m/sec (1 ft/sec), a mechanical imperfection of the center anemometer caused this anemometer to record slightly low speeds at times.)

Effect of Component Variation for Winds Parallel to Tunnel Axis

The nature of the test-section flow response to a transient wind approaching the inlet parallel to the tunnel axis is shown in figures 5 and 6 for low and high test-section speeds, respectively. Test-section speed and angularity traces are shown in parts (a) and (b) of the figures, respectively. Each figure contains data strips for seven inlet configurations labeled accordingly below each strip. Wind speeds ranged from 3 to 9 meters per second (10 to 30 ft/sec) with sudden changes in speed up to 4.5 meters per second (15 ft/sec) recorded.

The general effect of the transient wind was to produce oscillatory variations in both the test-section speed and angularity. The magnitudes and periods of these oscillations depended on the inlet configuration.

The effect of inlet loss can be seen from a comparison of the first three data strips of figures 5 and 6, which represent inlet configurations employing the inlet lip and one, three, and five screens, respectively. The one-screen configuration possessed 1- to 1.5-meter-per-second (3- to 5-ft/sec) speed oscillations and 2° to 3° angularity oscillations. The flow steadiness was progressively improved with the addition of screens. With five screens the speed and angularity oscillations are below 0.3 meter per second (1 ft/sec) and 1°, respectively. (The one- and three-screen angularity data strips show no starboard angularity trace because the tail vane was damaged during an earlier test.)

The last four data strips in figures 5 and 6 represent configurations employing the honeycomb, the lip, and two, three, four, and five screens, respectively. These data strips indicate that a significant reduction in test-section flow unsteadiness was achieved with the addition of the honeycomb. This improvement may be clearly seen from a comparison of the three-screen configurations with and without the honeycomb. Whereas the maximum speed oscillations recorded with the honeycomb were less than 0.3 meter per second (1 ft/sec), oscillations up to 1.2 meters per second (4 ft/sec) were recorded without the honeycomb. Angularity oscillations did not exceed 0.6° with the honeycomb, whereas values up to 3° were recorded without the honeycomb. As the number of screens employed with the honeycomb was increased from two to five, a reduction in flow unsteadiness was also noted. The best configuration, five screens, honeycomb, and lip, possessed a flow quality comparable to the reference condition. The effect of turbulence generated by the honeycomb itself could not be detected in the data.

An examination of the data indicates that there is no obvious correlation between specific fluctuations in the wind speed and specific speed responses in the test section. Also, uniform simultaneous increments of all three anemometers were not recorded. These data imply that a transient wind did not induce uniform increases and decreases in the average test-section speed.

Effect of Wind Angle

Winds blowing at angles other than $\theta_W = 0$ present flow quality problems in addition to the transient wind effect. Nonzero wind angles distort the inlet flow pattern, which, upon reaching the test section, can appear with velocity gradients, unsteadiness, and angularity. Complete attenuation of wind disturbances, then, must include not only the transient wind effect, but also the effect of wind angle.

To illustrate the effect of wind angle on test-section flow quality, the results obtained at low speed with an inlet having moderate sensitivity to wind angle are presented in figure 7. Figures 7(a) and (b) contain test-section speed and angularity data, respectively. The inlet configuration consisted of two screens, the honeycomb, and the lip. The nominal wind angle is shown below each data strip.

A comparison of the $\theta_W = 0$ and $\theta_W = 45^{\circ}$ speed and angularity data strips indicates that a similar flow quality was obtained at the two wind angles. The test-section speed and angularity oscillations were all below 0.4 meter per second (1.5 ft/sec) and 1°, respectively. These data, and the data for other inlet configurations which are not shown, indicate that there existed a range of wind angles about $\theta_W = 0$ for which the flow quality was comparable to that at $\theta_W = 0$. The magnitude of this range was dependent upon the particular inlet configuration; however, for all configurations it was at least $\pm 45^{\circ}$.

The third data strip in figures 7(a) and (b) shows the effect of a 60° wind angle. There is a significant increase in the speed fluctuation (fig. 7(a)) on the windward side of the test section (in this case, the starboard side). The center and leeward traces, however, remain similar to those for 0 and 45°. There is also an increase in the unsteady angularity on the windward side (fig. 7(b)). A slight increase in oscillation of the windward elevation was recorded, while the oscillation of the windward azimuth angle increased from a maximum of 1° for 0 and 45° wind angles to 3° at a 60° wind angle. Again, the center and leeward angularity traces are similar to those recorded at 0 and 45°.

A further increase in windward speed fluctuation was recorded at the 90° wind angle. Moreover, the time-averaged speed on the windward side was greater than the spatial average of the test-section speed. Thus, at 90° a nonuniform speed profile existed in the test section. Since this nonuniform profile was produced by large speed fluctuations, its instantaneous shape changed with time. In fact, no steady nonuniform speed profiles were recorded throughout the tests. The center and leeward speeds were unaffected by the 90° wind angle. Both the windward and center elevation were highly unsteady, with the leeward elevation showing some unsteadiness. The windward azimuth angle possessed large oscillations with the average value toward the center of the test section. The center and leeward azimuth angles were unaffected by the 90° wind angle.

The largest speed fluctuations were recorded at $\theta_W = 135^\circ$. Windward speed fluctuations up to 3 meters per second (9 ft/sec) and intermittent leeward fluctuations were recorded. The largest flow angularities were recorded at $\theta_W = 120^\circ$. At this wind angle the windward and center elevation angles showed the largest oscillations.

Tests were also made, but are not shown, at $\theta_W = 180^\circ$ with an inlet configuration having five screens, the honeycomb, and the lip. The flow quality recorded was comparable to the reference condition.

Effect of Component Variation at Wind Angle of 90°

The effect of wind angle on test-section flow quality depended on the inlet configuration. This dependence on configuration is shown in figure 8 for a 90° wind angle, a test-section velocity of 15 meters per second (50 ft/sec), and seven inlet configurations. The wind was approaching from the starboard side of the tunnel for all configurations except the third and fifth, where the wind approached from the port side.

The effect of a 90° wind angle for an inlet configuration having five screens and the lip but no honeycomb is shown in the first data strip of figures 8(a) and (b). Speed fluctuations in excess of 6 meters per second (20 ft/sec) and violent elevation and azimuth oscillations were recorded on the windward side of the test section. Smaller, but significant, disturbances were also recorded by the center and leeward anemometers. This violent flow appeared to be associated with a swirl which occurred at large wind angles but was not present at the smaller angles. This swirl produced such a large torque on the tail vane of the windward anemometer that this vane was completely torn from its shaft and the damage mentioned previously resulted. Obviously, configurations having fewer screens but no honeycomb were not tested.

The swirl was removed by the honeycomb; however, additional screens were required to attenuate the flow disturbances completely. The results obtained by varying the number of screens for an inlet configuration also employing the honeycomb and lip are shown in the second to fifth data strips of figures 8(a) and (b) for two, three, four, and five screens, respectively. As the number of screens was increased, the windward speed and angularity oscillations were progressively attenuated. The five-screen, honeycomb, and lip configuration possessed a flow quality comparable to the reference condition.

A significant increase in windward speed and angularity oscillation was recorded when the inlet lip was removed, as may be seen by a comparison of the two- and three-screen data strips with and without the inlet lip. This suggests that windward test-section flow unsteadiness was related to lip separation.

The data of figure 8, then, indicate that large wind angle effects were attenuated with a honeycomb, three to five screens, and an inlet lip.

SUMMARY OF RESULTS

The effect of a transient wind on the test-section flow quality of an open-circuit wind tunnel has been investigated experimentally. The investigation was restricted to correlation between test-section flow quality and wind effects associated with the tunnel inlet. Exit effects were minimized by employing high discharge velocities. The basic inlet, with a 13:6:1 contraction ratio, was varied by employing a set of screens, a removable honeycomb, and a removable inlet lip. Wind- to test-section-velocity ratios varied from 0.35 to 0.50.

The following result was obtained for one configuration which was not sensitive to external winds:

1. An inlet configuration with a honeycomb, five screens, and an inlet lip produced a test-section flow quality having speed fluctuations less than 0.3 meter per second (1 ft/sec), angularity oscillations less than 0.25°, and a uniform velocity profile for wind angles ranging from 0 to 180°.

The following results were obtained for inlet configurations which were sensitive to external winds:

2. A transient wind parallel to the tunnel axis produced unsteady speed and angularity oscillations in the test section. These oscillations appeared to be random in time and across the test section. Oscillations of the average test-section speed were not evident.

3. For every inlet configuration tested, the test-section flow quality remained unchanged as the wind angle was varied from 0 to 45° relative to the tunnel axis.

4. At large wind angles (90° or greater) the honeycomb was required to remove swirl.

5. Test-section flow disturbances produced by wind angle effects occurred primarily on the windward side of the test section. Nonuniform velocity profiles were produced by large speed fluctuations and hence were unsteady.

6. The largest flow disturbances were recorded at wind angles between 120° and 135°.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 14, 1972,
741-72.

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TABLE I. - INLET CONFIGURATIONS

[Contraction ratio, 13.6:1.]

Number of screens	Honeycomb	Inlet lip	Data figures
5	Off	On	5, 6, 8
3	Off	On	5, 6
1	Off	On	5, 6
5	On	On	4, 5, 6, 8
4	On	On	5, 6, 8
3	On	On	5, 6, 8
2	On	On	5, 6, 7, 8
3	On	Off	8
2	On	Off	8

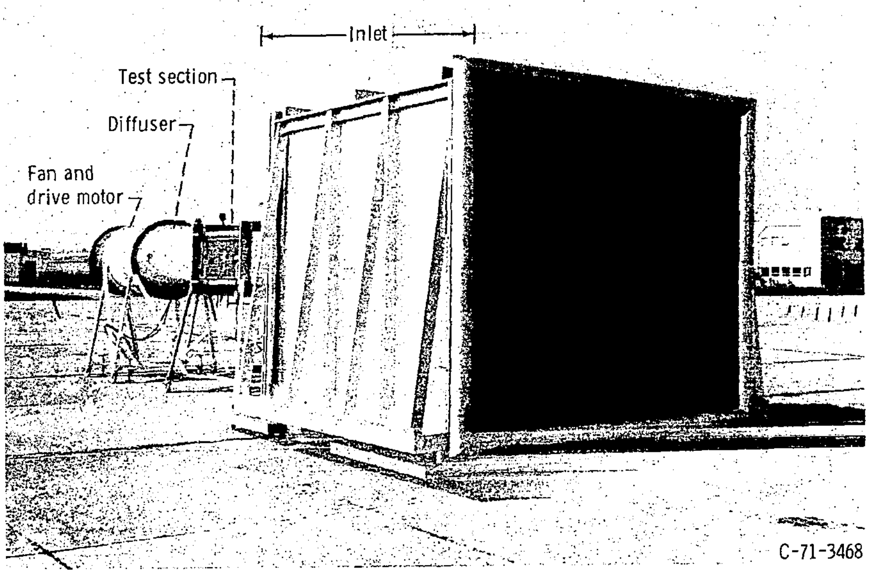


Figure 1. - Three-fourths view of open-circuit wind-tunnel model.

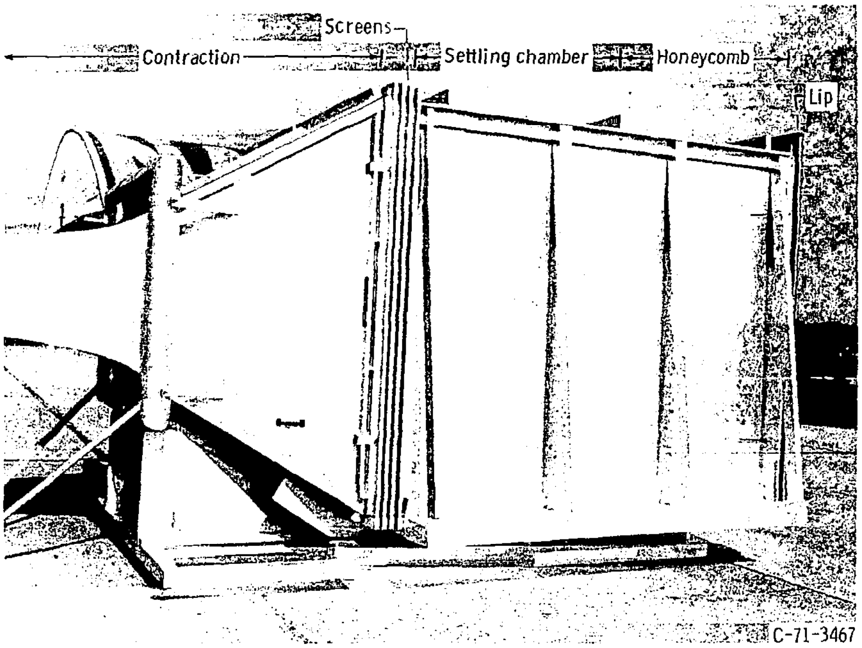


Figure 2. - Side view of inlet configuration.

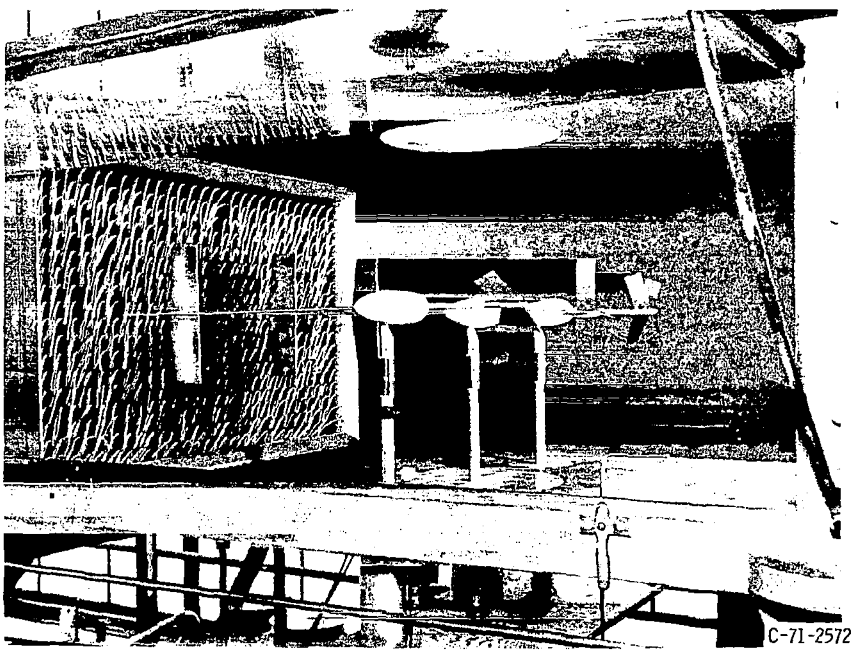
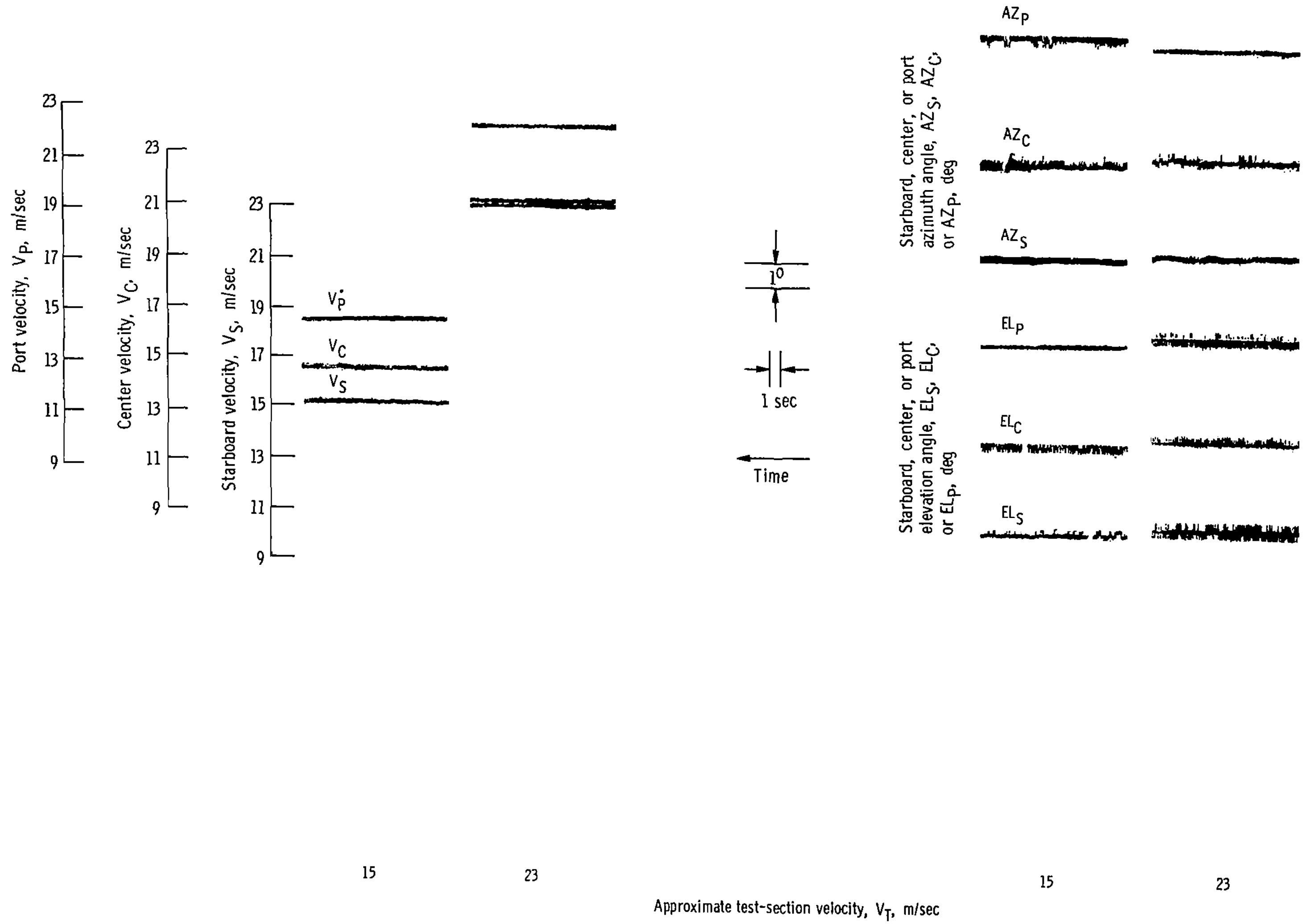


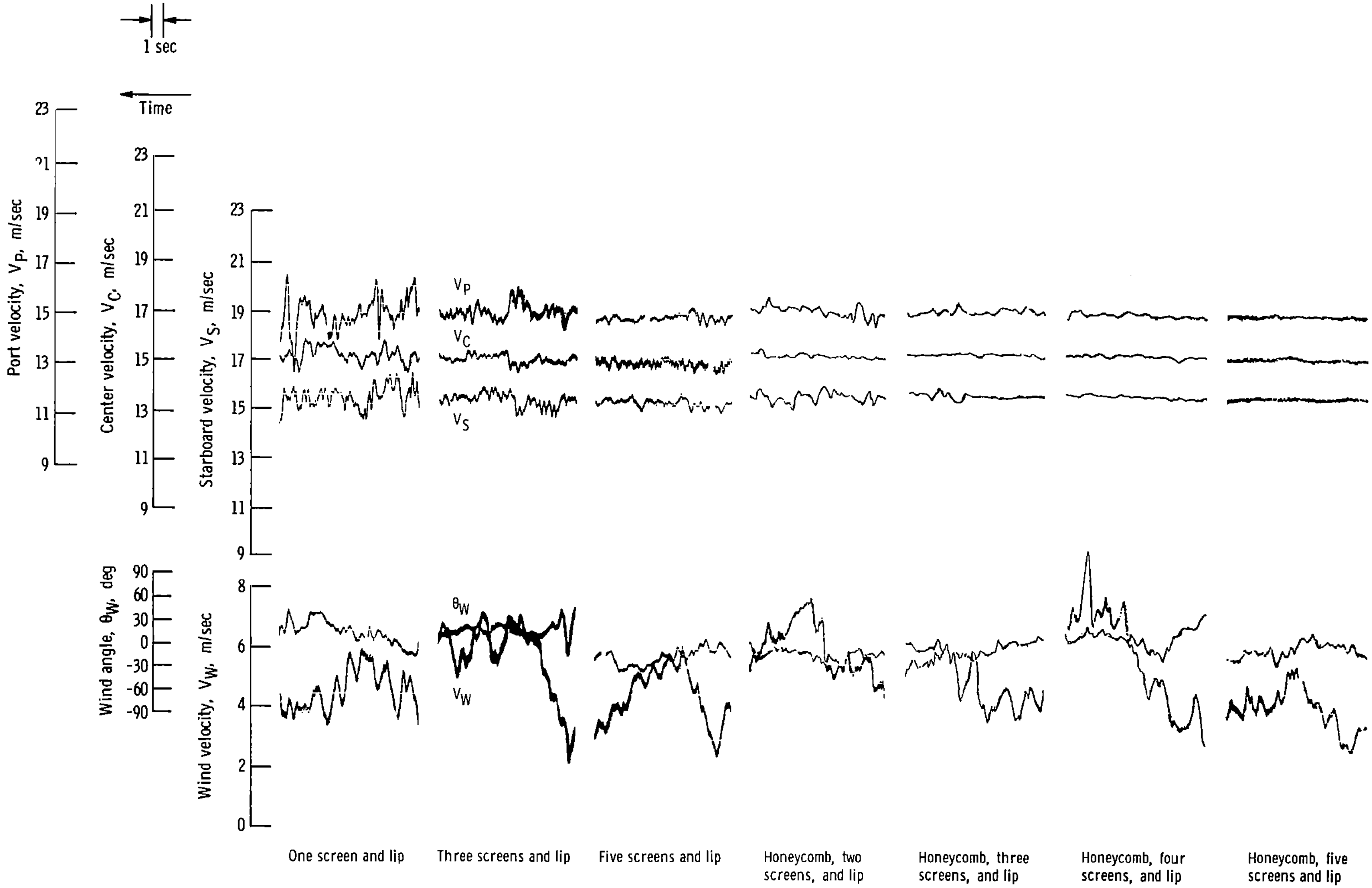
Figure 3. - Anemometers mounted in test section.



(a) Speed.

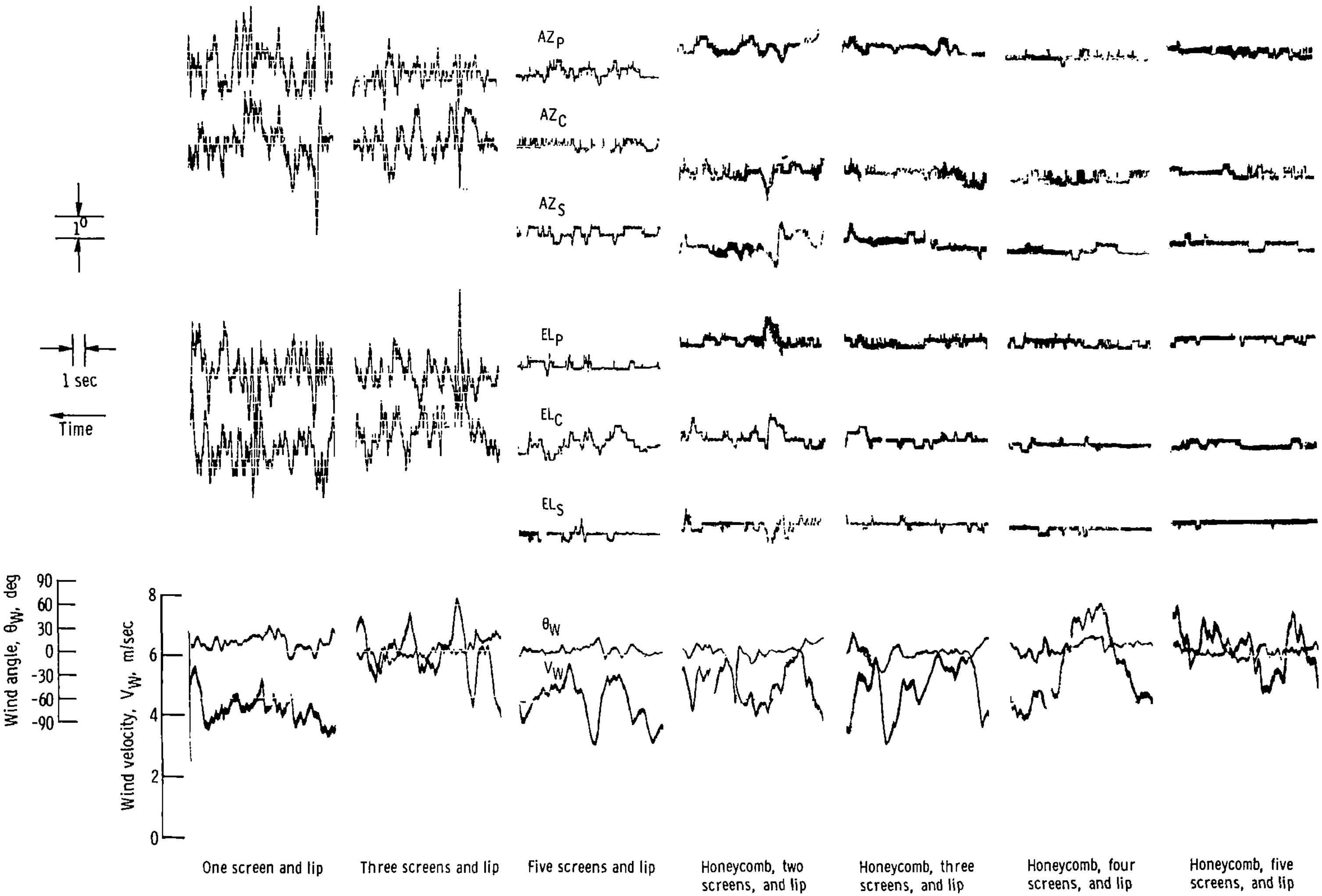
(b) Angularity.

Figure 4. - Reference test-section flow quality. Inlet configuration, honeycomb, five screens, and lip; wind velocity, zero.



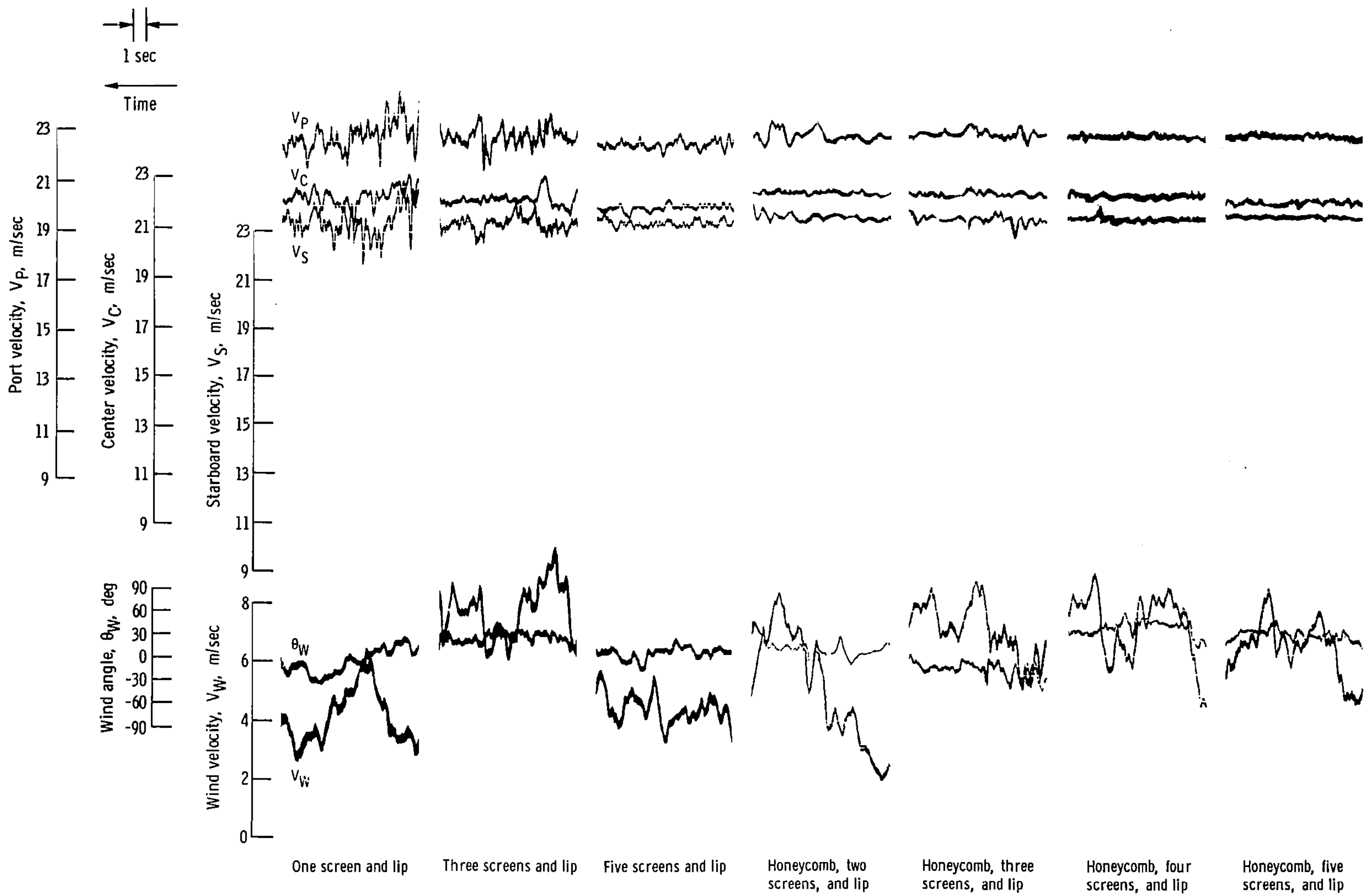
(a) Speed.

Figure 5. - Effect of inlet configuration on test-section flow quality for winds parallel to tunnel axis. Test-section velocity, approximately 15 meters per second.



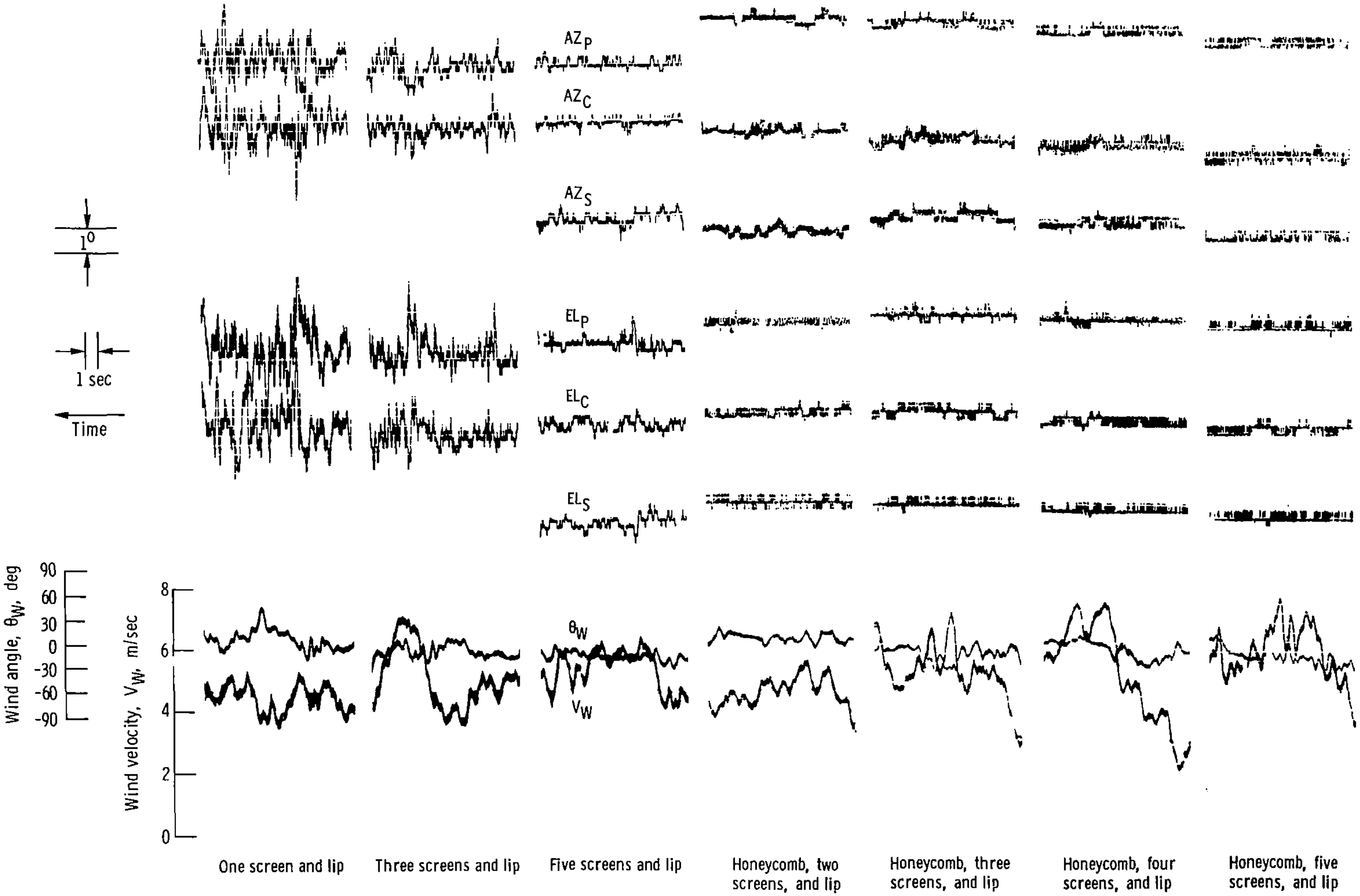
(b) Angularity.

Figure 5. - Concluded.



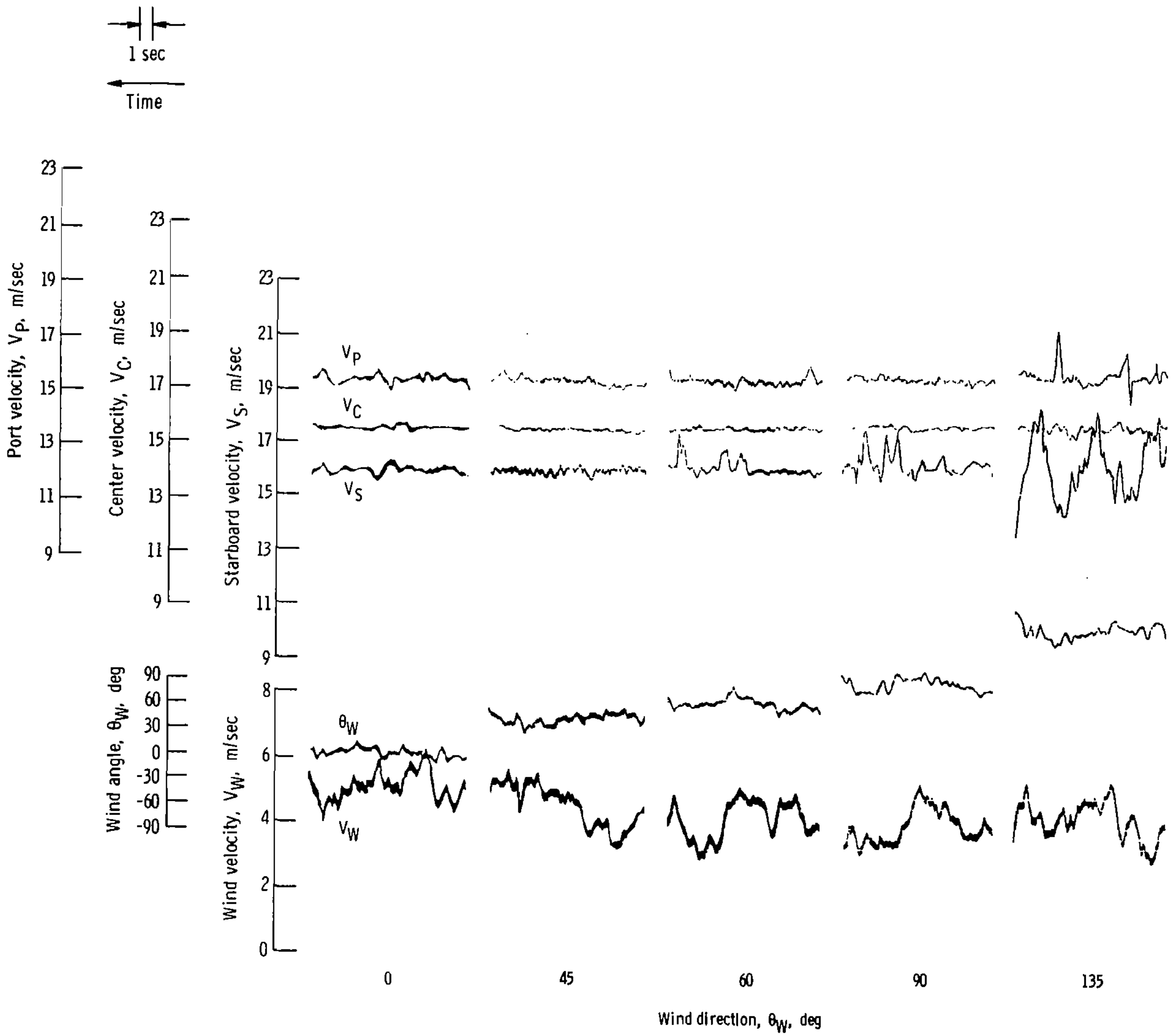
(a) Speed.

Figure 6. - Effect of inlet configuration on test-section flow quality for winds parallel to tunnel axis. Test-section velocity, approximately 23 meters per second.



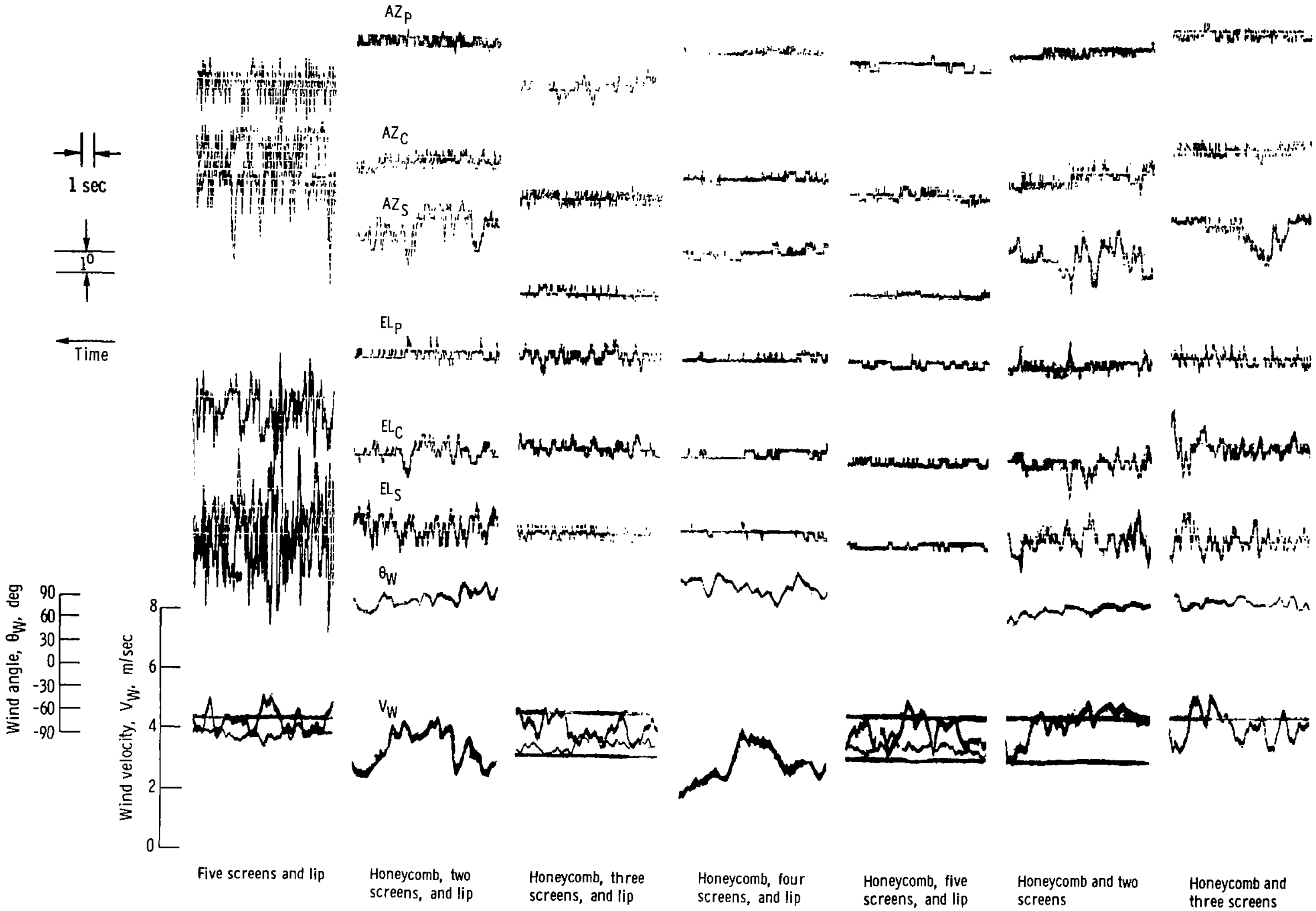
(b) Angularity.

Figure 6. - Concluded.



(a) Speed.

Figure 7. - Effect of wind angle on test-section flow quality. Inlet configuration, honeycomb, two screens, and lip; test-section velocity, approximately 15 meters per second.



(b) Angularity.

Figure 8. - Concluded.

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