95

WIND ENGINEERING STUDY OF

GEORGETOWN FACTORY STORES

by

Dr. David E. Neff

Dr. Robert N. Meroney

for

Mr. Wallace Yaffe

Chandler Properties

189 Wells Avenue

Newton, MA 02159

FLUID MECHANICS AND WIND ENGINEERING PROGRAM

Colorado State University

CSU Contract No. 53-6066

CER94-95-DEN-RNM-2

February 1995

WIND ENGINEERING STUDY OF GEORGETOWN FACTORY STORES

Prepared by

David E. Neff

FINAL REPORT
(February 1995)

for
Mr. Wallace Yaffe
Chandler Properties
189 Wells Avenue
Newton, MA 02159

FLUID MECHANICS AND WIND ENGINEERING PROGRAM

Colorado State University

EXECUTIVE SUMMARY

This report summarizes the results of a wind tunnel study on the performance of various wind fences designed to reduce pedestrian discomfort in and around the customer parking areas of the Georgetown Factory Stores. A 1:192 scale model of the Phase I development of the Georgetown Factory Stores was constructed and placed into a wind tunnel facility capable of reproducing atmospheric wind patterns. Wind speeds were measured at 35 locations for five critical wind directions with and without various wind fence arrangements in the parking, plaza and road areas. The overall wind environment in and around the Georgetown Factory Stores is expressed as percent of approach wind speeds that presently exist at the site without structures and landscaping. The benefit of the various fences were expressed as the percent reduction in wind speed that they achieved versus the no fence configuration.

The test results indicate that with the present site design average wind conditions in the parking and plaza areas would be of the order of 70-90 percent of the speeds approaching the site. The placement of 6 foot parking area fences reduced average wind speeds in the parking areas to ~ 20-40 percent of approaching winds. The placement of 4 foot wind screens in the plaza area in front of building C and increasing the frontal parapet heights from 4 to 8 feet reduced average wind magnitudes from 80 percent to below 20 percent of the approach flow in the vicinity of the main entrances on building C. The placement of a 16 foot wind screen between units C and D reduced average wind magnitudes from 70 percent to below 30 percent of the approach flow in this area. Wind magnitudes in the roadway paralleling the store front area remained fairly high (60-70 percent) under the present mitigation strategies. The landscape islands between the parking areas and this roadway should contain as many tall trees and bushes as possible, i.e., handicap parking should be in main parking zone and trees should be plant in these island areas.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

A significant characteristic of modern building design is the use of pedestrian plazas in the vicinity of the buildings. This has brought about a need to consider the effects of wind and gustiness in the design of these areas. The building geometry itself may increase or decrease wind effects on and in the vicinity the structure. Wind forces may be modified by nearby structures which can produce beneficial shielding or adverse increases. The intensity and frequency of objectionable winds in pedestrian areas is influenced both by the structure shape and by the shape and position of adjacent structures. Information on sidewalk level gustiness allows plaza areas to be protected by design changes before the structure is constructed.

Techniques have been developed for wind-tunnel modeling of proposed structures which allow the prediction of wind velocities and gusts in pedestrian areas adjacent to the building. In general, the requirements are that the model and prototype be geometrically similar, that the approach mean velocity at the building site have a vertical profile shape similar to the full-scale flow, that the turbulence characteristics of the flows be similar, and that the Reynolds number for the model building be greater than a critical value. These criteria are satisfied by constructing a scale model of the structure and its surroundings and performing the wind tests in a wind tunnel specifically designed to model atmospheric boundary-layer flows.

The wind-engineering study is performed on a building or building group modeled at scales ranging from 1:200 to 1:400 (1:192 for this project). The structure is modeled in enough detail to provide accurate flow patterns in the wind passing over the building surfaces. The building under test is often located, in a surrounding where nearby buildings or terrain may provide beneficial shielding or adverse wind loading. To achieve similarity in wind effects the area surrounding the test building is also modeled. A flow visualization study is first made (smoke is used to make the air currents visible) to define overall flow patterns and identify regions where local flow features might cause difficulties in building design or produce pedestrian discomfort.

Based on the visualization (smoke) tests and on a knowledge of heavy pedestrian use areas, several locations (35) are chosen in the vicinity of the building where wind velocities can be measured to determine the relative comfort or discomfort of pedestrians in plaza areas, near building entrances, near building corners, or on sidewalks and parking areas. Data are recorded, analyzed and processed by an on-line computerized data-acquisition system. These velocities were measured at 5 different wind directions (140, 150, 160, 170, 180 degrees from north) and 6 different model shelter configurations. The ratio of these local wind speeds to the approach flow wind speed was documented. These data can be combined with wind frequency and direction information from local meteorological records (note: currently there are no accurate meteorological records in the Georgetown area) to estimate of the percent time certain velocities are exceeded.

2 PEDESTRIAN WIND ACCEPTABILITY CRITERIA

Interpretation of pedestrian wind speed data is aided by a description of the effects of wind of various magnitudes on people. The earliest quantitative description of wind effects was established by Sir Francis Beaufort in 1806 for use at sea and is still in use today. Several recent investigators have added to the knowledge of wind effects on pedestrians. These investigations along with suggested criteria for acceptance have been summarized by Penwarden and Wise (1975) and Melbourne (1978). The Beaufort scale (from Penwarden and Wise (1975)), based on mean velocity only, is reproduced in Table 1 including qualitative descriptions of wind effects. Table 1 suggests that mean wind speeds below 12 mph are of minor concern and that mean speeds above 24 mph are definitely inconvenient. Quantitative criteria for which the frequency at which certain wind magnitudes are acceptable (Melbourne, 1978) are shown on Figure 1. The peak gust curves shown in Figure 1 are the percent of time during which a short gust of the stated magnitude could occur (say about one of these gusts per hour).

To enable a quantitative assessment of the wind environment, the wind-tunnel data are combined with wind frequency and direction information obtained at the local airport. Table 2 shows wind frequency by direction and magnitude obtained from summaries published by the National Weather Service at the Denver Stapleton Airport. These data, usually obtained at an elevation of about 20-40 feet, are converted to velocities at the reference velocity height for the wind-tunnel measurements and combined with the wind tunnel data to obtain cumulative probability distributions (percent time a given velocity is exceeded) for wind velocity at each measuring location. The percentage times are summed by wind direction to obtain a percent time exceeded at each measuring position independent of wind direction (but accounting for the fact that the wind blows from different directions with varying frequency). These data are overlaid on to figure 1 to determine the level of wind acceptability at each measurement location.

The Georgetown Site is not well represented by the historical wind data in Denver and unfortunately no local site has sufficient data to formulate a wind direction and magnitude distribution. Thus the model data was analyzed as the ratio of location wind speed to the wind speed experienced in the unobstructed approach flow. In an open-country environment typical ratios of pedestrian to gradient wind speeds are 40 to 45 percent for mean values and 80 to 90 percent for the largest gust velocities, represented by the mean plus 3 rms's.

3 INSTRUMENTATION AND MEASUREMENT METHODOLOGY

An overview of laboratory measurement capabilities and techniques along with conversion methods used to convert measured model quantities to their meaningful field equivalents are discussed in this section.

3.1 WIND TUNNEL FACILITIES

The Fluid Mechanics and Wind Engineering (FMWE) Program and the associated Fluid Dynamics and Diffusion Laboratory (FDDL) facilities are world recognized in the area of wind engineering. The laboratory has been among the world's most productive in research on wind environments, building aerodynamics, terrain aerodynamics, air pollution meteorology, pedestrian comfort, agricultural aerodynamics, and wind energy meteorology. In 1989 the National Society of Professional Engineers awarded the program for its distinguished research. Modern instrumentation and a variety of flow facilities support fundamental investigations on turbulence and turbulent diffusion. The FDDL has three large meteorological wind tunnels and seven smaller special purpose wind tunnels. Figure 2 shows the plan view layout of the FDDL laboratory facilities including the meteorological wind tunnel, environmental wind tunnel and industrial aerodynamics wind tunnel. All tunnels have a flexible roof adjustable in height to maintain a zero pressure gradient along the test section. The mean velocity can be adjusted continuously in each tunnel to the maximum velocity available.

The wind tunnel used for this investigation is the Environmental Wind Tunnel (EWT). A dimensional drawing of the EWT wind tunnel facility is shown in Figure 3. The EWT has a working section of 60 feet long and a cross section of 12 by 8 feet. This wind tunnel, especially designed to study atmospheric flow phenomena, incorporates special features such as an adjustable ceiling, a rotating turntable and a long test section to permit adequate reproduction of micro-meteorological behavior. Using wind speeds from 0 to 30 miles per hour, this facility provides excellent capability for investigation of wind effects on large areas.

The region upwind from the modeled area turntable is covered with a randomized roughness constructed using various sized cubes placed on the floor of the wind tunnel. Different roughness sizes may be used for different wind directions. Spires are installed at the test-section entrance to provide a thicker boundary layer than would otherwise be available. The thicker boundary layer permits a somewhat larger scale model than would otherwise be possible. The spires are approximately triangularly shaped pieces of 1/2-in. thick plywood 6 in. wide at the base and 1 in. wide at the top, extending from the floor to the top of the test section. They are placed so that the broad side intercepts the flow. A barrier is placed on the test-section floor downstream of the spires to aid in development of the boundary layer flow.

The distribution of the roughness cubes and the spires in the roughened area is designed to provide a boundary-layer thickness of approximately 5 feet and a velocity profile power-law exponent similar to that expected to occur in the region approaching the modeled area for each wind direction (a number of wind directions may have the same approach roughness). The wind-tunnel ceiling is adjusted after placement of the model to obtain a zero pressure gradient along the test section.

3.2 APPROACH FLOW VELOCITY MEASUREMENT TECHNIQUE

Mean velocity and turbulence intensity profiles are measured upstream of the model to determine that an approach boundary-layer flow appropriate to the project site has been established. Reference wind tunnel velocity measurements are made during each test so that variations in testing wind speed can be removed from the data.

Pitot-static probes are used as a velocity standard during the calibration of the different hot film systems and to provide the reference velocity measurements. The principles of operation of pitot-static probes are described in any fundamental text on fluid mechanics and will not be discussed in detail here. The operational relationship for these probes is $U = (2g_c\Delta P/\rho)^{1/2}$, where U = velocity, g_c = gravitational conversion constant, ΔP = difference between static and stagnation pressures, and ρ is the air density. ρ is calculated from ideal gas law and ΔP is measured using an MKS Electronic Manometer. The pitot-static probe measurements are accurate to within $\pm$ 2 percent of the actual velocity.

A Thermo Systems Inc. constant temperature anemometer (TSI 1050) along with a single-hot-film sensor (TSI 1220) are used to document the longitudinal turbulence levels. During calibration the probe voltages are recorded at several velocities covering the range of interest. These voltage-velocity (E,U) pairs are then regressed to the equation $E^2 = A + BU^c$ via a least squares approach for various assumed values of the exponent c. Convergence to the minimum residual error was accelerated by using the secant method to find the best new estimate for the exponent c. The hot-film-probe is mounted on a vertical traverse and positioned over the measurement location in the wind tunnel. The anemometer's output voltage is digitized and stored within an IBM AT computer. This voltage time series was converted to a velocity time series using the inverse of the calibration equation; $U = [(E^2\text{-}A)/B]^{1/c}$. The velocity time series is then analyzed for pertinent statistical quantities, such as mean velocity and root-mean-square turbulent velocity fluctuations. The computer system moves the velocity probe to a vertical position, acquire the data, then moves on to the next vertical positions, thus obtaining an entire vertical velocity profile automatically. The calibration curve yields hot film anemometer velocities that were always within 2 percent of the known calibrator velocity. Considering the accumulative effect of calibrator, calibration curve fit and other errors the model velocity time series should be accurate to within 5 percent. A flow-logic chart of velocity calibration system, velocity measurement system, and the positioning system within the wind tunnel is displayed in Figure 4.

The variation of mean wind speed with height above the ground (referred to as the boundary layer) at the study site is deduced from empirical equations known to correlate atmospheric data. The log-linear velocity profile relationship should be used for heights up to 100 meters. This relationship is expressed as:

$$U/u_* = 2.5 * \ln[(z-d)/z_o]; \qquad (1)$$

where u_* = friction velocity,
d = displacement height,
z_o = roughness length.

Several references suggested values of the roughness length for various types of ground cover. A roughness length of 0.2 to 0.4 meters is an appropriate value for wind approaching a typical suburban site.

The mean velocity through the entire depth of the boundary layer is represented by the power law equation:

$$U/U_\infty = (z/\delta)^p \; ; \tag{2}$$

where U = mean wind speed at height z,
U_∞ = wind speed at boundary layer height δ,
δ = boundary layer height = 600 meters
p = power law index.

A power law index of ~0.2 is an appropriate value for wind approaching a typical suburban site.

Velocity measurements obtained in this study are summarized and presented through plots of vertical profiles of mean velocity and longitudinal turbulence intensity. The velocity coordinates are normalized by a reference model velocity at a reference height. Since a neutral boundary layer's velocity is invariant with respect to wind speed, the normalized profiles can be converted to any field velocity at a specific height by the appropriate multiplicative constant.

3.3 PEDESTRIAN WIND SPEED MEASUREMENT TECHNIQUE

Mean velocity and turbulence intensity measurements are made near model pedestrian surfaces at several locations on and near the building for the configurations and wind directions desired. The surface measurements are indicative of the wind environment to which a pedestrian at the measurement location would be subjected. The locations are chosen to determine the degree of pedestrian comfort or discomfort at the building corners where relatively severe conditions are frequently found, near building entrances and on adjacent sidewalks where pedestrian traffic is heavy, and in open plaza areas. In most studies a reference pedestrian position, located about a block away, is also tested. These data are helpful in evaluating the degree of pedestrian comfort or discomfort in the proposed plaza area in terms of the undisturbed environment in the immediate vicinity.

Measurements are made with either a single hot-wire anemometer mounted with its axis vertical or with Irwin pedestrian velocity sensors mounted into the model. When pedestrian velocity data are taken with a vertical wire the wire is calibrated via the same techniques discussed in the section on approach flow measurements. When pedestrian velocity data are taken with Irwin sensors mounted into model surfaces a pressure data acquisition system is employed. Figure 5 displays the geometry and typical calibration of the Irwin sensors utilized. Figure 6 displays a schematic of the data acquisition system which measures the differential pressure generated by each of the Irwin sensors. This differential pressure is related to the pedestrian wind speeds via a previously obtained calibration against a vertical axis hot-film sensor in an undisturbed environment (smooth floor area).

The individual Irwin sensors are connected (see Figure 6) to four forty-eight port pressure switching valves mounted near the model via 0.0625 inch I.D. plastic tubing. The four pneumatic outputs from these valves are connected to the dynamic and reference sides of two differential pressure transducers via short lengths of plastic tubing. The pressure transducers used are the Honeywell Microswitch with a 0.18 psid range. The computer controls a stepper motor which changes the position of all four multi-port pressure valves simultaneously. The computer keeps track of switch positions and a digital readout of position is provided at the wind tunnel.

Outputs from these four pressure transducers along with a pressure transducer signal monitoring the free stream pitot probe are low pass filtered and sent on to an on-line data acquisition system consisting of an IBM AT computer with a Data Translations analog to digital conversion board. The data are processed immediately and stored for printout or further analysis. All four transducers are recorded simultaneously for 40 seconds at a 100 sample-per-second rate. The tubing system frequency response was tuned to create the highest flat frequency response possible. A longer tubing system results in a lower frequency response. The tubing length required in these tests was 180 cm and the maximum frequency response was tuned to 25 Hz. The pressure transducer outputs for these tests were low pass filtered at 30 Hz.

3.4 VISUALIZATION TECHNIQUES

Flow visualization in the vicinity of the model is helpful in;

i) understanding and interpreting mean and fluctuating velocities,
ii) defining zones of separated flow and reattachment and zones of vortex formation where turbulence may be expected to be high, and
iii) indicating areas where pedestrian discomfort may be a problem.

Smoke is released from sources on and near the model to make the flow lines visible to the eye and to make it possible to obtain motion picture records of the tests.

A video camera system was used to document flow visualization. Phenomena observed over the model in the wind tunnel will occur faster than that observed at full scale. Given a model to field length scale ratio of 1:192 then the time scale ratio between the field and the model is the 192. If the TV tapes were replayed in slower motion (192 times slower than the recorded speed) the observed trajectories and motions would appear realistic.

3.5 MODELING WIND FLOW PHYSICS

Wind-tunnel model tests must satisfy certain similarity criteria in order to be representative of field conditions. The approach flow needs to be dynamically similar between model and prototype. This will be achieved if the wind approaching the model has the same value for the main nondimensional flow parameters as the prototype flow and geometry of surfaces approaching the site are properly scaled. In the present study the main flow parameter is represented by;

$$\text{Reynolds Number} = U_H L/\nu, \tag{3}$$

where U_H = reference wind speed,
L = reference length,
ν = kinematic viscosity of air,

The Reynolds number relates the relative ratio of inertial and viscous forces in the flow. It is impossible and/or undesirable to match the field and model Reynolds number in the present case. It is well established that flows over sharp edged objects are independent of Reynolds numbers, for moderately high Reynolds numbers. The Reynolds number was greater than this critical value for all tests. Wind tunnel studies conducted in boundary-layer flows require proper scaling of the prototype boundary layer approaching the study site. This is verified via comparison of measured wind tunnel mean wind and turbulence approach profiles and expected atmospheric profiles for the conditions being modeled.

4 EXPERIMENTAL CONFIGURATION AND PROCEDURES

4.1 Wind Tunnel and Flow Conditions

This portion of the study was performed in the Environmental Wind Tunnel facility described previously in the section on Instrumentation. The wind tunnel setup for this project is depicted in Figure 7. Figure 8 displays the mean velocity and turbulence intensity profiles of the modeled flow along with the curves indicating the ANSI Exposure A, B, and C classifications. The model wind profile approaching the site was representative of a field exposure classification between B and C. The scope of the current project did not permit the modeling of the mountainous topography and its resultant local wind conditions approaching the site. All five wind directions, 140, 150, 160, 170, and 180 degrees from north, used this same approach wind profile.

4.2 Building Model

In order to obtain an accurate assessment of local velocities, models are constructed to the largest scale that does not produce significant blockage in the wind-tunnel test section. The models are constructed of foam, masonite and plastic. Significant variations in the building surface, such as mullions, are attached or machined into the model surface. Irwin pedestrian velocity sensors are placed in areas that need investigation.

A circular area, 1200 feet in radius, of the surrounding buildings and terrain is modeled in detail. Structures within the modeled region are made from Styrofoam and cut to the individual building geometries. They are mounted on the wind tunnel turntable in their proper locations. Significant terrain features are included as needed. The model is mounted on a turntable near the downwind end of the wind tunnel test section. Any buildings which do not fit on the turntable are placed on removable pieces upwind of the turntable for the appropriate wind directions. A overall plan view of the building and its surroundings is shown in Figure 9. Figure 10 shows the arrangement of model fences and sensor locations in the plaza areas around building units C and D. A photograph of the completed model in the wind tunnel is shown in Figure 11.

4.3 Pedestrian Wind Speed Measurement Methodology

Pedestrian velocities were measured at 35 locations using Irwin sensors. The placement of these measurement locations relative to the Georgetown Factory Stores is shown in Figures 9 and 10. These Irwin sensors were connected to two pressure transducers through four 48 port scanivalves driven by a stepping motor and a controller interfaced with an IBM-AT based control/data acquisition system, Figure 6. For each test case, the mean, peak and rms velocity were measured. The two pressure transducers electrical outputs were recorded for 40 seconds at a 100 sample-per-second rate. The tubing system frequency response was tuned to create the highest flat frequency response possible. A longer tubing system results in a lower frequency response. The tubing length required in these tests was 180 cm and the maximum frequency response was tuned to 25 Hz. The pressure transducer outputs for these tests were low pass filtered at 30 Hz. The sampling frequency and sample time duration were demonstrated by repeat testing to give stable results.

5 RESULTS AND CONCLUSIONS

Six configurations of differing wind screen heights and wind screen positions were studied. For each of these configurations pedestrian wind speed measurements were obtained at 35 locations for five wind directions (140, 150, 160, 170, and 180 degrees from north). The testing program run conditions are summarized in Table 3. The wind screen height at different rows and placements (parking, plaza, road) are listed for each configuration in Table 3. Figures 9 and 10 show the location of the referenced wind screen row numbers along with measurement locations.

The first configuration (see Table 3) was the base condition of no protective wind screen fences at the site. Configurations 2 and 3 tested the effectiveness of placing 4 and 8 foot wind screens in the parking areas. Configuration 4 tested the additional effectiveness (over that of parking area only wind screens) of 4 foot high wind screen placements in the plaza areas. Configuration 5 tested the additional effectiveness (over that of Config. #4) of placement of a 16 foot wall between Units C and D as well as employing an 8 foot parapet height on the front sides of Units C and D. Configuration 6 tested the additional effectiveness (over that of Config. #5) of placement of 4 foot fences placed across the road between the plaza and parking areas.

The pedestrian wind speed data is presented two ways, 1) each measured wind speed value is normalized w.r.t. the unimpeded wind speed (sensor #1) approaching the site, and 2) each measured wind speed value is normalized w.r.t. that measured, at the same location, with no protective wind screen present (configuration #1).

5.1 Pedestrian Wind Speeds as Percentage of Approach Winds

The pedestrian mean wind speed percentages of the wind speed in the unobstructed approach flow (sensor #1) are listed in Tables 4 through 9 for each configuration. The pedestrian largest effective gust velocity data (mean plus three times the root-mean-square) percentages of the gust velocity data in the unobstructed approach flow (sensor #1) are listed in Tables 10 through 15 for each configuration. The minimum, average, and maximum mean velocity, over the five wind directions tested, are graphically presented in figures 12 through 17 for each configuration.

The maximum mean velocity, at each location over the five wind directions, for configurations 1, 2, and 3 are graphically presented in figure 18. The average mean velocity, at each location over the five wind directions, for configurations 1, 2, and 3 are graphically presented in figure 19.

5.2 Pedestrian Wind Speeds as Percentage of No Wind Screen Condition

The percentage reduction of pedestrian mean wind speed, for configurations 2 through 6, over that of the wind speed measured with no wind screen fencing, configuration 1, are listed in Table 16. Figure 20 shows the *maximum*, over all 5 wind directions, of the wind speed reduction achieve by configurations 2 through 6. Figure 21 shows the comparison for the *average* over all 5 wind directions.

5.3 Discussion

Configuration 1 - Existing Site Plan Base Conditions

The test results shown in figure 12 indicate that with the present site design average wind conditions in the parking and plaza areas would be of the order of 70-90 percent of the speeds approaching the site.

Configurations 2 and 3 - Parking Area Improvements

Relating the measurement positions shown in figures 18 and 19, which present data normalized w.r.t. the upwind conditions, to their physical locations shown in figure 9 one sees that the wind screens in the parking areas effectively reduce winds in this area. Figure 19, for the average wind magnitudes over the five tested wind directions shows reductions from ~70-90 percent without fences to 20-30 percent for 8' fences and 30-50 percent for 4' fences. Relating the measurement positions shown in figures 20 and 21, which present data normalized w.r.t. the no fence condition, to their physical locations shown in figure 9 one sees that the parking area fences generally achieve a 40 to 80 percent reduction in the average and 30 to 70 in the maximum pedestrian wind speeds over that which would be experienced without fences. Parking area fences do an effective job of reducing winds in the parking areas and do not generate detrimental effects elsewhere. The wind magnitudes near the main entrance in front of building C are always relatively high for configurations 2 and 3.

Configurations 4, 5 and 6 - Plaza/Road Area Improvements

Figure 15, displaying data for configuration 4, shows that the placement of 6 foot parking area fences reduced average wind speeds in the parking areas to ~20-40 percent of approaching winds. The placement of 4 foot wind screens in the plaza area in front of building C and increasing the frontal parapet heights (see figure 10) from 4 to 8 feet reduced average wind magnitudes from 80 percent to below 20 percent of the approach flow in the vicinity of the main entrances on building C. The placement of a 16 foot wind screen between units C and D reduced average wind magnitudes from ~70 percent to below 30 percent of the approach flow in this area (compare locations 27,28 in figures 12 and 16). Relating the measurement positions shown in figures 20 and 21, which present data normalized w.r.t. the no fence condition, to their physical locations shown in figure 9 one sees that wind screens, as well as increased parapet height, will improve comfort levels in the plaza area substantially (see position 32).

Wind magnitudes in the roadway paralleling the store front area remained fairly high (60-70 percent) under the present mitigation strategies (see locations 30,31,33,34 in figures 16,17). The landscape islands between the parking areas and this roadway should contain as many tall trees and bushes as possible, i.e., handicap parking should be in main parking zone and trees should be plant in these island areas.

REFERENCES

American Society of Civil Engineers and American National Standards Institute, "Minimum Design Loads for Buildings and Other Structures," ANSI/ASCE 7-88, 1988.

Cermak, J. E. , "Laboratory Simulation of the Atmospheric Boundary Layer," AIAA Jl., Vol-9, September 1971.

Cemak, J. E. , "Aerodynamics of Buildings," Annual Review of Fluid Mechanics, Vol. 8, 1976, pp. 75-106.

Hollister, S. C., "The Engineering Interpretation of Weather Bureau Records for Wind Loading on Structures," Building Science Series 30--Wind Loads on Buildings and Structures, National Bureau of Standards, 1970, pp. 151-164.

Melbourne, W. H., "Criteria for Environmental Wind Conditions," JI. Industrial Aerodynamics, Vol. 3, 1978, pp. 241-247.

Penwarden, A. D. and Wise, A. F. E., "Wind Environment Around Buildings," Building Research Establishment Report, HMSO, 1975.

FIGURES

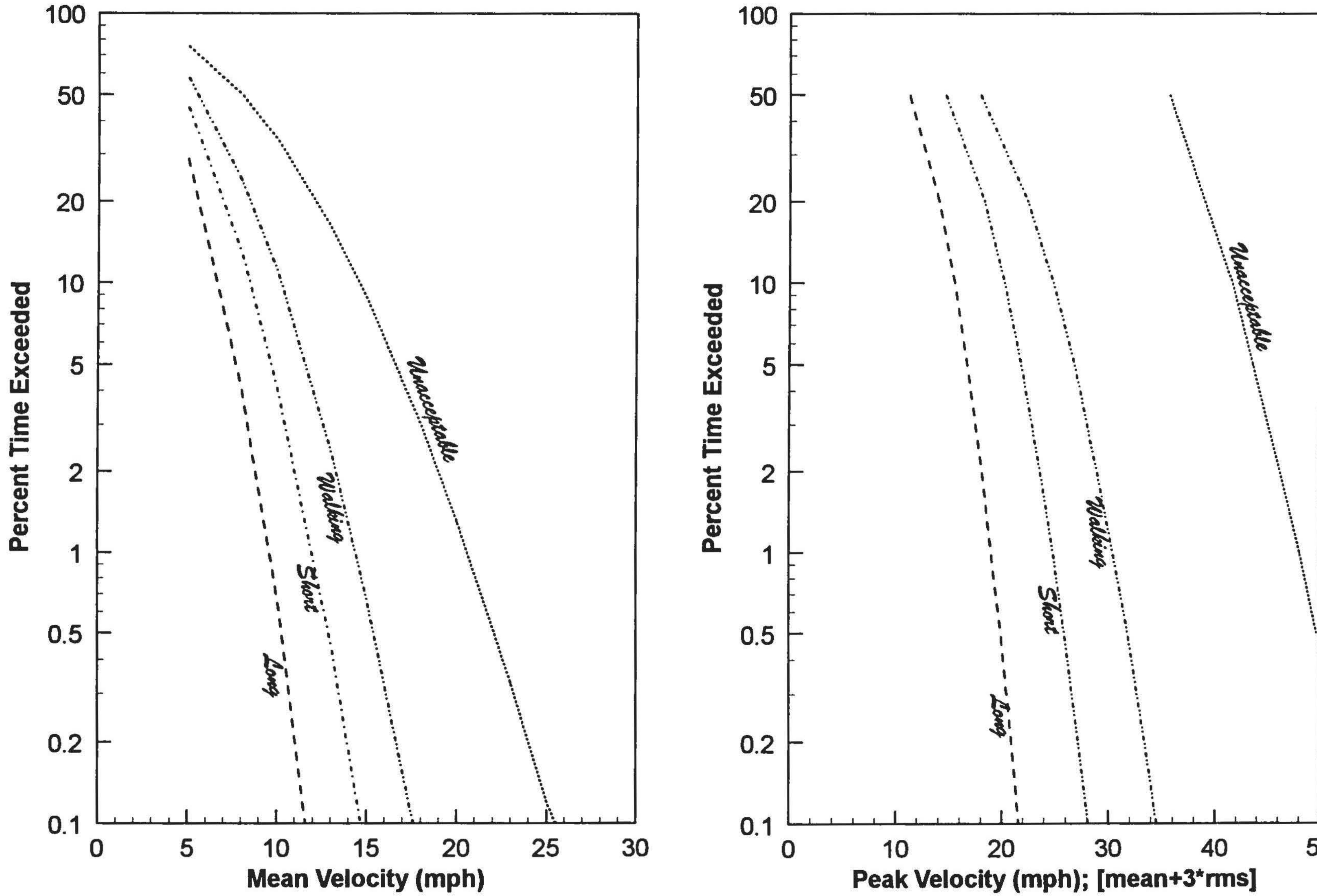


Figure 1 Pedestrian Acceptability Criteria for Frequency of Wind Speeds

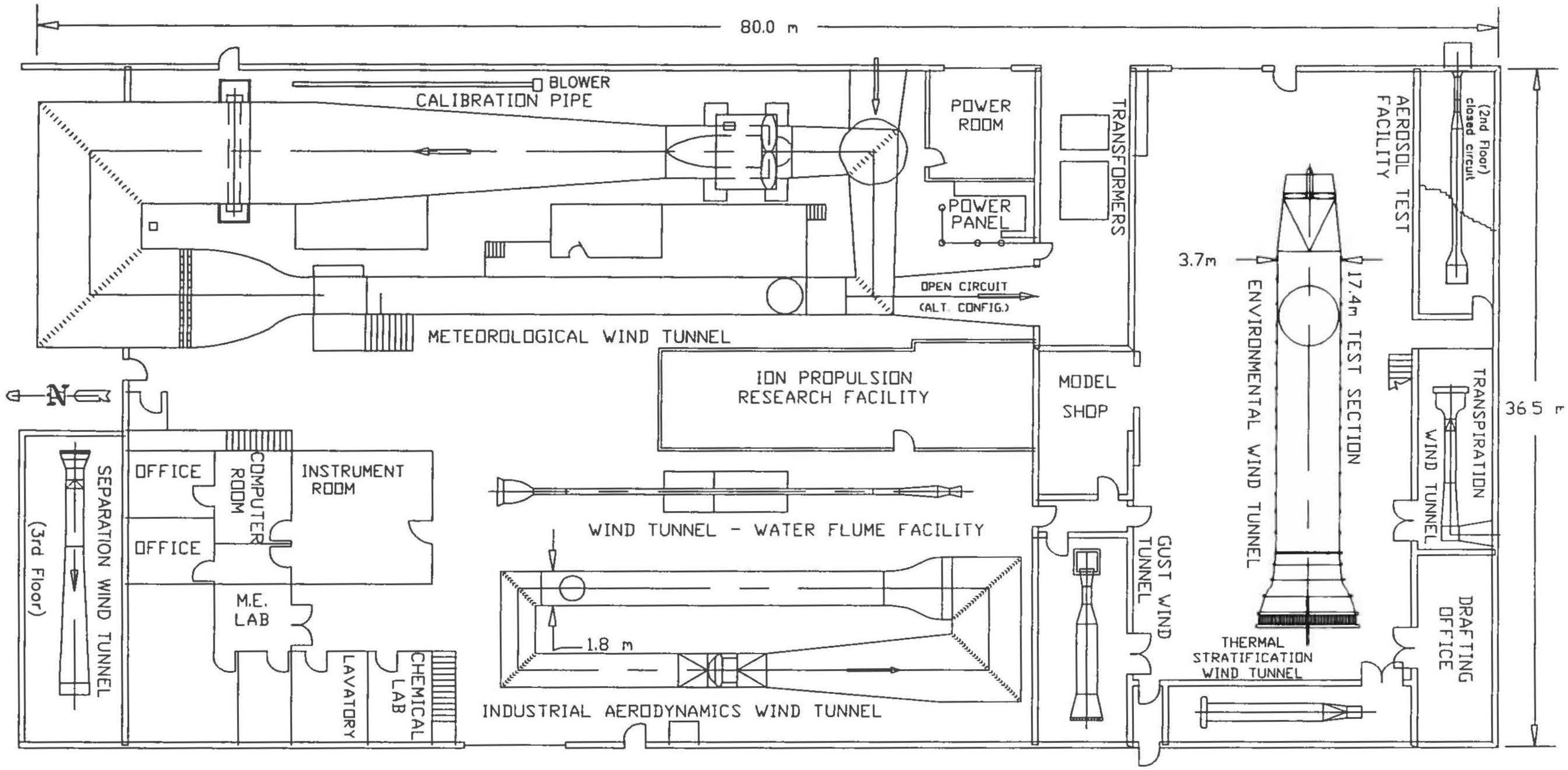


Figure 2 Fluid Dynamics and Diffusion Laboratory Floor Plan

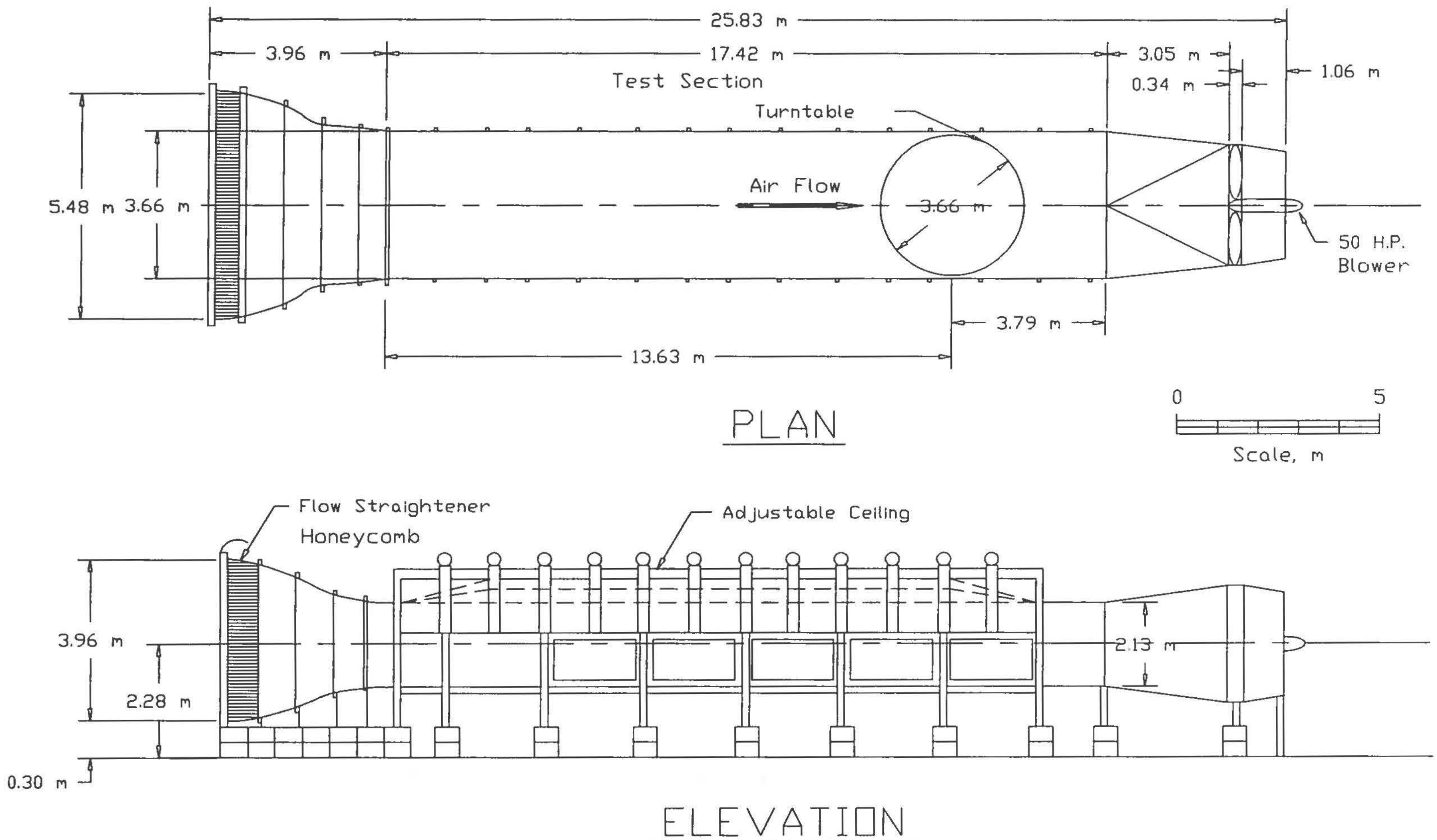


Figure 3 Environmental Wind Tunnel Testing Facility

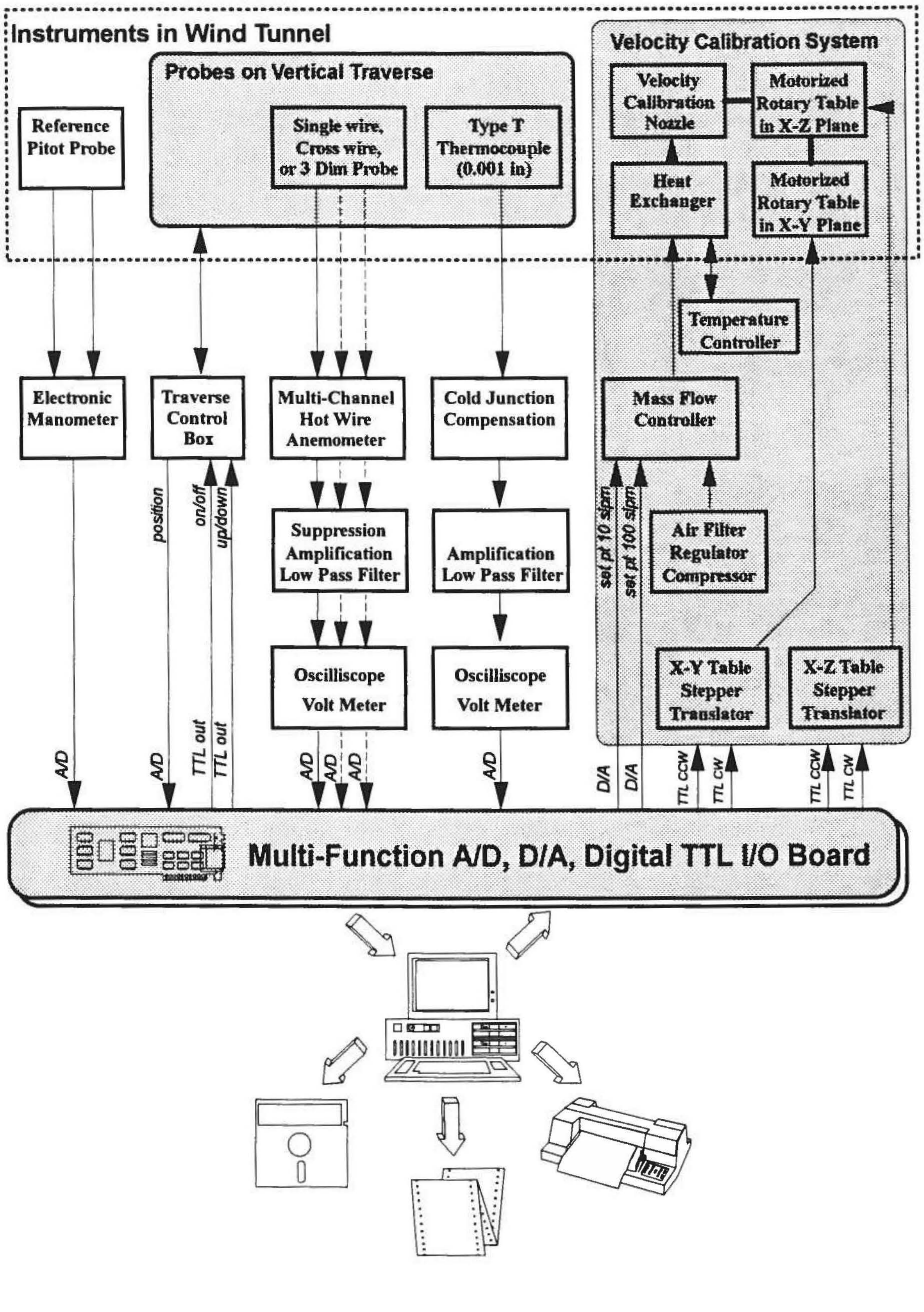
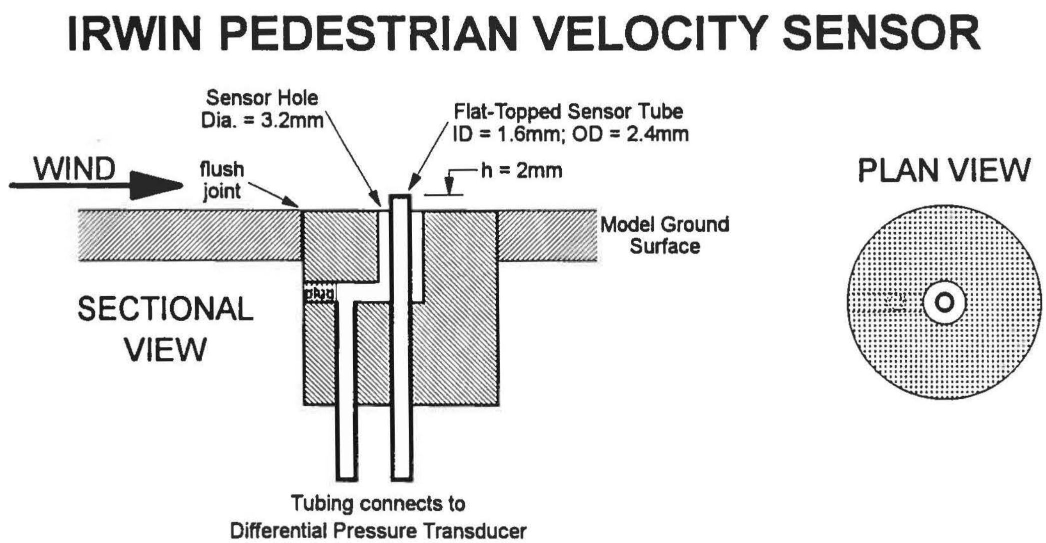


Figure 4 Approach Flow Velocity Measurement System



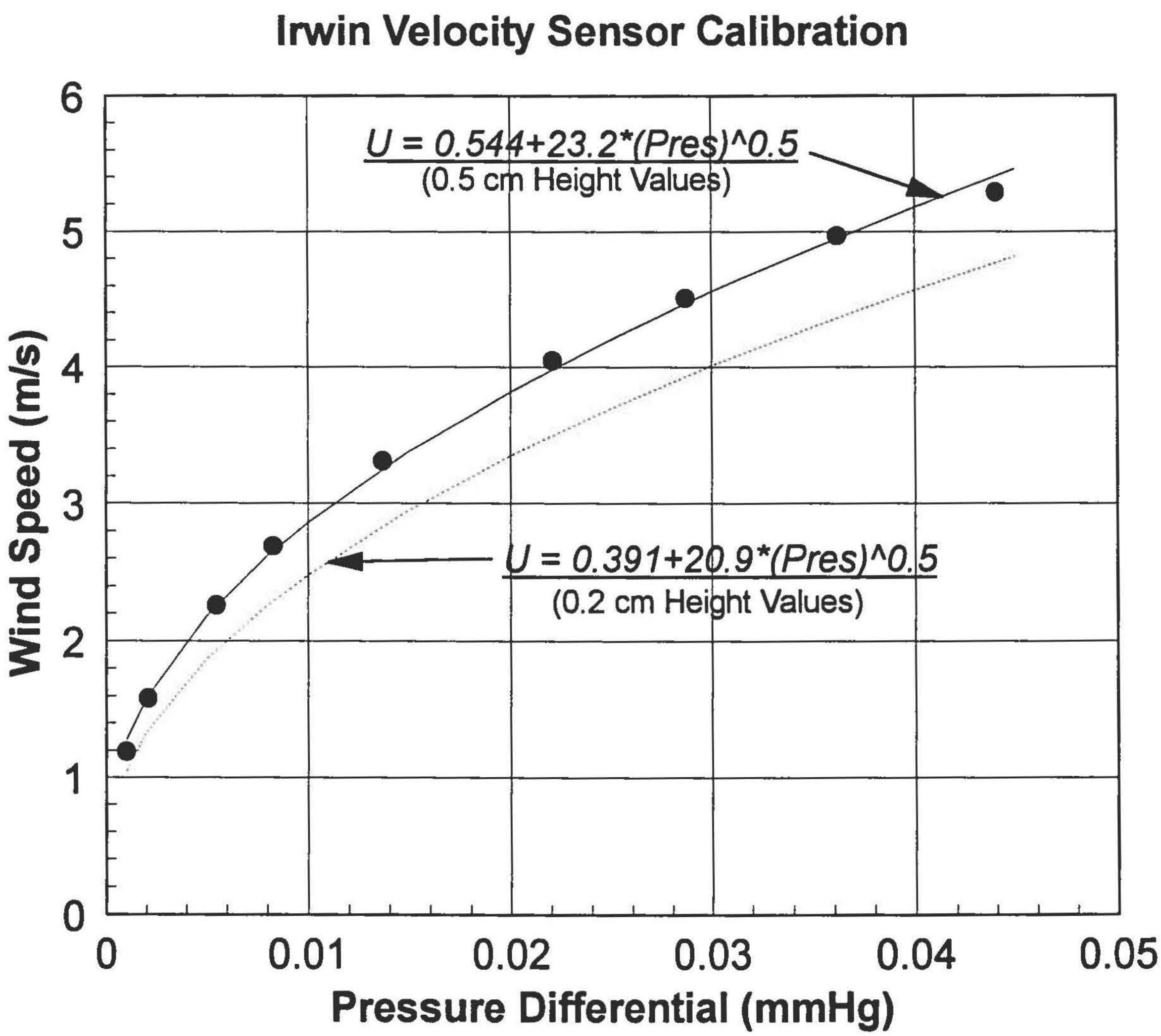


Figure 5 Irwin Pedestrian Velocity Measurement Sensor Geometry and Calibration

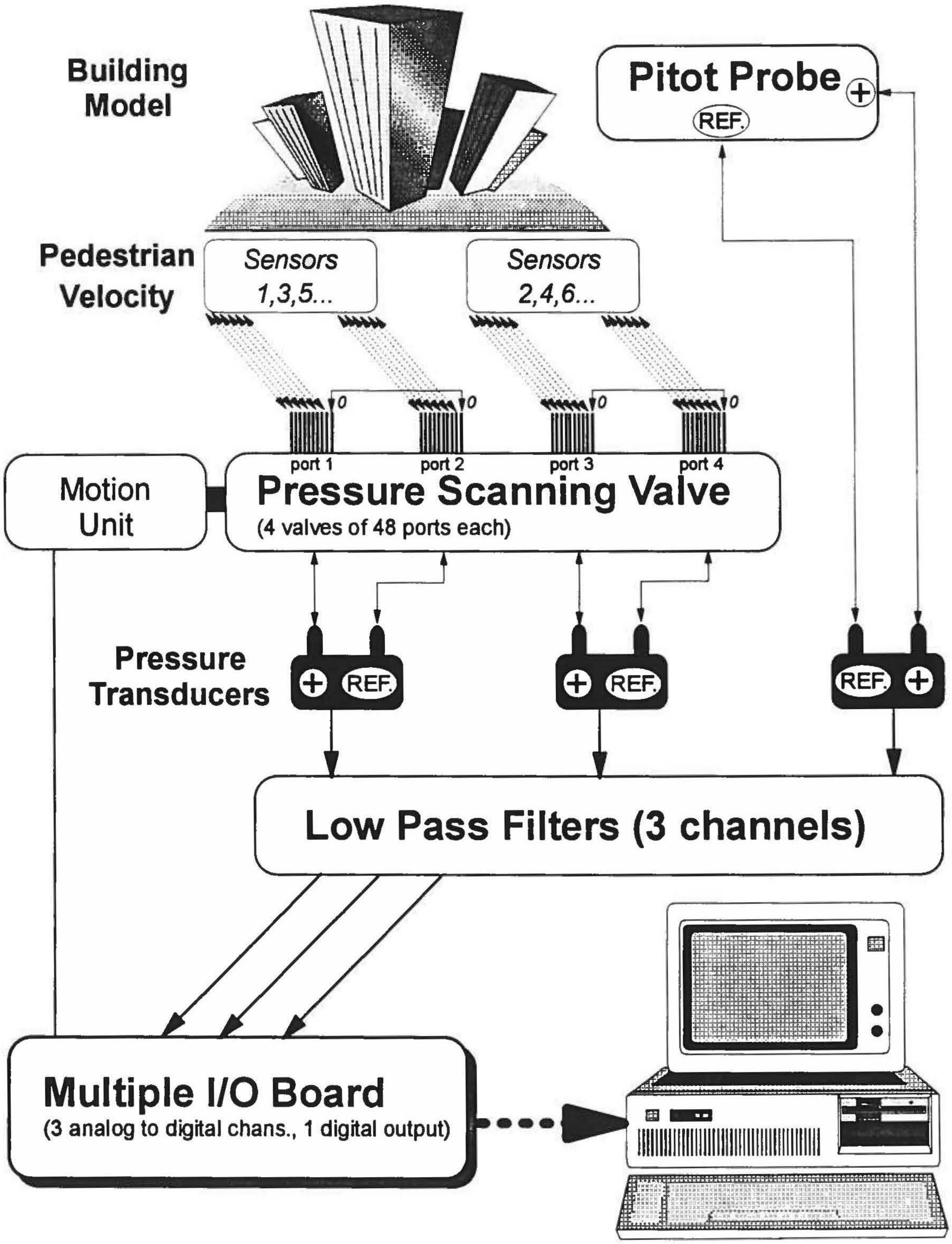


Figure 6 Pedestrian Velocity Measurement System

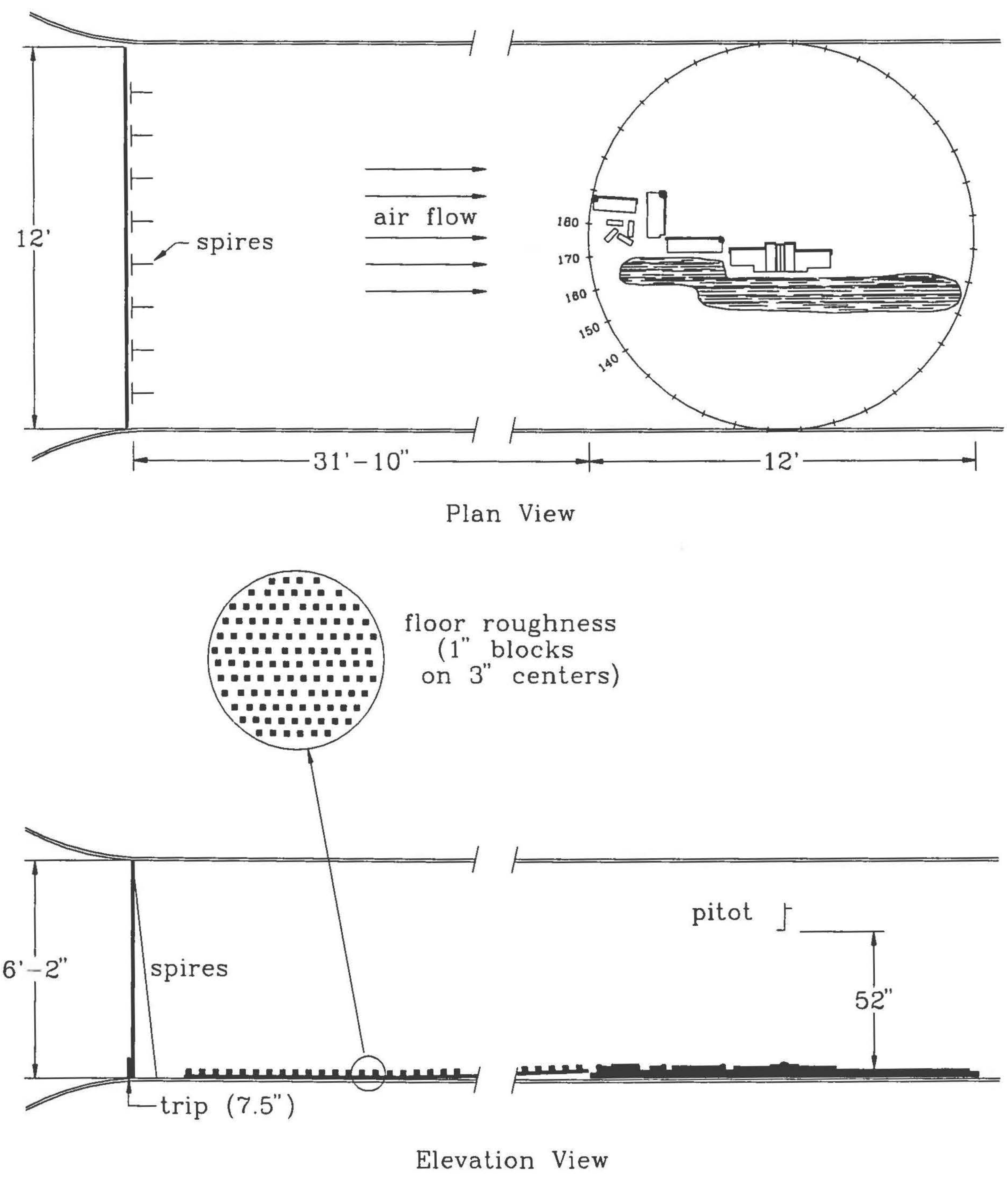


Figure 7 Wind Tunnel Configuration

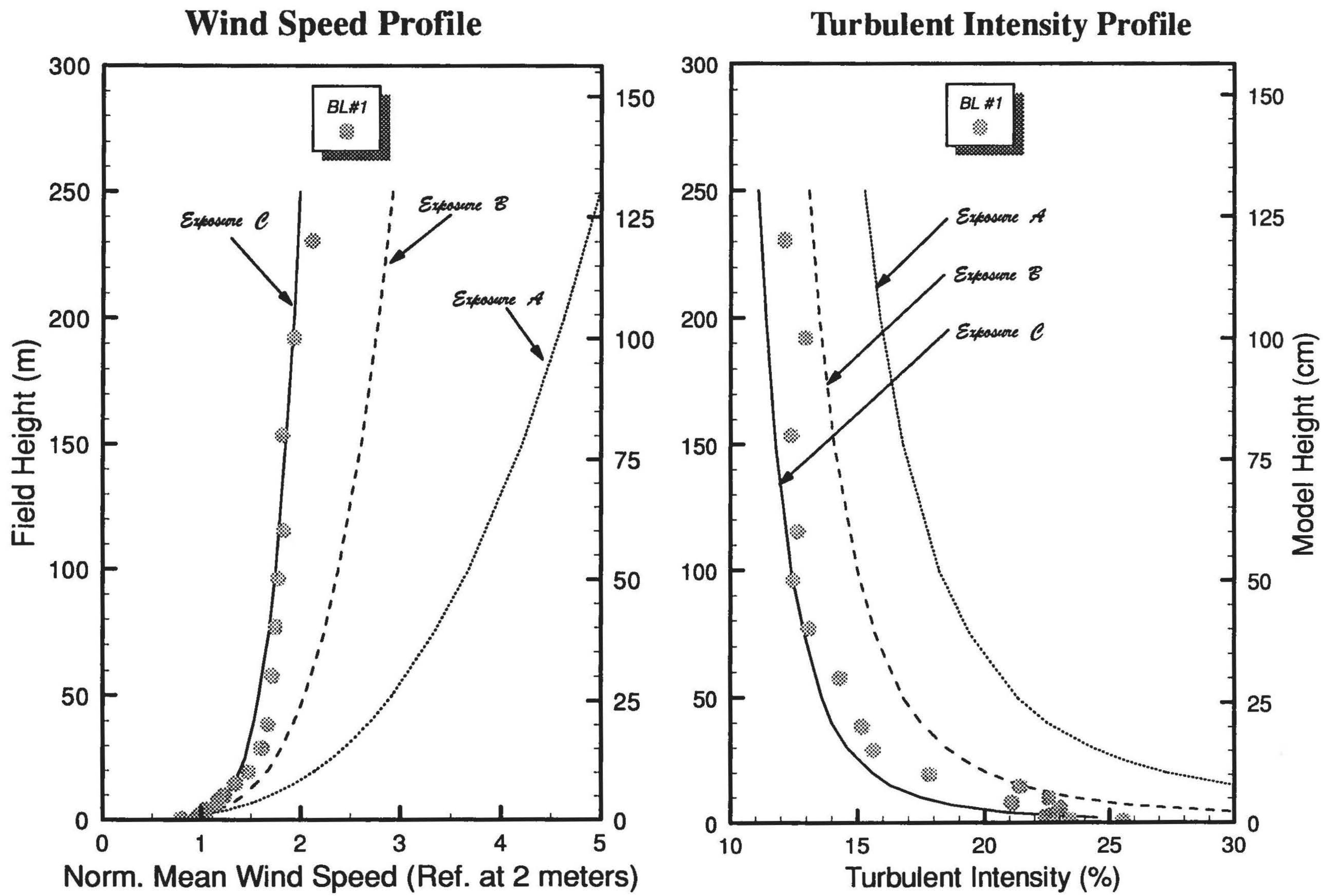


Figure 8 Approach Flow Mean Velocity and Turbulent Intensity Profiles

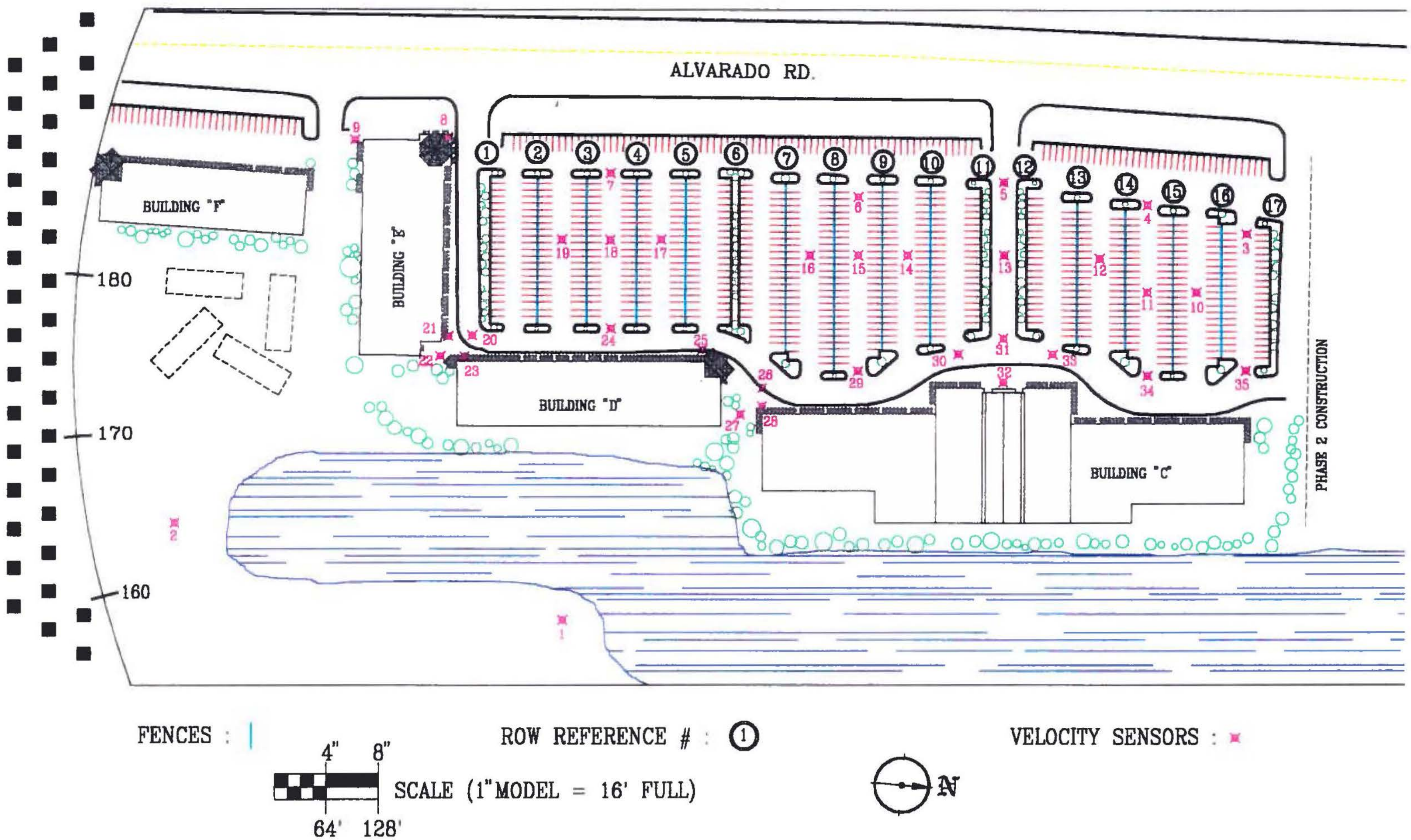


Figure 9 Model Turntable Site Area with Wind Speed Measurement Locations

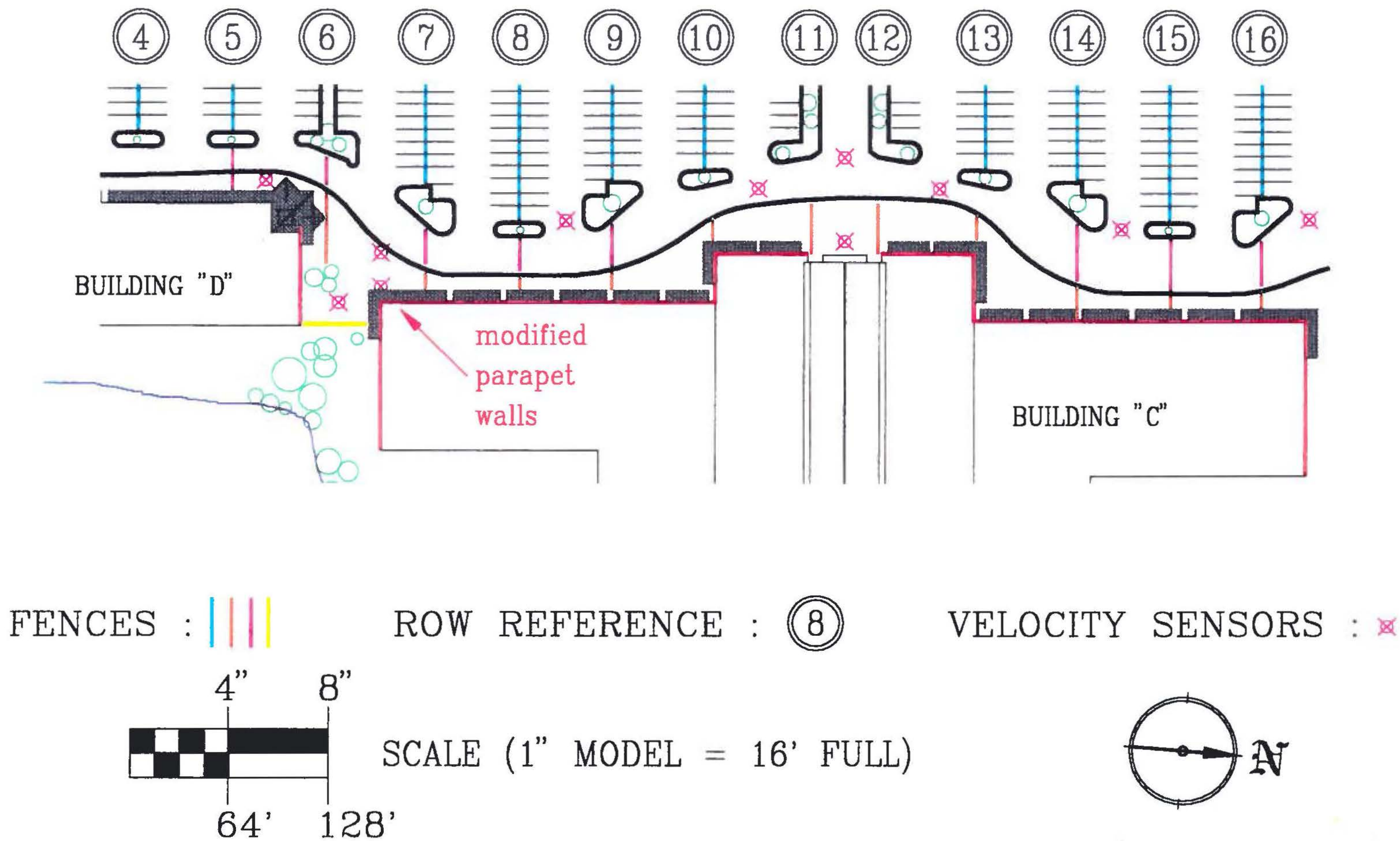
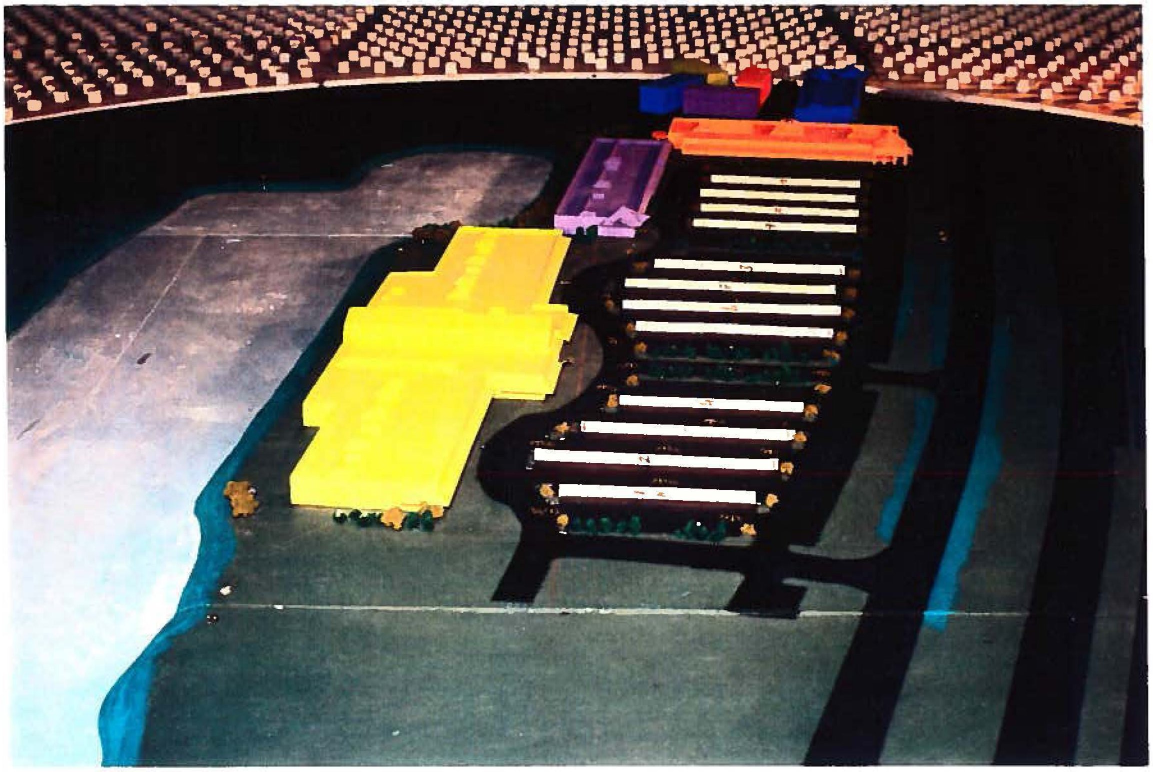


Figure 10 Model Plaza Area with Screen Locations



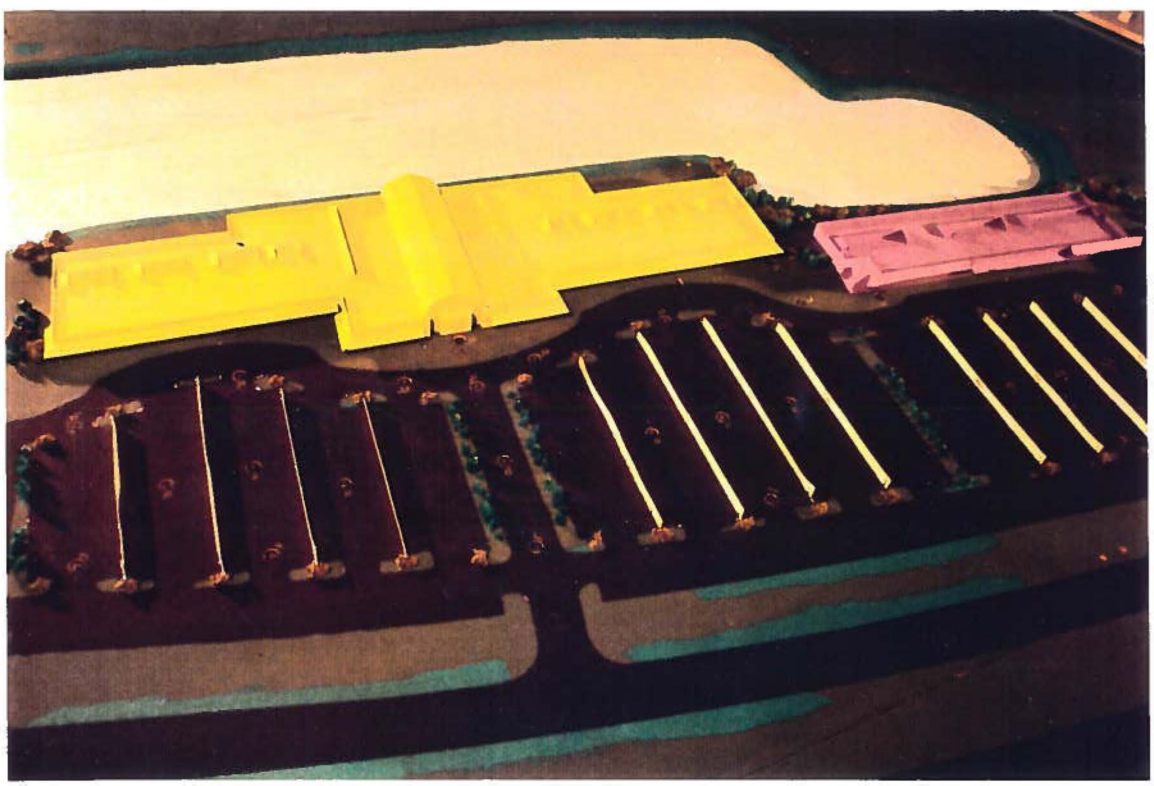


Figure 11 Photographs of the Scaled Model

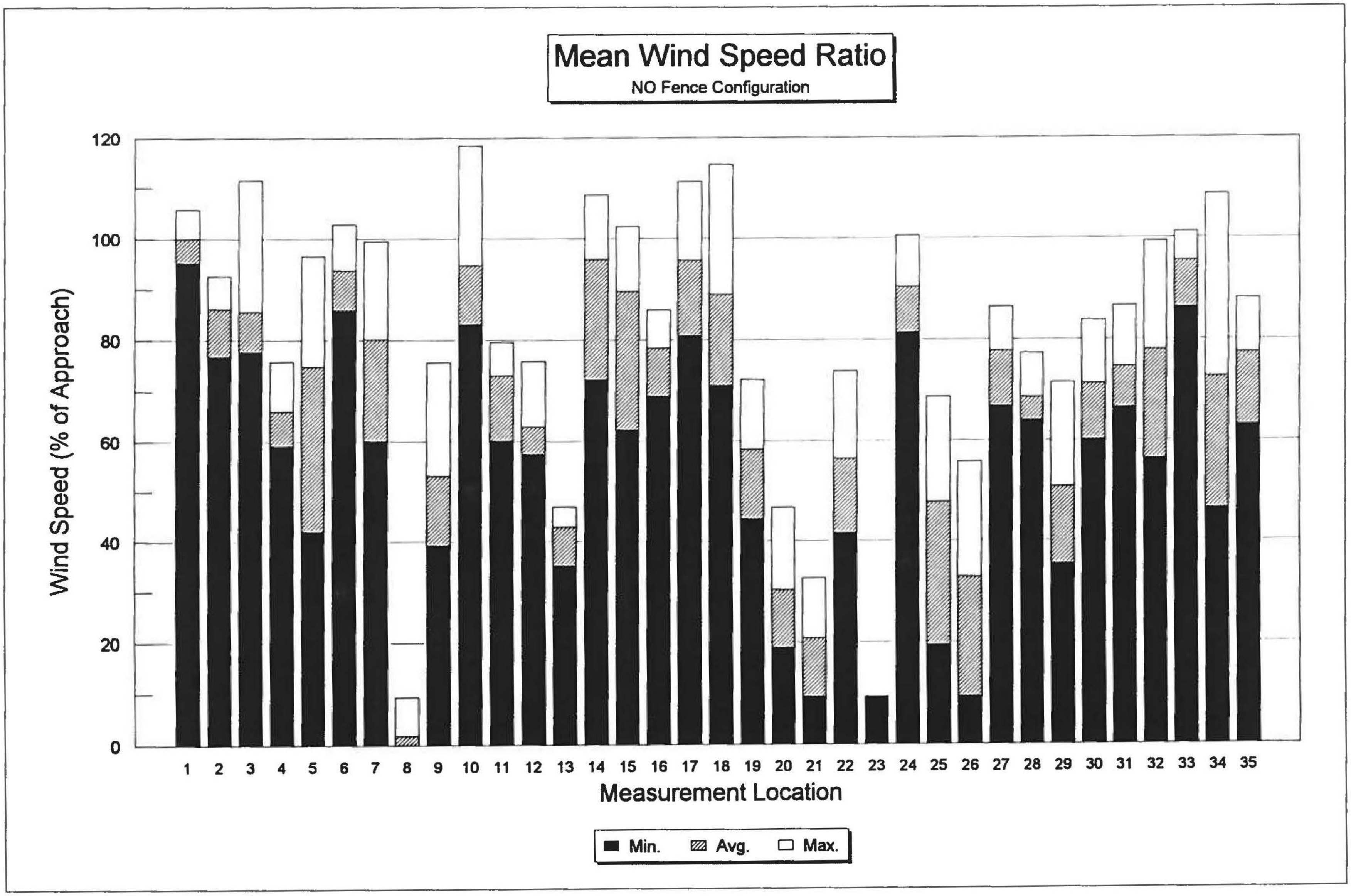


Figure 12 Config. #1 - % of Approach Wind (Min., Avg. Max. over all Wind Dir.)

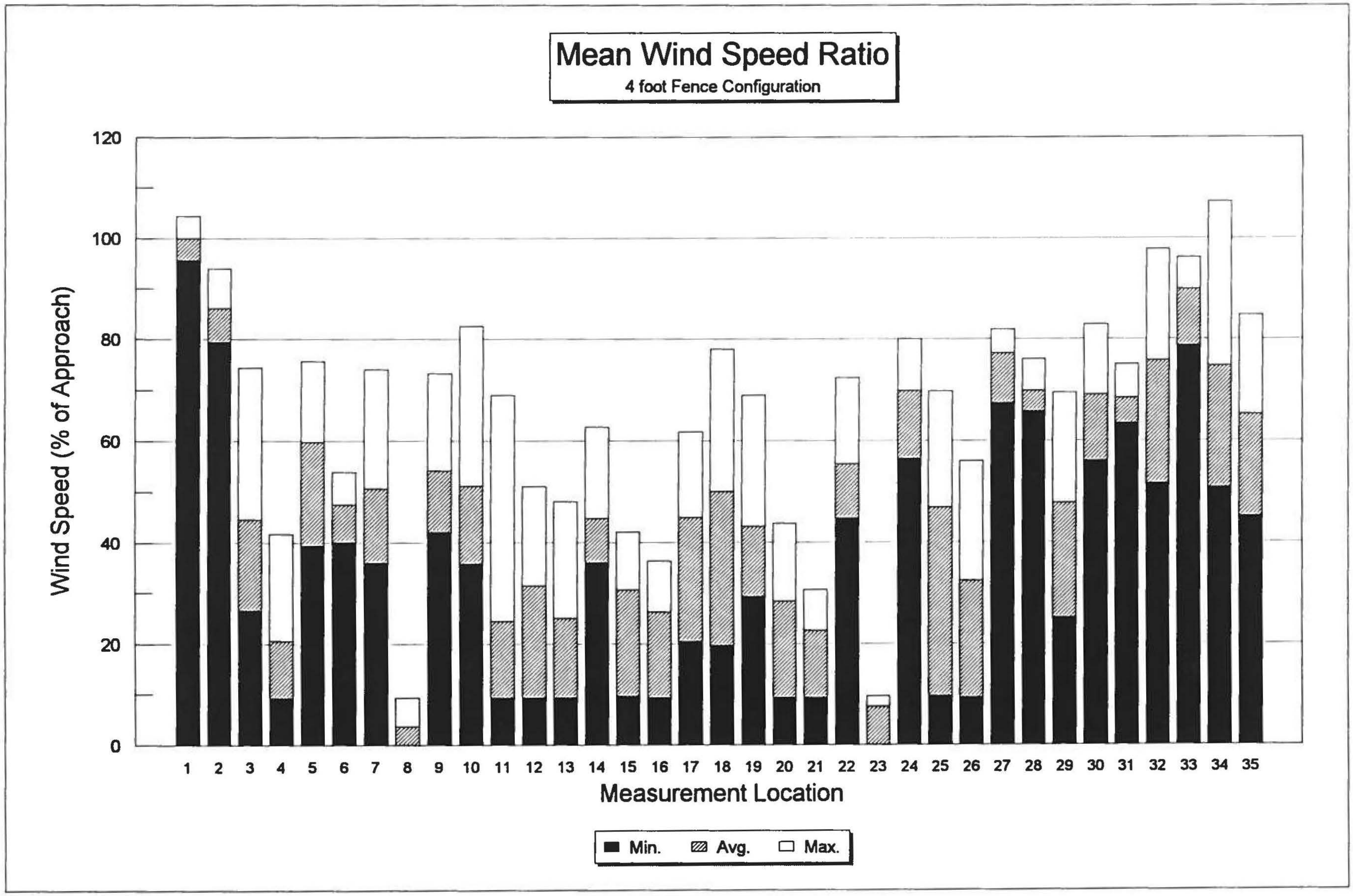


Figure 13 Config. #2 - % of Approach Wind (Min., Avg. Max. over all Wind Dir.)

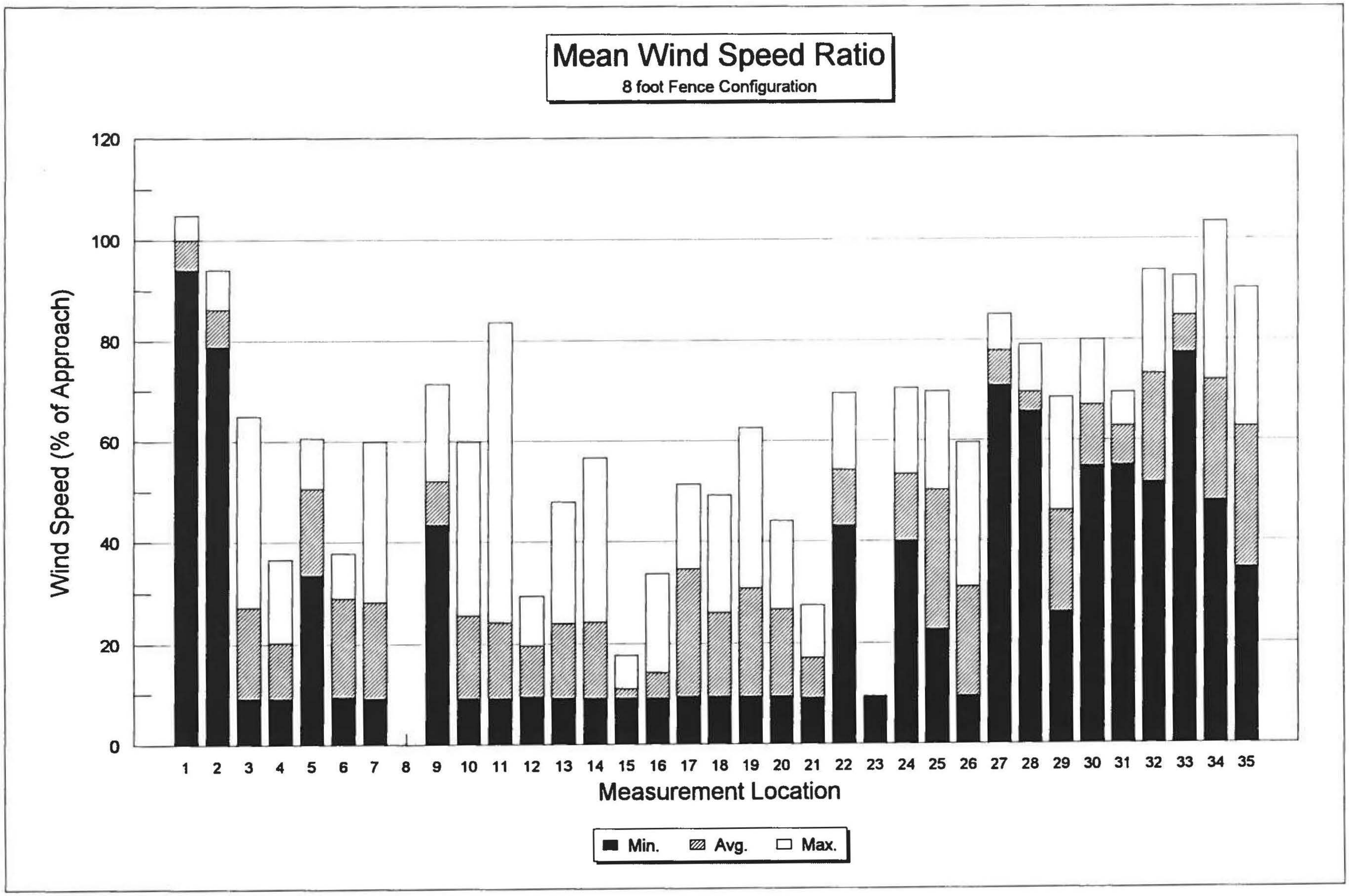


Figure 14 Config. #3 - % of Approach Wind (Min., Avg. Max. over all Wind Dir.)

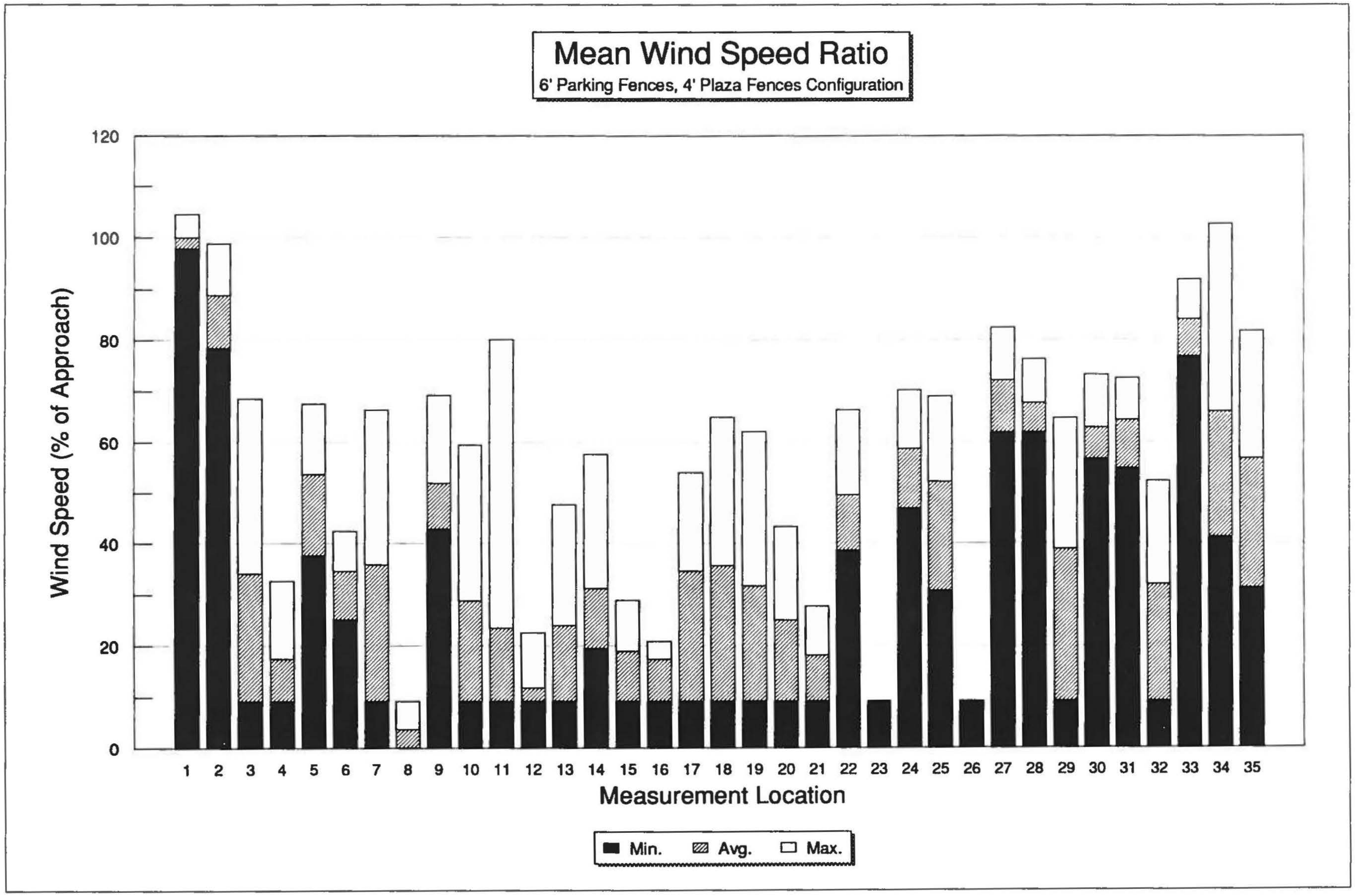


Figure 15 Config. #4 - % of Approach Wind (Min., Avg. Max. over all Wind Dir.)

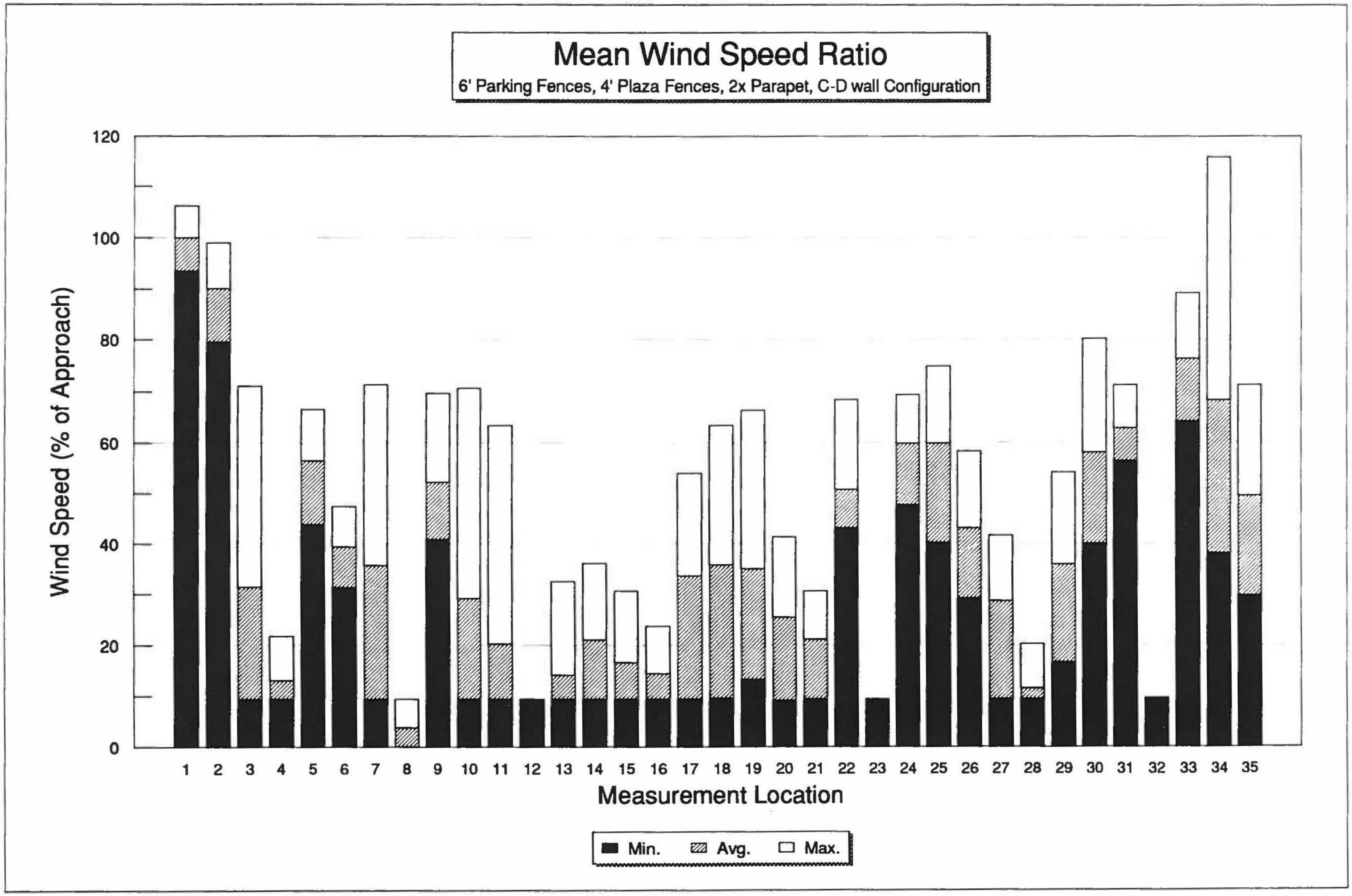


Figure 16 Config. #5 - % of Approach Wind (Min., Avg. Max. over all Wind Dir.)

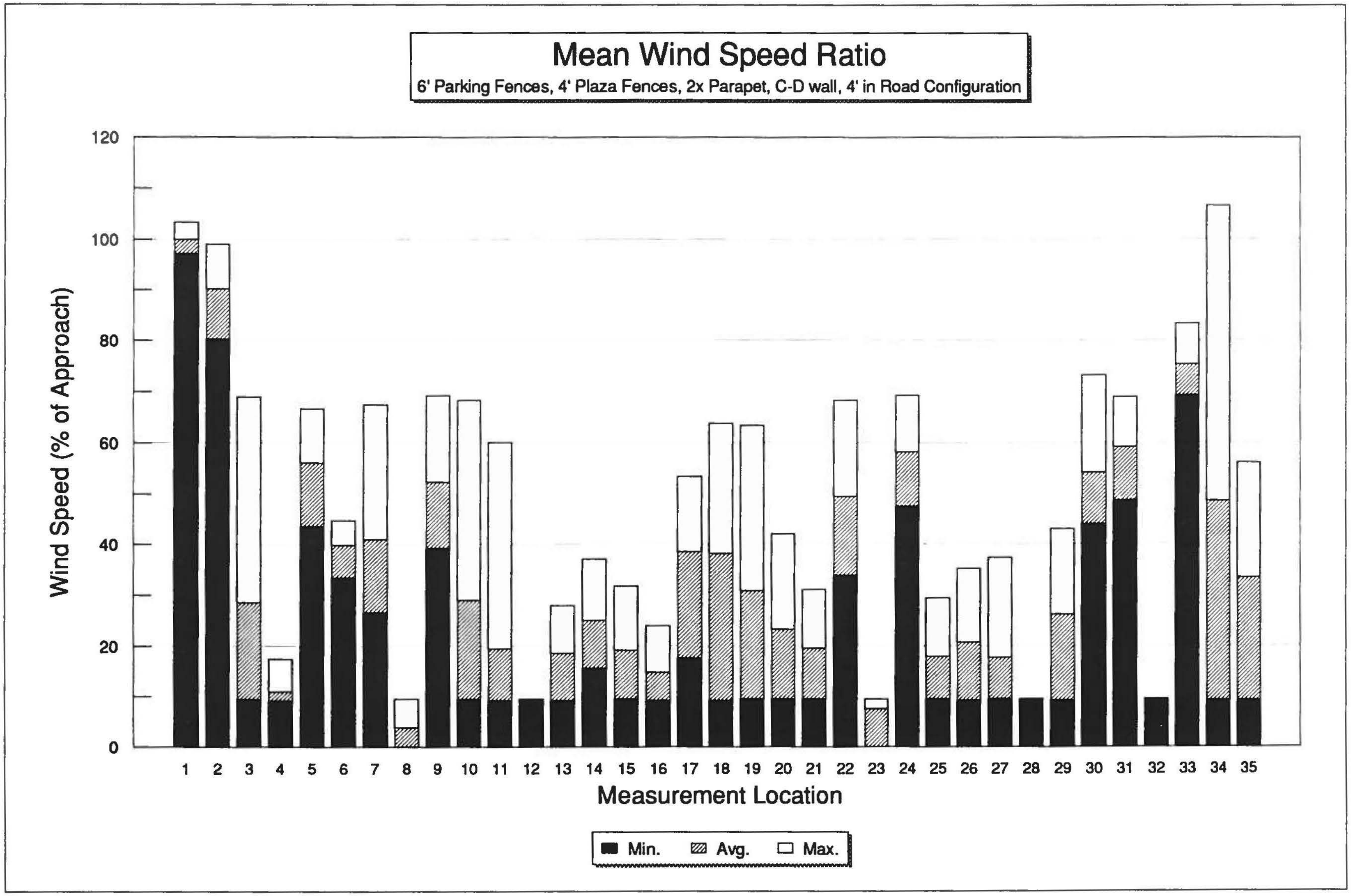


Figure 17 Config. #6 - % of Approach Wind (Min., Avg. Max. over all Wind Dir.)

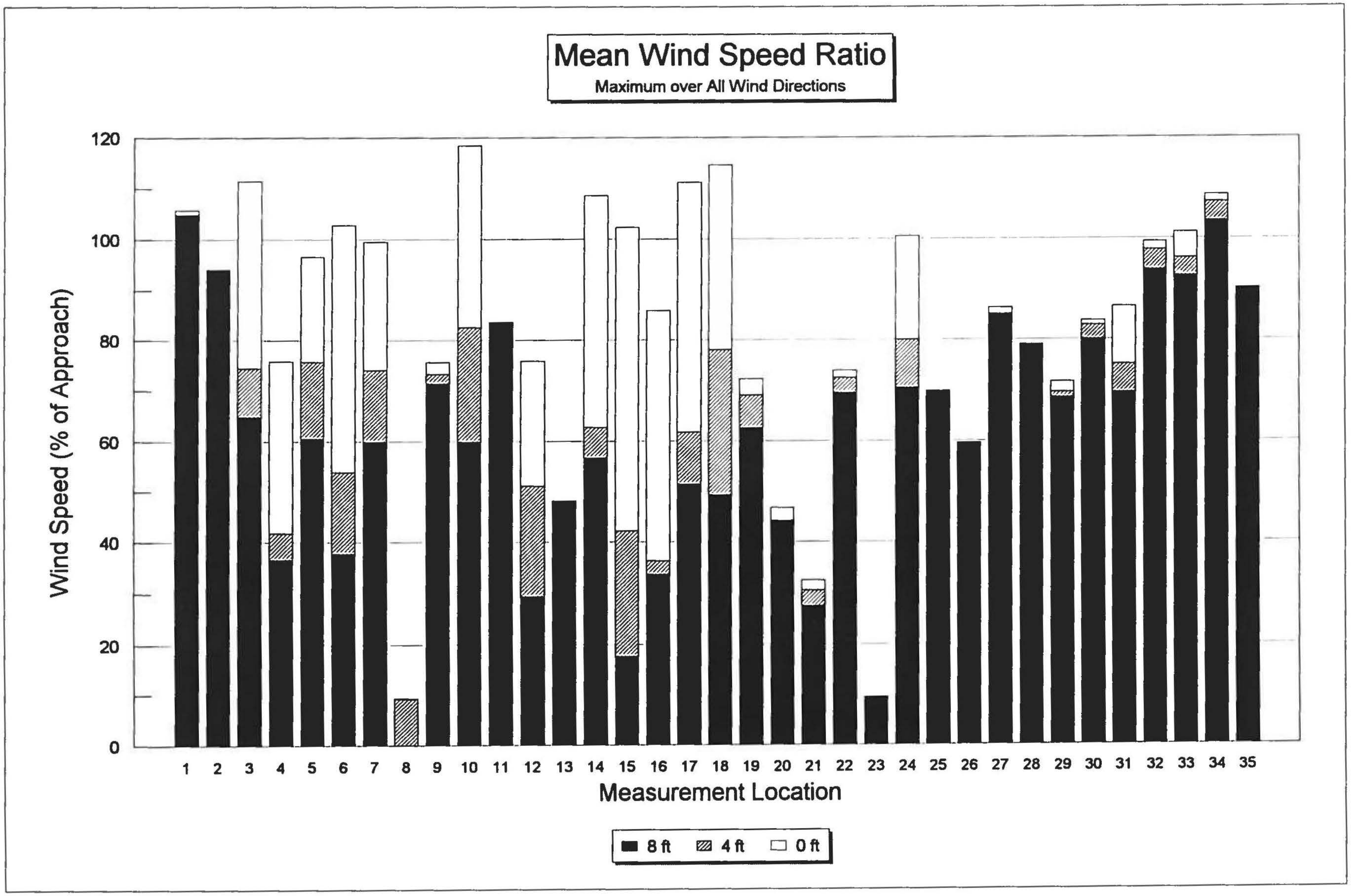


Figure 18 Configs. #1, #2, #3 - % of Approach Wind (Max. over all Wind Dir.)

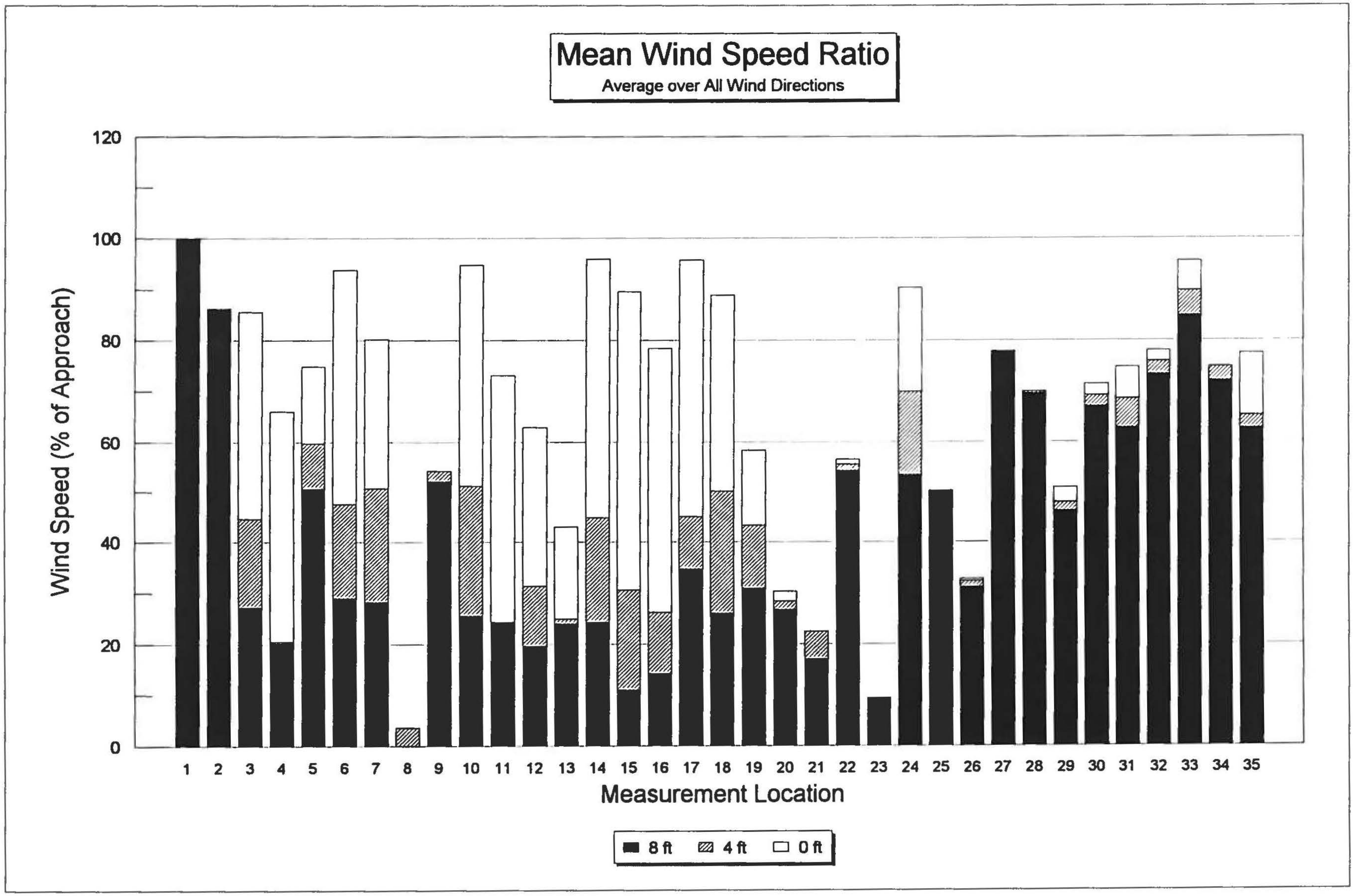


Figure 19 Configs. #1, #2, #3 - % of Approach Wind (Avg. over all Wind Dir.)

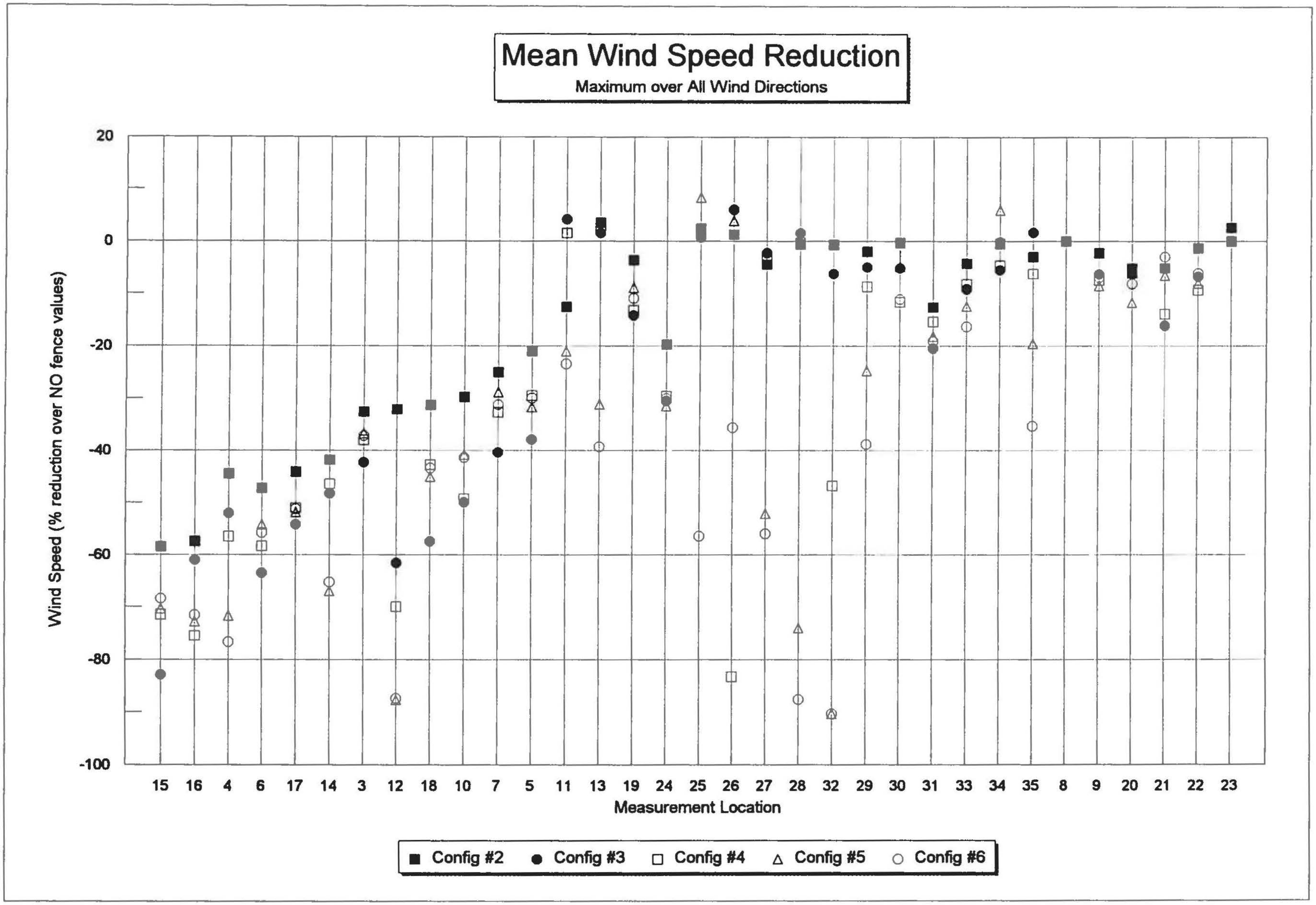


Figure 20 Wind Speed % Reduction vs No Fence Config. (Max. over all Wind Dir.)

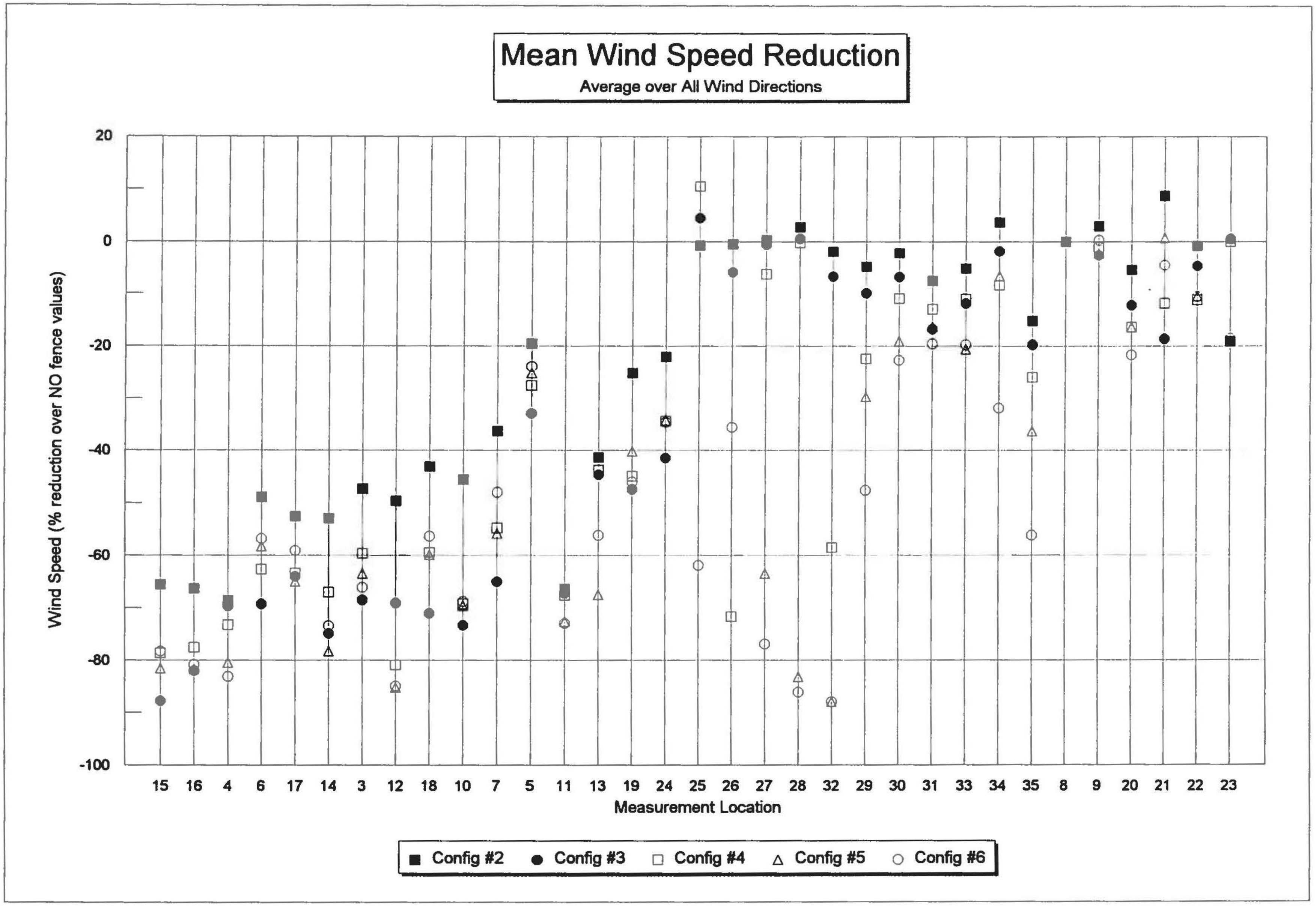


Figure 21 Wind Speed % Reduction vs No Fence Config. (Avg. over all Wind Dir.)

TABLES

Wind Description	Beaufort number	Speed (mph)	Effects
Calm, light air	0,1	0-3	Calm, no noticeable wind
Light breeze	2	4-7	Wind felt on face
Gentle breeze	3	8-12	Wind extends light flag Hair is disburbed Clothing flaps
Moderate breeze	4	13-18	Raises dust, dry soil and loose paper Hair disarranged
Fresh breeze	5	19-24	Force of wind felt on body Drifting snow becomes airborne Limit of agreeable wind on land
Strong breeze	6	25-31	Umbrellas used with difficulty Hair blown straight Difficult to walk steadily Wind noise on ears unpleasant Windborne snow above head height (blizzard)
Near gale	7	32-38	Inconvenience felt when walking
Gale	8	39-46	Generally impedes progress Great difficulty with balance in gusts
Strong gale	9	47-54	People blown over by gusts

Note : Table from Penwarden and Wise (1975), page 40

Table 1 Summary of Wind Effects on People

Denver Stapleton Airport Annual Wind Frequency Table from NOAA

Wind Dir.	Wind Speed (Knots) 0-3	4-6	7-10	11-16	17-21	22-27	28-33	34-40	Over 40	Total	Avg. Speed
N	0.6	2.9	3.2	1.6	0.3	0.1				8.9	8.3
NNE	0.4	1.5	1.6	0.8	0.2					4.5	8.1
NE	0.4	1.6	1.6	0.6	0.1					4.3	7.4
ENE	0.4	1.5	1.3	0.5						3.8	6.9
E	0.7	2.6	1.9	0.5						5.7	6.6
ESE	0.5	1.9	1.4	0.3						4.2	6.6
SE	0.5	1.8	1.3	0.4						4.1	6.6
SSE	0.5	1.9	1.4	0.5	0.1					4.4	7.2
S	1.2	7.2	8.9	2.5	0.3					20.1	7.6
SSW	0.7	4.6	4.4	1.0	0.1					10.8	7.0
SW	0.7	2.4	1.6	0.4	0.1					5.2	6.6
WSW	0.4	1.3	0.7	0.2	0.1					2.7	6.4
W	0.2	0.8	0.9	0.8	0.3	0.1				3.1	9.8
WNW	0.2	0.7	0.9	0.9	0.4	0.1				3.5	10.8
NW	0.3	1.4	1.3	0.9	0.3	0.1				4.2	9.2
NNW	0.3	1.5	1.4	0.7	0.1					4.0	8.0
Calm	6.5									6.5	
Total	14.6	35.8	33.7	12.6	2.6	0.6	0.1			100.0	7.1

Notes
1) 1965-1974; 29215 observations
2) Anemometer Height of 20 feet
3) n=0.14 Zg=1000'

Wind Speed values are converted to mph at a 10 meter height

Wind Dir.	Median Wind Speed (mph at 10m) 2.5	6.8	11.1	17.3	24.1	30.8	38.2	45.6	Over	Total	Avg. Speed
N	0.6	2.9	3.2	1.6	0.3	0.1				8.7	10.9
NNE	0.4	1.5	1.6	0.8	0.2					4.5	10.6
NE	0.4	1.6	1.6	0.6	0.1					4.3	9.9
ENE	0.4	1.5	1.3	0.5						3.7	9.3
E	0.7	2.6	1.9	0.5						5.7	8.6
ESE	0.5	1.9	1.4	0.3						4.1	8.5
SE	0.5	1.8	1.3	0.4						4.0	8.7
SSE	0.5	1.9	1.4	0.5	0.1					4.4	9.3
S	1.2	7.2	8.9	2.5	0.3					20.1	10.0
SSW	0.7	4.6	4.4	1.0	0.1					10.8	9.4
SW	0.7	2.4	1.6	0.4	0.1					5.2	8.7
WSW	0.4	1.3	0.7	0.2	0.1					2.7	8.7
W	0.2	0.8	0.9	0.8	0.3	0.1				3.1	12.9
WNW	0.2	0.7	0.9	0.9	0.4	0.1				3.2	13.8
NW	0.3	1.4	1.3	0.9	0.3	0.1				4.3	11.7
NNW	0.3	1.5	1.4	0.7	0.1					4.0	10.2
Calm	6.5									6.5	
Total	14.5	35.6	33.8	12.6	2.4	0.4				99.3	9.3

Table 2 Wind Speed and Direction Probabilities Chart

Config. Number	Parking Screen (Height)	Parking Screen (# Pos.)	Plaza Screen (Height)	Plaza Screen (# Pos.)	Road Screen (Height)	Road Screen (# Pos.)	Units C-D Wall (Height)	Parapet (Height)
1	0'	0	0'	0	0'	0	0'	1x
2	4'	12	0'	0	0'	0	0'	1x
3	8'	12	0'	0	0'	0	0'	1x
4	6'	12	4'	11	0'	0	0'	1x
5	6'	12	4'	11	0'	0	16'	2x
6	6'	12	4'	12	4'	8	16'	2x

Screen Porosity = 50 Percent *Wind Direction = 140, 150, 160, 170, 180*

Configuration #1 - Screen Heights

Screen	Placement		
Row	Parking	Plaza	Road
1	0'	0'	0'
2	0'	0'	0'
3	0'	0'	0'
4	0'	0'	0'
5	0'	0'	0'
6	0'	0'	0'
7	0'	0'	0'
8	0'	0'	0'
9	0'	0'	0'
10	0'	0'	0'
11	0'	0'	0'
12	0'	0'	0'
13	0'	0'	0'
14	0'	0'	0'
15	0'	0'	0'
16	0'	0'	0'
17	0'	0'	0'

Configuration #2 - Screen Heights

Screen	Placement		
Row	Parking	Plaza	Road
1	0'	0'	0'
2	4'	0'	0'
3	4'	0'	0'
4	4'	0'	0'
5	4'	0'	0'
6	0'	0'	0'
7	4'	0'	0'
8	4'	0'	0'
9	4'	0'	0'
10	4'	0'	0'
11	0'	0'	0'
12	0'	0'	0'
13	4'	0'	0'
14	4'	0'	0'
15	4'	0'	0'
16	4'	0'	0'
17	0'	0'	0'

Configuration #3 - Screen Heights

Screen	Placement		
Row	Parking	Plaza	Road
1	0'	0'	0'
2	8'	0'	0'
3	8'	0'	0'
4	8'	0'	0'
5	8'	0'	0'
6	0'	0'	0'
7	8'	0'	0'
8	8'	0'	0'
9	8'	0'	0'
10	8'	0'	0'
11	0'	0'	0'
12	0'	0'	0'
13	8'	0'	0'
14	8'	0'	0'
15	8'	0'	0'
16	8'	0'	0'
17	0'	0'	0'

Configuration #4 - Screen Heights

Screen	Placement		
Row	Parking	Plaza	Road
1	0'	0'	0'
2	6'	0'	0'
3	6'	0'	0'
4	6'	0'	0'
5	6'	0'	0'
6	0'	4'	0'
7	6'	4'	0'
8	6'	4'	0'
9	6'	4'	0'
10	6'	4'	0'
11	0'	4'	0'
12	0'	4'	0'
13	6'	4'	0'
14	6'	4'	0'
15	6'	4'	0'
16	6'	4'	0'
17	0'	0'	0'

Configuration #5 - Screen Heights

Screen	Placement		
Row	Parking	Plaza	Road
1	0'	0'	0'
2	6'	0'	0'
3	6'	0'	0'
4	6'	0'	0'
5	6'	0'	0'
6	0'	4'	0'
7	6'	4'	0'
8	6'	4'	0'
9	6'	4'	0'
10	6'	4'	0'
11	0'	4'	0'
12	0'	4'	0'
13	6'	4'	0'
14	6'	4'	0'
15	6'	4'	0'
16	6'	4'	0'
17	0'	0'	0'

Unit C-D 16' Wall; 2x Parapet Height

Configuration #6 - Screen Heights

Screen	Placement		
Row	Parking	Plaza	Road
1	0'	0'	0'
2	6'	0'	0'
3	6'	0'	0'
4	6'	0'	0'
5	6'	4'	4'
6	0'	4'	4'
7	6'	4'	4'
8	6'	4'	4'
9	6'	4'	4'
10	6'	4'	0'
11	0'	4'	0'
12	0'	4'	0'
13	6'	4'	0'
14	6'	4'	4'
15	6'	4'	4'
16	6'	4'	4'
17	0'	0'	0'

Unit C-D 16' Wall; 2x Parapet Height

Table 3 Wind Tunnel Testing Program

Pedestrian Wind Speed Results
Configuration #1 -- NO FENCE
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	95	104	106	99	97	95	100	106
2	90	77	85	93	87	77	86	93
3	111	80	78	78	81	78	86	111
4	66	76	59	65	64	59	66	76
5	42	65	83	88	97	42	75	97
6	94	103	100	87	86	86	94	103
7	100	94	85	63	60	60	80	100
8	0	0	0	0	9	0	2	9
9	76	53	39	44	53	39	53	76
10	118	83	89	88	95	83	95	118
11	60	72	79	75	80	60	73	80
12	66	76	58	57	57	57	63	76
13	47	44	35	43	46	35	43	47
14	72	87	106	109	105	72	96	109
15	62	91	102	99	93	62	90	102
16	69	83	86	80	75	69	78	86
17	111	107	93	87	81	81	96	111
18	115	89	86	84	71	71	89	115
19	72	60	61	54	44	44	58	72
20	23	19	25	38	47	19	30	47
21	33	26	9	9	27	9	21	33
22	74	60	51	42	55	42	56	74
23	9	9	9	9	9	9	9	9
24	88	100	87	81	96	81	90	100
25	19	46	51	54	69	19	48	69
26	9	25	31	42	56	9	33	56
27	86	81	78	77	67	67	78	86
28	77	67	64	68	67	64	69	77
29	72	42	35	46	59	35	51	72
30	60	73	65	75	84	60	71	84
31	71	72	67	78	87	67	75	87
32	56	69	76	89	99	56	78	99
33	86	100	97	94	101	86	96	101
34	109	95	50	46	63	46	73	109
35	76	88	78	63	81	63	77	88

Table 4 Config. #1 - Mean Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #2 – 4 ft Parking Fence
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc	Wind Directions					Min.	Avg.	Max.
No.	140	150	160	170	180	Value	Value	Value
1	96	101	104	99	99	96	100	104
2	87	79	82	94	88	79	86	94
3	75	52	38	27	31	27	45	75
4	33	42	9	9	9	9	21	42
5	39	46	66	72	76	39	60	76
6	45	54	52	47	40	40	48	54
7	74	56	49	38	36	36	51	74
8	0	0	0	9	9	0	4	9
9	73	56	42	48	51	42	54	73
10	83	59	40	39	36	36	51	83
11	69	25	9	9	9	9	24	69
12	37	51	35	25	9	9	31	51
13	46	48	13	9	9	9	25	48
14	63	37	43	45	36	36	45	63
15	9	36	42	38	28	9	31	42
16	20	36	34	30	9	9	26	36
17	62	60	46	37	20	20	45	62
18	78	65	45	43	20	20	50	78
19	69	37	42	39	29	29	43	69
20	20	9	32	37	44	9	28	44
21	31	9	25	18	29	9	22	31
22	72	53	54	45	54	45	55	72
23	9	0	9	9	9	0	7	9
24	56	74	72	67	80	56	70	80
25	9	41	56	59	70	9	47	70
26	9	9	39	49	56	9	32	56
27	82	79	80	78	67	67	77	82
28	76	66	68	73	67	66	70	76
29	70	25	37	49	58	25	48	70
30	56	68	66	73	83	56	69	83
31	69	67	63	69	75	63	68	75
32	51	65	76	89	98	51	76	98
33	79	94	93	87	96	79	90	96
34	107	94	54	51	67	51	75	107
35	68	85	80	47	45	45	65	85

Table 5 Config. #2 - Mean Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #3 – 8 ft Parking Fence
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	94	101	105	102	98	94	100	105
2	86	79	83	94	89	79	86	94
3	65	43	9	9	9	9	27	65
4	36	37	9	9	9	9	20	37
5	43	34	56	61	60	34	51	61
6	34	32	38	32	9	9	29	38
7	60	34	29	9	9	9	28	60
8	0	0	0	0	0	0	0	0
9	71	49	43	46	50	43	52	71
10	60	40	9	9	9	9	26	60
11	84	9	9	9	9	9	24	84
12	9	29	26	24	9	9	20	29
13	48	44	9	9	9	9	24	48
14	57	9	20	27	9	9	24	57
15	9	9	9	18	9	9	11	18
16	9	9	34	9	9	9	14	34
17	51	48	37	27	9	9	35	51
18	49	40	22	9	9	9	26	49
19	62	34	27	22	9	9	31	62
20	9	9	32	38	44	9	27	44
21	25	14	9	9	27	9	17	27
22	69	54	49	43	55	43	54	69
23	9	9	9	9	9	9	9	9
24	40	47	51	58	70	40	53	70
25	23	48	54	57	70	23	50	70
26	9	9	31	46	60	9	31	60
27	85	79	78	76	71	71	78	85
28	79	66	66	69	67	66	69	79
29	68	26	31	44	61	26	46	68
30	55	68	62	70	80	55	67	80
31	67	61	55	61	69	55	63	69
32	52	64	73	84	94	52	73	94
33	77	93	85	78	90	77	85	93
34	103	91	52	48	65	48	72	103
35	70	90	75	35	43	35	63	90

Table 6 Config. #3 - Mean Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #4 -- 6' Parking, 4' Plaza Fences
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	98	100	105	99	99	98	100	105
2	88	78	84	96	99	78	89	99
3	68	51	25	9	17	9	34	68
4	27	33	9	9	9	9	17	33
5	38	39	61	64	68	38	54	68
6	30	42	42	34	25	25	35	42
7	66	41	38	9	25	9	36	66
8	0	0	0	9	9	0	4	9
9	69	51	43	46	50	43	52	69
10	59	50	17	9	9	9	29	59
11	80	9	9	9	9	9	23	80
12	9	23	9	9	9	9	12	23
13	48	44	9	9	9	9	24	48
14	58	19	26	31	23	19	31	58
15	9	9	28	29	19	9	19	29
16	9	20	17	20	21	9	17	21
17	53	54	32	26	9	9	35	54
18	65	54	30	20	9	9	36	65
19	62	32	29	27	9	9	32	62
20	11	9	26	36	43	9	25	43
21	27	18	9	9	28	9	18	28
22	66	53	45	39	45	39	50	66
23	9	9	9	9	9	9	9	9
24	47	60	59	57	70	47	59	70
25	31	50	54	57	69	31	52	69
26	9	9	9	9	9	9	9	9
27	82	75	72	70	62	62	72	82
28	76	67	64	70	62	62	68	76
29	65	34	9	38	49	9	39	65
30	58	62	57	64	73	57	63	73
31	73	63	55	63	68	55	64	73
32	9	9	39	52	50	9	32	52
33	77	92	87	79	85	77	84	92
34	103	90	41	43	53	41	66	103
35	60	82	74	36	31	31	57	82

Table 7 Config. #4 - Mean Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #5 – 6' Parking, 4' Plaza, 8' Parapet
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	93	101	106	99	100	93	100	106
2	90	80	86	96	99	80	90	99
3	71	46	22	9	9	9	31	71
4	22	15	9	9	9	9	13	22
5	44	47	62	62	67	44	56	67
6	39	47	44	36	31	31	39	47
7	71	45	38	9	14	9	36	71
8	0	0	0	9	9	0	4	9
9	70	54	41	45	51	41	52	70
10	71	47	10	9	9	9	29	71
11	63	9	9	9	9	9	20	63
12	9	9	9	9	9	9	9	9
13	33	10	9	9	9	9	14	33
14	36	10	20	30	9	9	21	36
15	9	10	24	31	9	9	17	31
16	9	9	24	20	9	9	14	24
17	54	50	33	22	9	9	34	54
18	63	53	32	21	10	10	36	63
19	66	35	31	30	13	13	35	66
20	9	9	28	40	41	9	25	41
21	31	18	9	23	25	9	21	31
22	68	54	44	43	45	43	51	68
23	9	9	9	9	9	9	9	9
24	48	62	60	60	69	48	60	69
25	40	57	60	66	75	40	60	75
26	29	36	45	58	47	29	43	58
27	9	26	30	42	36	9	29	42
28	9	9	10	20	9	9	12	20
29	38	32	17	40	54	17	36	54
30	40	47	53	71	80	40	58	80
31	63	56	57	67	71	56	63	71
32	9	10	9	9	9	9	9	10
33	64	73	74	81	89	64	76	89
34	116	93	38	44	50	38	68	116
35	53	71	59	35	30	30	50	71

Table 8 Config. #5 - Mean Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #6 -- 6' Parking, 4' Plaza, 4' Road, 8' Parapet
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc	Wind Directions					Min.	Avg.	Max.
No.	140	150	160	170	180	Value	Value	Value
1	98	103	103	99	97	97	100	103
2	89	80	86	97	99	80	90	99
3	69	45	9	9	9	9	29	69
4	9	17	9	9	9	9	11	17
5	44	47	62	62	67	44	56	67
6	39	45	43	39	33	33	40	45
7	67	47	36	28	27	27	41	67
8	0	0	0	9	9	0	4	9
9	69	55	39	46	53	39	52	69
10	68	49	9	9	9	9	29	68
11	60	9	9	9	9	9	19	60
12	9	9	9	9	9	9	9	9
13	28	24	9	23	9	9	19	28
14	37	16	16	32	24	16	25	37
15	9	9	24	32	21	9	19	32
16	9	22	10	24	9	9	15	24
17	53	53	36	32	18	18	39	53
18	64	55	33	30	9	9	38	64
19	63	33	27	22	9	9	31	63
20	9	9	20	36	42	9	23	42
21	31	21	9	9	27	9	20	31
22	68	53	47	34	46	34	50	68
23	9	9	9	0	9	0	7	9
24	48	60	60	55	69	48	58	69
25	9	13	29	9	28	9	18	29
26	29	9	9	20	35	9	21	35
27	9	9	9	23	37	9	18	37
28	9	9	9	9	9	9	9	9
29	42	27	9	9	43	9	26	43
30	51	46	44	58	73	44	54	73
31	64	54	49	60	69	49	59	69
32	9	9	9	9	9	9	9	9
33	69	75	76	73	83	69	75	83
34	107	90	28	9	9	9	49	107
35	50	56	43	9	9	9	33	56

Table 9 Config. #6 - Mean Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #1 -- NO FENCE
Peak Wind Speed to Avg. Peak Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	97	101	105	100	97	97	100	105
2	98	89	94	97	93	89	94	98
3	125	108	100	93	94	93	104	125
4	96	96	88	85	84	84	90	96
5	79	100	111	108	106	79	101	111
6	107	108	108	102	101	101	105	108
7	112	107	104	94	90	90	101	112
8	0	0	0	0	48	0	10	48
9	82	74	66	69	76	66	74	82
10	134	117	110	102	105	102	114	134
11	108	105	103	95	95	95	101	108
12	96	97	87	81	80	80	88	97
13	80	79	71	73	76	71	76	80
14	105	103	110	110	111	103	108	111
15	94	104	109	105	106	94	104	109
16	94	95	96	94	93	93	94	96
17	119	118	106	105	102	102	110	119
18	118	105	102	105	98	98	106	118
19	98	85	85	83	79	79	86	98
20	68	66	73	76	78	66	72	78
21	66	66	54	60	69	54	63	69
22	84	78	79	83	88	78	83	88
23	54	39	24	16	44	16	35	54
24	106	111	103	103	113	103	107	113
25	65	70	70	71	79	65	71	79
26	54	67	70	75	79	54	69	79
27	92	87	84	84	80	80	85	92
28	84	81	81	86	87	81	84	87
29	96	78	74	78	85	74	82	96
30	89	92	84	88	91	84	89	92
31	94	93	84	87	93	84	90	94
32	86	88	97	99	102	86	94	102
33	103	113	112	103	105	103	107	113
34	115	113	90	80	86	80	97	115
35	96	100	101	90	98	90	97	101

Table 10 Config. #1 - Peak Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #2 – 4 ft Parking Fence
Peak Wind Speed to Avg. Peak Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	99	100	103	99	99	99	100	103
2	95	92	92	98	96	92	95	98
3	94	91	75	71	74	71	81	94
4	82	76	65	55	52	52	66	82
5	78	85	96	98	99	78	91	99
6	75	75	75	73	78	73	75	78
7	95	81	81	77	82	77	83	95
8	0	0	0	19	32	0	10	32
9	80	76	64	73	76	64	74	80
10	105	105	78	74	74	74	87	105
11	118	81	70	64	56	56	78	118
12	77	78	74	67	55	55	70	78
13	78	83	64	60	50	50	67	83
14	97	71	70	70	69	69	75	97
15	66	71	71	69	69	66	69	71
16	67	69	69	67	57	57	66	69
17	82	79	74	71	70	70	75	82
18	91	93	78	78	75	75	83	93
19	95	75	75	75	72	72	78	95
20	65	57	73	74	77	57	69	77
21	64	58	66	65	69	58	64	69
22	82	75	78	78	87	75	80	87
23	44	0	39	38	36	0	31	44
24	87	95	91	93	103	87	94	103
25	58	70	71	72	81	58	70	81
26	51	52	71	74	82	51	66	82
27	89	86	85	84	80	80	85	89
28	83	81	83	86	86	81	84	86
29	95	77	71	71	78	71	78	95
30	86	93	87	86	92	86	89	93
31	93	91	84	83	83	83	87	93
32	83	86	92	95	101	83	91	101
33	100	110	110	99	104	99	105	110
34	114	113	90	79	87	79	96	114
35	91	100	105	79	73	73	90	105

Table 11 Config. #2 - Peak Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #3 – 8 ft Parking Fence
Peak Wind Speed to Avg. Peak Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	97	102	103	101	97	97	100	103
2	95	88	91	99	99	88	94	99
3	93	90	66	60	60	60	74	93
4	83	78	63	60	51	51	67	83
5	82	82	88	91	92	82	87	92
6	76	75	74	73	68	68	73	76
7	87	78	75	62	63	62	73	87
8	0	0	0	0	0	0	0	0
9	78	72	64	70	76	64	72	78
10	94	93	60	59	42	42	70	94
11	126	75	61	62	54	54	76	126
12	68	74	71	68	52	52	67	74
13	81	81	61	58	47	47	66	81
14	89	65	65	69	48	48	67	89
15	67	52	63	67	50	50	60	67
16	58	60	69	57	38	38	56	69
17	82	78	73	71	45	45	70	82
18	82	80	72	60	38	38	66	82
19	88	79	71	69	60	60	73	88
20	58	57	73	75	78	57	68	78
21	65	62	57	59	68	57	62	68
22	80	75	77	81	86	75	80	86
23	45	29	26	33	47	26	36	47
24	79	87	89	91	105	79	90	105
25	66	71	71	72	80	66	72	80
26	54	52	71	74	79	52	66	79
27	90	85	85	83	79	79	85	90
28	84	80	83	84	84	80	83	84
29	92	74	71	73	82	71	78	92
30	88	94	86	87	92	86	90	94
31	90	86	82	81	84	81	85	90
32	80	86	94	97	99	80	91	99
33	97	110	104	97	101	97	102	110
34	111	112	92	79	84	79	96	112
35	92	105	107	82	74	74	92	107

Table 12 Config. #3 - Peak Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #4 -- 6' Parking, 4' Plaza Fences
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	102	100	103	99	97	97	100	103
2	96	90	96	98	100	90	96	100
3	92	91	73	60	68	60	77	92
4	84	77	61	57	54	54	67	84
5	81	81	90	89	91	81	86	91
6	76	76	74	72	77	72	75	77
7	94	78	77	65	77	65	78	94
8	0	0	0	16	38	0	11	38
9	77	73	66	69	74	66	72	77
10	92	96	73	62	62	62	77	96
11	123	81	66	58	56	56	77	123
12	62	71	63	52	52	52	60	71
13	77	79	62	57	58	57	66	79
14	91	66	66	65	65	65	71	91
15	65	60	70	69	68	60	66	70
16	60	66	64	64	66	60	64	66
17	79	78	71	69	62	62	72	79
18	88	84	75	74	65	65	77	88
19	90	76	71	71	61	61	74	90
20	62	59	72	75	76	59	69	76
21	64	63	53	59	68	53	61	68
22	78	74	75	77	81	74	77	81
23	50	35	22	30	36	22	34	50
24	81	88	90	89	107	81	91	107
25	67	70	70	72	78	67	71	78
26	56	49	36	40	46	36	45	56
27	90	85	81	79	77	77	82	90
28	83	79	82	85	83	79	82	85
29	89	76	62	71	77	62	75	89
30	87	88	84	82	87	82	85	88
31	90	89	83	82	83	82	85	90
32	58	42	72	78	81	42	66	81
33	97	107	105	97	99	97	101	107
34	112	110	88	76	82	76	94	112
35	87	104	103	78	72	72	89	104

Table 13 Config. #4 - Peak Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #5 – 6' Parking, 4' Plaza, 8' Parapet
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	97	101	104	99	99	97	100	104
2	94	90	94	97	102	90	96	102
3	100	93	72	58	60	58	77	100
4	79	71	62	58	51	51	64	79
5	81	83	91	91	92	81	88	92
6	78	76	75	76	77	75	76	78
7	94	78	76	67	74	67	78	94
8	0	0	0	18	39	0	11	39
9	78	77	67	71	78	67	74	78
10	107	102	64	59	57	57	78	107
11	120	68	60	59	49	49	71	120
12	58	62	61	55	40	40	55	62
13	78	67	55	57	49	49	61	78
14	80	59	65	67	55	55	65	80
15	61	61	70	71	57	57	64	71
16	59	58	68	64	49	49	60	68
17	81	76	71	68	52	52	70	81
18	88	88	77	73	57	57	77	88
19	91	77	73	74	66	66	76	91
20	61	58	73	75	78	58	69	78
21	65	63	54	67	68	54	63	68
22	79	74	75	77	81	74	77	81
23	47	34	19	36	21	19	32	47
24	82	90	90	92	105	82	92	105
25	69	73	73	74	84	69	75	84
26	70	72	77	81	79	70	76	81
27	54	64	65	66	66	54	63	66
28	33	40	44	63	51	33	46	63
29	78	73	68	75	84	68	76	84
30	83	82	83	86	91	82	85	91
31	96	89	81	83	86	81	87	96
32	30	49	47	55	55	30	47	55
33	94	99	98	96	100	94	97	100
34	126	119	89	74	78	74	97	126
35	87	100	100	78	73	73	87	100

Table 14 Config. #5 - Peak Pedestrian Wind Speeds (% Approach Flow)

Pedestrian Wind Speed Results
Configuration #6 – 6' Parking, 4' Plaza, 4' Road, 8' Parapet
Mean Wind Speed to Avg. Mean Approach Wind Speed (%)

Loc No.	Wind Directions 140	150	160	170	180	Min. Value	Avg. Value	Max. Value
1	101	100	101	102	96	96	100	102
2	97	92	94	99	102	92	97	102
3	98	91	66	60	63	60	76	98
4	70	72	63	56	57	56	64	72
5	82	87	91	91	90	82	88	91
6	78	75	77	75	75	75	76	78
7	90	80	78	76	77	76	80	90
8	0	0	0	28	51	0	16	51
9	77	74	66	67	76	66	72	77
10	105	99	60	62	63	60	78	105
11	118	72	57	58	59	57	73	118
12	59	64	54	62	56	54	59	64
13	76	74	53	66	61	53	66	76
14	81	65	65	66	66	65	68	81
15	57	63	70	71	70	57	66	71
16	58	68	63	68	58	58	63	68
17	80	77	74	71	67	67	74	80
18	88	85	79	75	64	64	78	88
19	91	77	72	71	62	62	75	91
20	61	58	70	73	76	58	68	76
21	65	65	56	55	69	55	62	69
22	78	74	75	77	82	74	77	82
23	49	31	26	0	38	0	29	49
24	81	89	92	91	101	81	91	101
25	52	63	66	56	65	52	60	66
26	70	59	59	69	69	59	65	70
27	55	55	57	63	64	55	59	64
28	40	35	34	25	51	25	37	51
29	76	73	48	48	74	48	64	76
30	87	83	79	80	87	79	83	87
31	93	91	84	83	86	83	87	93
32	48	49	41	39	56	39	47	56
33	96	100	101	93	99	93	98	101
34	116	116	87	44	58	44	84	116
35	85	89	87	47	58	47	73	89

Table 15 Config. #6 - Peak Pedestrian Wind Speeds (% Approach Flow)

Percent Reduction in Mean Wind Speed to Wind for NO Fence Conditions, Config. #1
(Each Value is Maximum over All Wind Dir.)

Loc No.	Configuration 2	3	4	5	6
1					
2					
3	-33	-42	-38	-37	-37
4	-44	-52	-56	-72	-77
5	-21	-38	-29	-32	-30
6	-47	-63	-58	-54	-56
7	-25	-40	-33	-29	-31
8	0	0	0	0	0
9	-2	-6	-8	-9	-7
10	-30	-50	-49	-41	-41
11	-13	4	2	-21	-23
12	-32	-62	-70	-88	-87
13	4	2	3	-31	-39
14	-42	-48	-46	-67	-65
15	-58	-83	-71	-70	-68
16	-57	-61	-75	-73	-72
17	-44	-54	-51	-52	-51
18	-31	-57	-43	-45	-43
19	-4	-14	-13	-9	-11
20	-5	-6	-6	-12	-8
21	-5	-16	-14	-7	-3
22	-1	-7	-9	-8	-6
23	3	0	0	0	3
24	-20	-30	-30	-31	-30
25	2	1	1	8	-56
26	1	6	-83	4	-36
27	-4	-2	-4	-52	-56
28	-1	2	-0	-74	-88
29	-2	-5	-9	-25	-39
30	-0	-5	-12	-5	-11
31	-13	-20	-15	-18	-19
32	-1	-6	-47	-90	-90
33	-4	-9	-8	-13	-16
34	-0	-6	-5	6	-0
35	-3	2	-6	-20	-35

Percent Reduction in Mean Wind Speed to Wind for NO Fence Conditions, Config. #1
(Each Value is Average over All Wind Dir.)

Loc No.	Configuration 2	3	4	5	6
3	-47	-68	-60	-63	-66
4	-69	-70	-73	-80	-83
5	-20	-33	-28	-25	-24
6	-49	-69	-63	-58	-57
7	-36	-65	-55	-56	-48
8	0	0	0	0	0
9	3	-3	-1	-2	0
10	-46	-73	-69	-70	-69
11	-66	-67	-68	-73	-73
12	-50	-69	-81	-85	-85
13	-41	-45	-44	-67	-56
14	-53	-75	-67	-78	-73
15	-66	-88	-79	-82	-78
16	-66	-82	-78	-82	-81
17	-53	-64	-63	-65	-59
18	-43	-71	-59	-60	-56
19	-25	-47	-45	-40	-46
20	-6	-12	-16	-16	-22
21	9	-19	-12	1	-5
22	-1	-5	-11	-11	-11
23	-19	1	0	1	-19
24	-22	-42	-34	-34	-35
25	-1	5	11	24	-62
26	-0	-6	-72	31	-36
27	0	-1	-6	-64	-77
28	3	1	-0	-83	-86
29	-5	-10	-22	-30	-48
30	-2	-7	-11	-19	-23
31	-8	-17	-13	-16	-20
32	-2	-7	-59	-88	-88
33	-5	-12	-11	-21	-20
34	4	-2	-8	-7	-32
35	-15	-20	-26	-36	-56

Table 16 Mean Wind % Reduction over No Fence Configuration