COMPARISON OF MODEL AND FULL SCALE NATURAL VENTILATION STUDIES

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1. INTRODUCTION

Historically, man has achieved human comfort in summertime by opening building windows and ventilating. Design guidelines on window size, shape, placement in buildings have been suggested after investigating scale model buildings in uniform speed tunnels in the fifties and early sixties (Refs. 1, 2, 3) and later on by model testing in boundary layer wind tunnels (Refs. 4, 5, 6). To our knowledge, except for the qualitative flow visualization comparisons performed by the Texas researchers (Ref. 7), the literature is devoid of any quantitative comparison of model and full scale naturally ventilated buildings. This is why, as part of our investigation into quantitative understanding of natural ventilation, we decided to undertake this comparison of full scale and model scale internal velocities of naturally ventilated rooms. The full scale studies were performed at the Florida Solar Energy Center in Cape Canaveral, Florida. The model scale studies were performed by the Colorado State University Fluid Dynamics and Diffusion laboratory personnel under the guidance of Dr. Jack E. Cermak.

2. FULL SCALE AND MODEL BUILDINGS

The FSEC site is located within a mile of the Atlantic Ocean as shown in Figure 2.1. The FSEC Passive Cooling Lab (PCL), an experimental building with a fixed roof supported by columns whose floor plan and ceilings are reconfigurable, is the building used in this study. Figure 2.2 is a photograph of the PCL showing its south and east facades. The east wall shows the two 120° overhangs above the openings. This southeast room was the room where the ventilation experiments were carried out. Figure 2.3 shows a closer view of the southeast room with the wingwalls in place. The purpose of the wingwalls are to hopefully increase the ventilation in the room for south, southeast, northeast and northerly winds. The room is not otherwise cross ventilated. Figure 2.4 shows the surrounding buildings -- this photo was taken from a point approximately 400 feet southeast of the PCL.

For testing in the CSU wind tunnel, they built a 1:25 scale model faithfully reproducing the PCL with its movable walls and ceilings. The model was constructed from 1/16" (for roof) and 3/16" thick (for walls) acrylic with steel and aluminum framing as needed. Figure 2.5 shows the floor plan of the PCL. The southeast room is the test room. The velocities and pressure taps for this room are shown in the drawing. All measurements were at mid room height (i.e., 4'0" full scale) above PCL floor in the model. Table 1 compares the model and full scale dimensions as tested.

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C.U.P. 1982. T.A. Reinhold (Editor)

Table 1. Model and Full Scale Dimensions as Tested
Nominal Model Scale is 1:25

Dimension	Model	Full Scale	Scale
Interior room length	217 mm	17.60 ft	1:24.7
Interior room width	141 mm	11.70 ft	1:25.3
Interior room height	95 mm	8.05 ft	1:25.8
Window width	48.5mm	3.88 ft	1:24.4
Window Height	36.5mm	3.00 ft	1:25.0

3. EXPERIMENTAL PROCEDURES

The full scale tests were conducted during evening and early night hours so that atmospheric ΔT was nearly zero corresponding to a thermally neutral atmosphere like that in the wind tunnel. The atmospheric measurements consists of six instruments on a mast located about 150 feet away from the building. The mast had instrumentation at two levels, approximately 10 m and 1 m above ground. Each level had a precision cup anemometer (threshold 0.5 mph, full accuracy 1.5 mph), wind vane and a thermocouple in a naturally aspirated radiation shield. The velocities inside the room were measured by a TSI model 1620 omnidirectional air speed probe. These appear to have an accuracy of ±10% over a range of 0.1 to 5 mph.

The probes have a small (2 mm) sphere with hot wires as the sensing element and are temperature compensated. They have a nonlinear output which was curve fitted and read by the data processing software. The response time constant of the field probels are given in Table 2.

Table 2. Response Time for Field Probes

Probe	Time Constant
omniprobe	< 2 seconds
cup anemometer	< 2 seconds
wind vane	< 10 seconds

Generally only one omniprobe was present in the room at location #1 or #2. As noted later, most of the time, the height above floor was 4'5" rather than 4'0". Some data was also obtained by bringing the lower cup anemometer from outside to location #1 inside.

All data channels were simultaneously recorded every 10 seconds, the fastest scan rate available. Typically, data were averaged over five minute intervals.

The CSU, Fluid Dynamics and Diffusion Lab meteorological wind tunnel (MWT) was used for all model studies (Figure 3.1). Neighbouring buildings were modeled from styrofoam or masonite and installed upwind as appropriate. An atmospheric surface layer approximately 30 m deep was simulated by following techniques recommended by Cook (Ref. 8). Six-ft wood spires were positioned across the MWT at the test section entrance. These were followed by a 7-inch trip and varying degrees of

surface roughness. The four spires were located at 17-inch intervals, while the trip was continuous across the tunnel. In addition, 7.87-inch roughness cubes were positioned near the MWT entrance to further enhance development of the desired boundary layer. The floor of the test section was covered with 28 feet of one-inch roughness cubes, followed by 48 ft of one-half inch roughness and terminated with 8 ft of one-quarter inch smooth masonite upon which the PCF model rested. Graphic illustration of the MWT configuration (complete with pertinent dimensions) is included _ Figure 3.2 and 3.3.

The velocities were measured by quick response hot film anemometers with the sensor axis vertical. TSI 1211-10 and 1210-20 cylindrical hot film sensors were used. CSU experience has been that mean velocities measured are accurate to ±10 percent, similar to expectations of full scale accuracy.

4. RESULTS

The full scale tests were conducted during February and March of 1982. Four out of five of the full scale data sets reported here correspond to a thermally neutral atmosphere with a ΔT <0.1°C and were collected during the evening and early night hours with ambient temperatures between 19°C and 21.5°C. Wind speeds ranged between 4 and 16 mph encompassing the speeds prevalent during ventilation conditions (4-7 mph or less) and stronger winds. Wind directions were generally between east and south -- summertime directions coming from the ocean.

Figures 4.1 and 4.2 compare the full scale and model scale internal to external velocity ratios for several wind directions. In 4.1 one sees the comparisons for the configuration without the wingwalls for internal probe location #1 (see Figure 2.5) Note that the field data overlapped for two different days (3/13 and 3/14) for WD = 135 and were about 30 percent lower than the model data. The data set for WD = 90, collected daytime under bright sun and high ΔT and fairly low winds (4-6 mph) appear to be ≅ 30 percent higher than the model data.

All three sets of data in Figure 4.2 are for the configuration with the wingwalls in place for internal probe location #2 (see Figure 2.5). All data are for nearly neutral atmospheres. Unfortunately the field and model internal probe locations were not identical in the z coordinate as noted in the graph. As can be seen, for WDs of 135 and 180 (SE and S) the full scale ratios exceed the model scale by about 30 to 40 percent and for WD = 90° by about 200 percent.

In order to understand this discrepancy, Figures 4.3 through 4.6 were drawn from the data of 2/2, 2/15 and 2/16. (Figure 4.6 contains some additional points.) Figure 4.3 compares the atmospheric velocity ratio at 1.1 m and 9.7 m above ground. It can be seen that the atmospheric mean speed variation with height is well modeled in the tunnel and so is the turbulence at the lower level as evidenced by Figure 4.4. However, Figure 4.5 shows that the atmospheric turbulence at the 9.7 m level is about twice as great as the tunnel. This is perhaps explained

by the fluctuations in the atmospheric wind direction shown in Figure 4.6. The wind tunnel fluctuations in wind direction are less than perhaps two degrees.

5. DISCUSSIONS

It may be useful to list and discuss the differences during the full scale and model tests.

i) Small dimensional differences -- See Table 1. Due to the likely predominantly 2-D nature of the flow at the internal velocity probe locations, this is unlikely to explain the large observed differences.

ii) Differences in the probe types -- The external wind measurements were done by sensitive cup anemometers which should measure the same mean horizontal vector wind speed as the vertical hot film probe in the model scale. One could argue that since the wind tunnel internal probe measured only the horizontal mean airspeed and the full scale internal probe was omni-directional, the model mean velocities would be lower if the mean flow was three dimensional. To check this, full scale tests were conducted where the omni-directional probe and a cup anemometer were placed as close together as possible at measurement location #1, with the small (2 mm) omni probe upstream of the 6-inch cup to minimize interference. Figure 4.7 compares the readings from the two probes. The higher airspeeds were obtained with the wingwalls with the probes 4'5" above the floor and the lower airspeeds (< 0.5 mph) for probes located 4'0" above the PCL floor and without the wingwalls. Both sets of data were for southeasterly winds.

It can be seen that below about 1.5 mph the cup reads lower than the omniprobe, and above 1.5 mph the readings are essentially identical. It could be that at lower airspeeds the airflow is more three dimensional but the more likely reason for this behavior is the fact that the cup threshold is 0.5 mph and full accuracy of the cup is not reached until 1.5 mph. With this information, we proceeded to plot V_1 (omniprobe) and U_1 (cup) as shown in Figure 4.8 for the criterion of $U_1 > 1.5$ mph. A cup at 10 meters was not available and so the U_1 and V_1 were nondimensionalized with an outside atmospheric cup anemometer located level with the internal probes or at 1.57 m above ground. The other difficulty with this data set was due to an instrumentation problem with the WD vane. Lot of data on WD had to be discarded and as a result only 1 minute (6 point) averages could be plotted on figure 4.8. (All the other graphs have been plotted with 5 minute averages). In spite of the data scatter it does appear that there is closer agreement between full scale and model data.

iii) Height Differences -- The PCL floor is 8½" above zero ground (≡ CSU tunnel floor) and that is the way it was built at CSU. However, the real ground is wavy and the field mast base is actually 9½" below zero ground. There was some confusion in sensor heights. The

model scale results were taken with internal probes located at midheight of the room and external measurement reported with tunnel floor as zero height. As noted earlier, prior to March 12, 1982 all field internal probes were located at slightly above room midheight (4'5" above PCL floor rather than @ 4'0"). The outside cup locations also varied with the 10 m cup at 9.7 meters before 3/12/82 and at 9.9 m after. The lower cup was at 1.1 m before 3/1/82 and at 1.57 m during 3/4 and 3/5/82. These should cause only minor differences in the comparisons.

iv) Reynolds No. differences -- The model test were conducted at a Re of 1.26e+05 corresponding to a tunnel speed of 21.5 mph (9.6 m/sec), a kinematic viscosity of 1.7e-05 sq.m/sec and a model aerodynamic radius of 0.224m. The full scale Re equals 1.68e+05 per mph of wind speed for a kinematic viscosity of 1.5e-05 sq.m/sec. So full scale Re for the 4-16 mph range would vary between 6.7 and 26.9e+05 -- 5 to 20 times greater than model scale. However, a plot of internal airspeed vs. Re for NE winds showed it to be independent of Re for Re > 0.7e+05 although the internal turbulence intensity kept on varying up to Re=1.26e+05. This would seem to imply Re would have little effect on mean internal airspeeds.

v) Time Scale and Wind Direction -- If a time scale is defined as the aerodynamic radius divided by the wind speed, the tunnel time scale was 0.01 seconds and the field time scale varied between 0.78 and 3.13 seconds corresponding to 16 to 4 mph winds. This in conjunction with the differences in wind direction variations and sensor time constants may explain part of the differences between field and model scale turbulence intensities.

vi) Nature of Flow -- The mean pressure differences at the apertures (closed) without the wingwalls are very small. Table 3 lists the Cp's for the two pressure taps #24 and #26 (see figure 2.5) as measured in the model.

TABLE 3. Mean Pressure Coefficients (Cp's) at taps #24 and #26

WD	#24	#26	ΔCp
90 E	+0.517	+0.472	0.045
135 SE	-0.096	-0.134	0.038

Indeed the forcing mean pressures are about an order of magnitude smaller than that prevalent for cross ventilated rooms. So the flow will definitely be affected by turbulence characteristics. So for these cases the disagreements as seen in figures 4.1 and 4.2 are perhaps not surprising in view of figure 4.5 which shows that the turbulence at the 10 m level was not exactly modeled. The large 200 percent discrepancy for easterly winds with wingwalls can be due to the highly unsteady nature of the flow. Full scale smoke pictures taken show that the apertures were alternating as inlets and outlets. Moreover there are not sufficient number of data points near WD = 90.

However, comparing and extrapolating the V_1's for the southeastern winds one notes that full scale $V_1/U_{9.9}$ goes from about 0.07 for no wingwall

(Figure 4.1) to about 0.4 with the wingwall (figure 4.8, assuming $U_{1.57}/U_{9.9} \sim 0.7$) -- a 500% increase! This seems to indicate that now the flow is predominantly mean pressure driven. And indeed the discrepancy between model and full scale appears to decrease (Figure 4.8).

6. CONCLUSIONS

To the authors' knowledge, this is the first time quantitative comparisons have been performed for model and full scale naturally ventilated structures. The results show small disagreements between full scale and model internal velocities for flows not driven by mean pressures. This is partly explained by the inexact modelling of the atmospheric turbulence of speed and direction. For flows which are mean pressure driven, e.g., SE winds with wingwalls, the agreement between model and full scale internal velocities are quite good.

These data lead us to believe that boundary layer wind tunnel testing is indeed a good method for performing tradeoff studies as has been done by Sobin, Aynsley and Vickery (Refs. 4, 5, 6) -- especially since in good natural ventilation designs, airflows are produced mainly by mean pressure differences.

Future research should be aimed at turbulence modelling (vibrating the model in the tunnel may be an interesting approach). Also some model to full scale comparisons should be conducted with uniform speed wind tunnels to determine the validity of existing natural ventilation data collected in uniform speed tunnels.

7. NOMENCLATURE

TI - Turbulence intensity defined as standard deviation divided by the average of the instantaneous airspeed indications.

U - Mean airspeed in the horizontal plane i.e. all model velocities and all full scale velocities measured by the cup anemometers. Subscripts 1 and 2 i.e., U_1, U_2, refer to locations #1 and #2 in Figure 2.5. Two or three digit subscripts like $U_{1.57}$ or U_{10} refer to free stream velocity at 1.57 or 10 m (full scale) above ground.

V_1, V_2 - Mean airspeed measured in full scale by the TSI omniprobes (model 1620)

Δ T - Atmospheric temperature difference in the field between that measured at 0.71 m and 9.46 above zero ground.

WD - Wind Direction with respect to the PCL measured at a height of 9.7 or 9.9 m above ground.

8. ACKNOWLEDGEMENTS

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colleagues at the Colorado State University, Fluid Dynamics and Diffusion Laboratory, in conducting the model tests. This work is funded by U.S. Department of Energy, San Francisco Operations office, contract No. DE-AC03-SF11510 under the Passive and Hybrid Solar Cooling program; Ms. J. Neville, program manager.

9. REFERENCES

1. Texas A&M research reports #22, 33, 36, 45, 50 now out of print. For a summary by one of the original authors see Evans, B.H., "Energy Conservation with Natural Airflow Through Windows," ASHRAE Transactions, vol. 85, part 2, 1979, pp 641-650.

2. Van Straaten, J.F., Thermal Performance of Buildings, Elsevier Architectural Science Series, Elsevier 1967, ch. 14.

3. Givoni, B., Man, Climate and Architecture, 2nd Ed. Applied Science, London, 1976.

4. Sobin, H., Window Design for Passive Ventilative Cooling: An Experimental Model Scale Study, Proceedings, AS/ISES International Passive and Hybrid Cooling Conference, Maimi Beach, 1981, pp. 191-195.

5. Aynsley, R.M., Tropical Housing Comfort by Natural Airflow, Building Research and Practice, U.K. July/August 1980, pp 242-252. Also see Proceedings of the Fifth International Wind Engineering Conference, Fort Collins, CO, 1979, Pergamon Press.

6. Vickery, B.J., The Use of Wind Tunnel in the Analysis of Naturally Ventilated Structures. Proceedings - AS/ISES International Passive and Hybrid Cooling Conference, Miami Beach, 1981, pp. 728-742.

7. Smith, E.G., The Feasibility of Using Models for Predetermining Natural Ventilation. Research Report #26, Texas Engineering Experiment station, Texas A&M University, June 1951.

8. Cook, N.J., "Determination of the Model Scale Factor in Wind Tunnel Simulations of Adiabatic Atmospheric Boundary Layer," J. Industrial Aerodynamics, vol. 2, No. 4, pp 321-331.

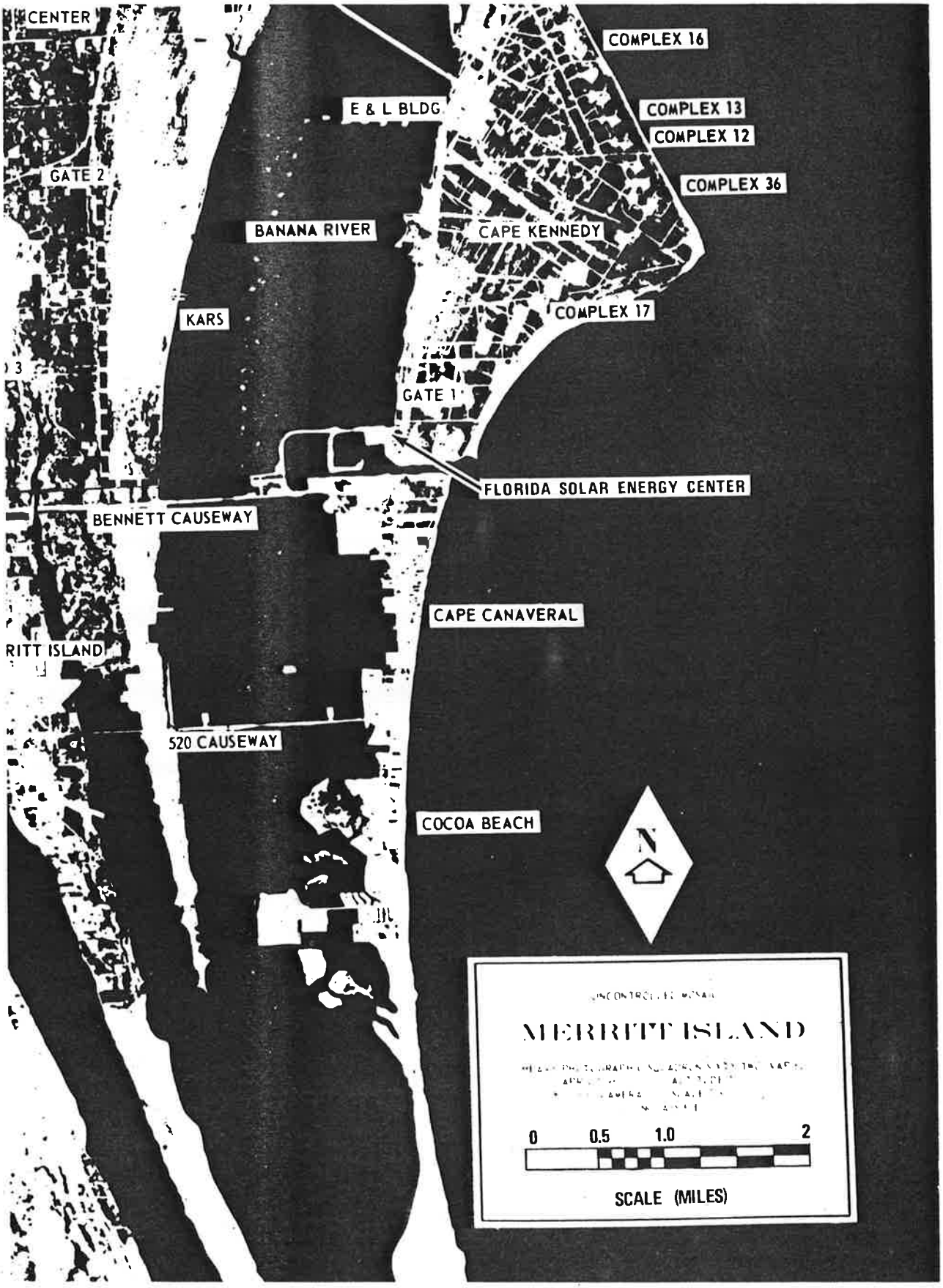

FIGURE 2.1 FSEC Site and Surrounding Area

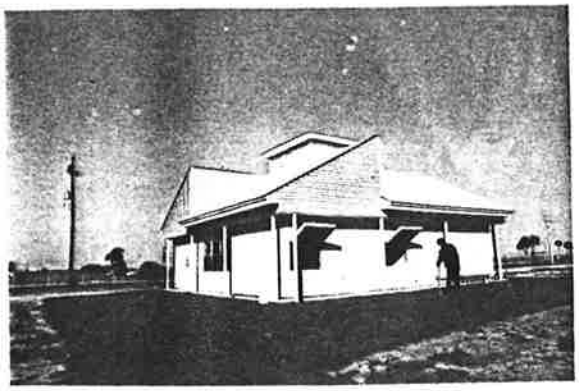

Figure 2.2 The FSEC PCL, SE view without wingwalls

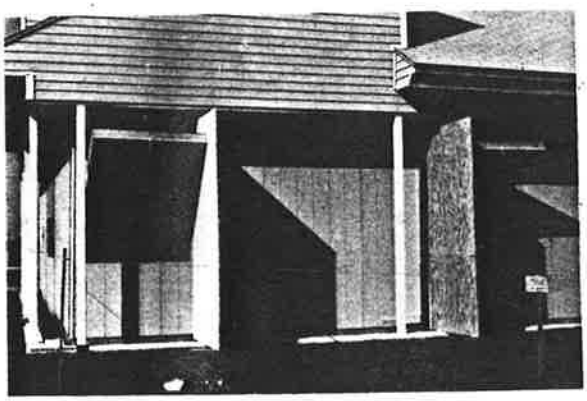

Figure 2.3 Closeup of the test room exterior showing the removable wingwalls in place

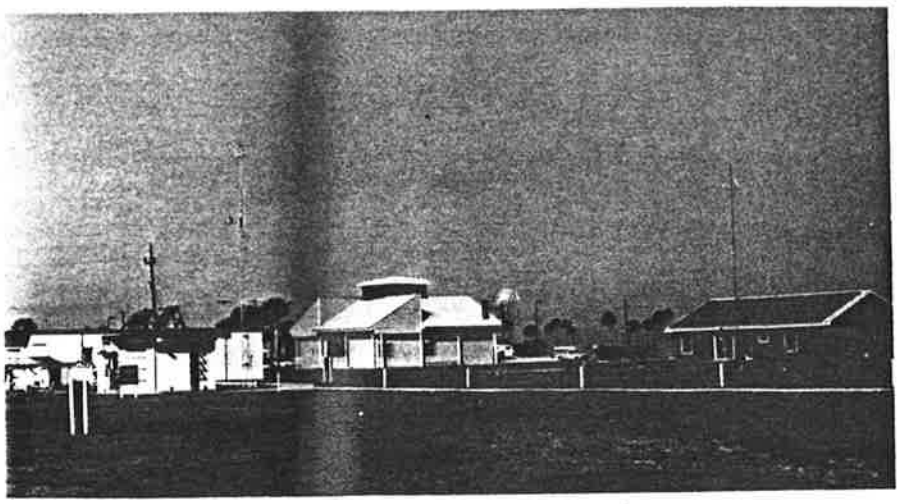

Figure 2.4 Buildings near the PCL (SE view from a point about 400 ft. from PCL)

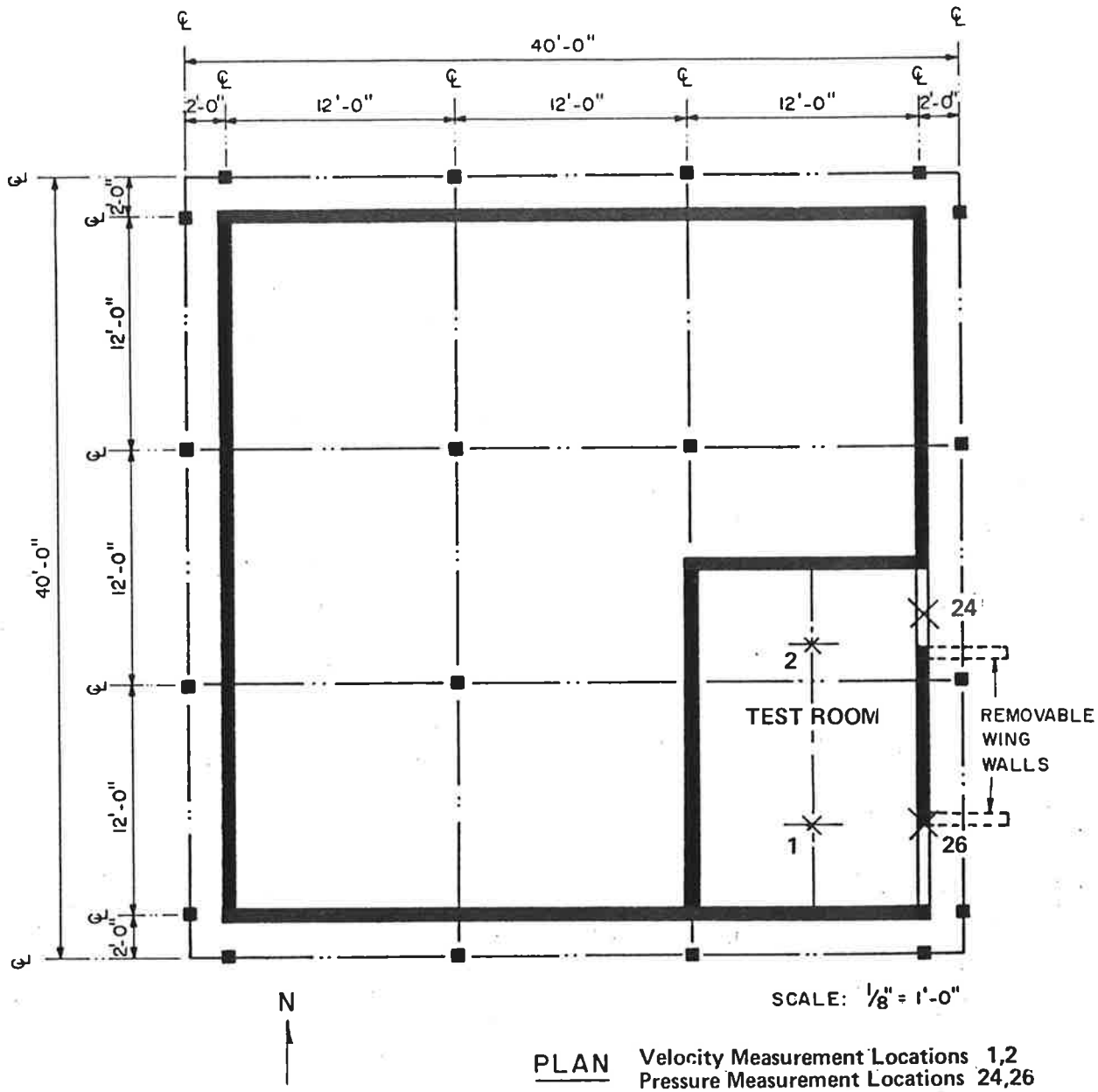

FIGURE 2.5. Plan View of the PCL Model
(full-scale dimensions showing velocity and pressure locations)

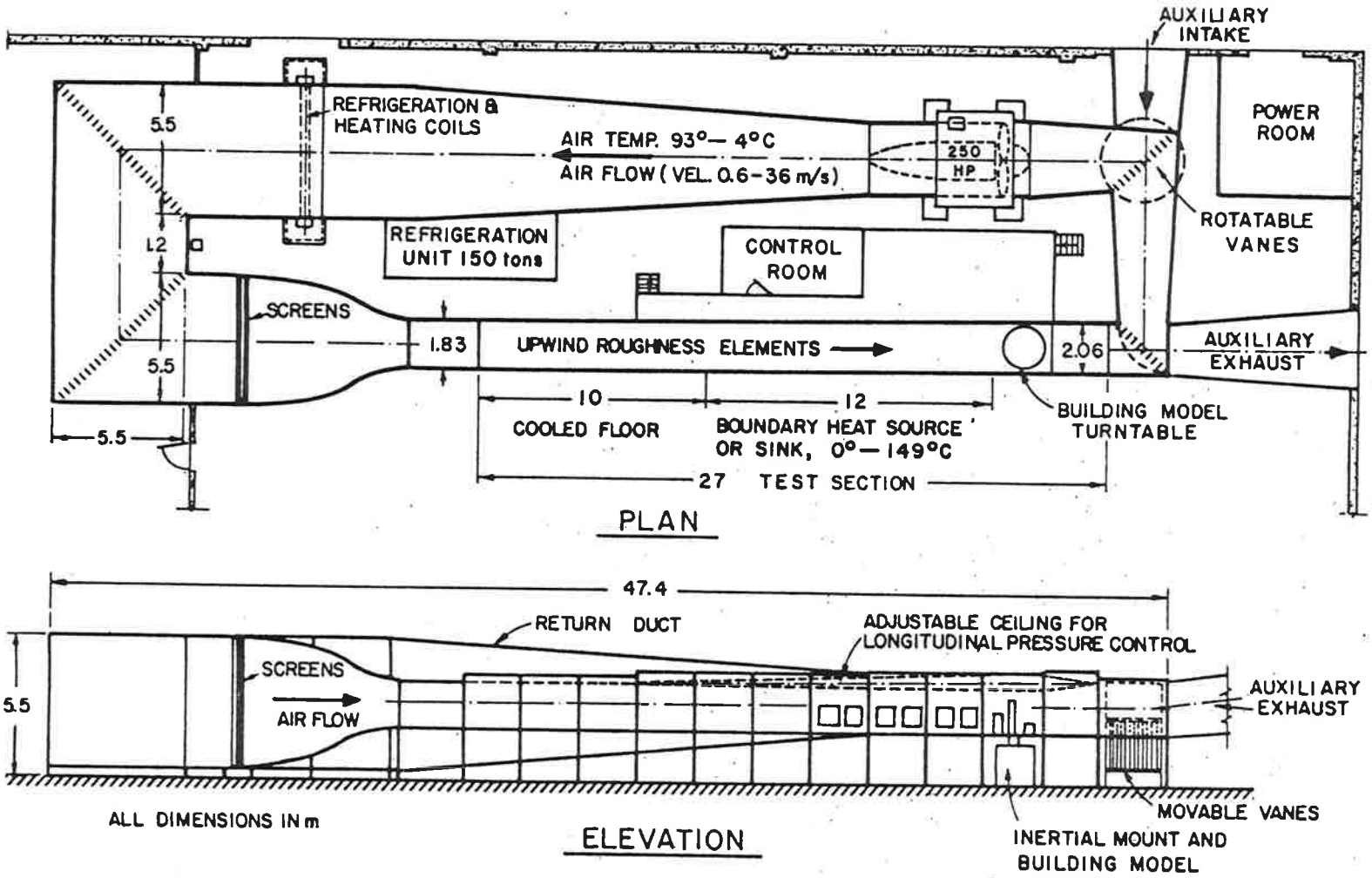

FIGURE 3.1. METEOROLOGICAL WIND TUNNEL
FLUID DYNAMICS & DIFFUSION LABORATORY
COLORADO STATE UNIVERSITY

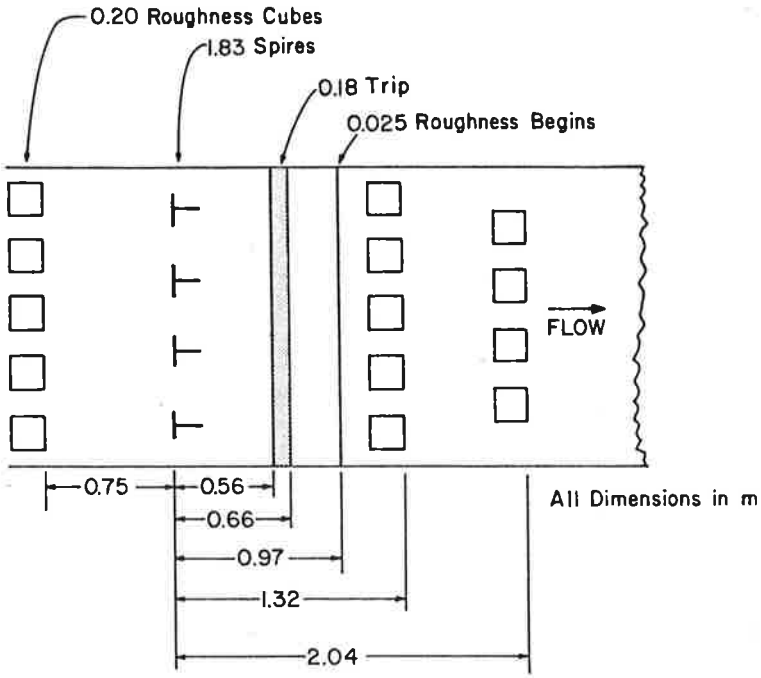

FIGURE 3.2. Wind-Tunnel Entrance Configuration for Passive Cooling Laboratory Study

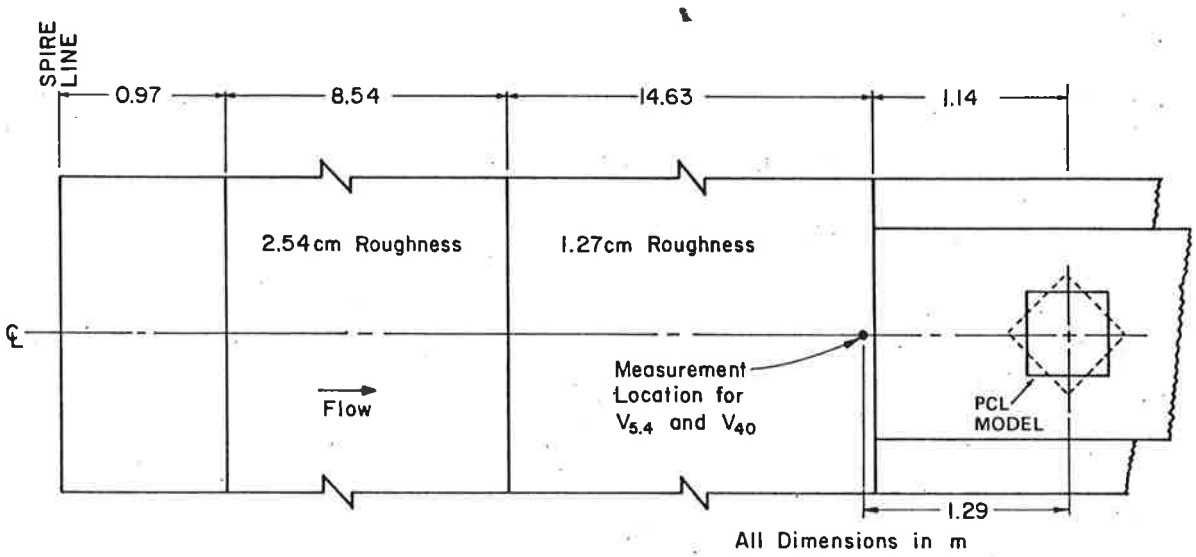

FIGURE 3.3. Wind-Tunnel Test Selection Configuration for Passive Cooling Laboratory Study

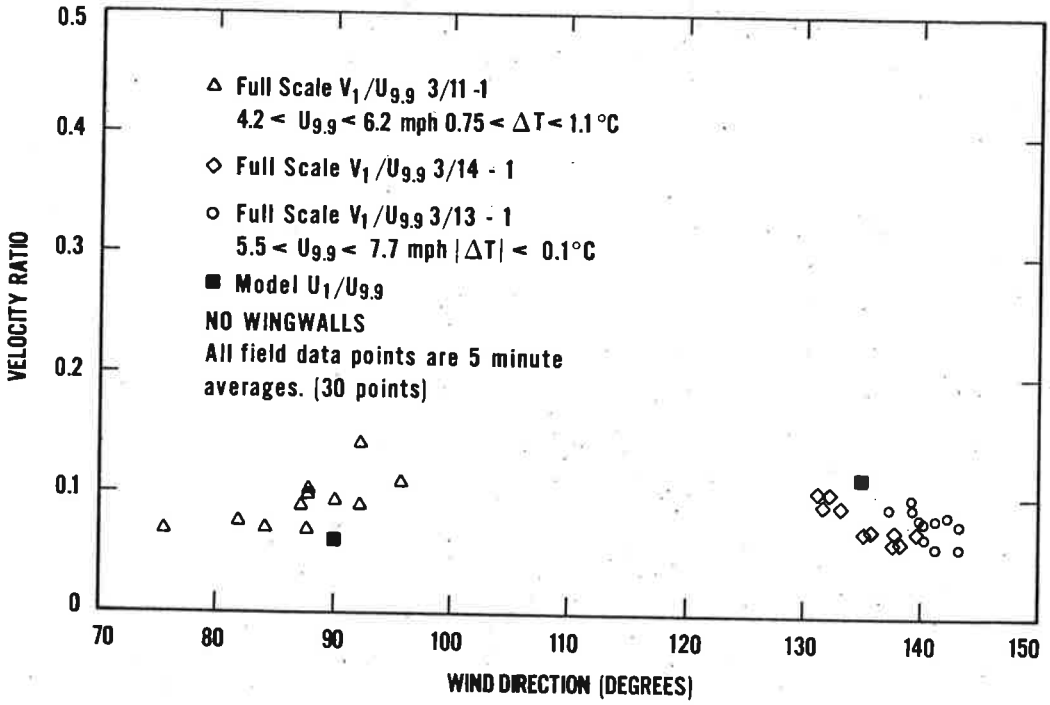

Figure 4.1 Comparison of full scale and model internal velocities without wingwalls

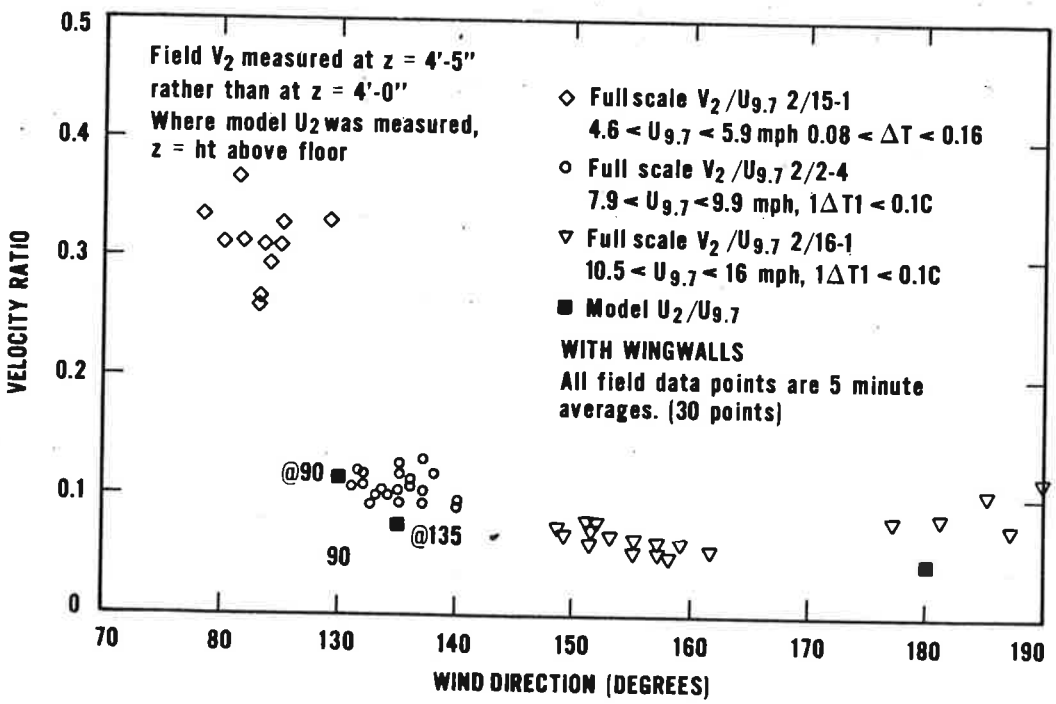

Figure 4.2 Comparison of full scale and model internal velocities with wingwalls

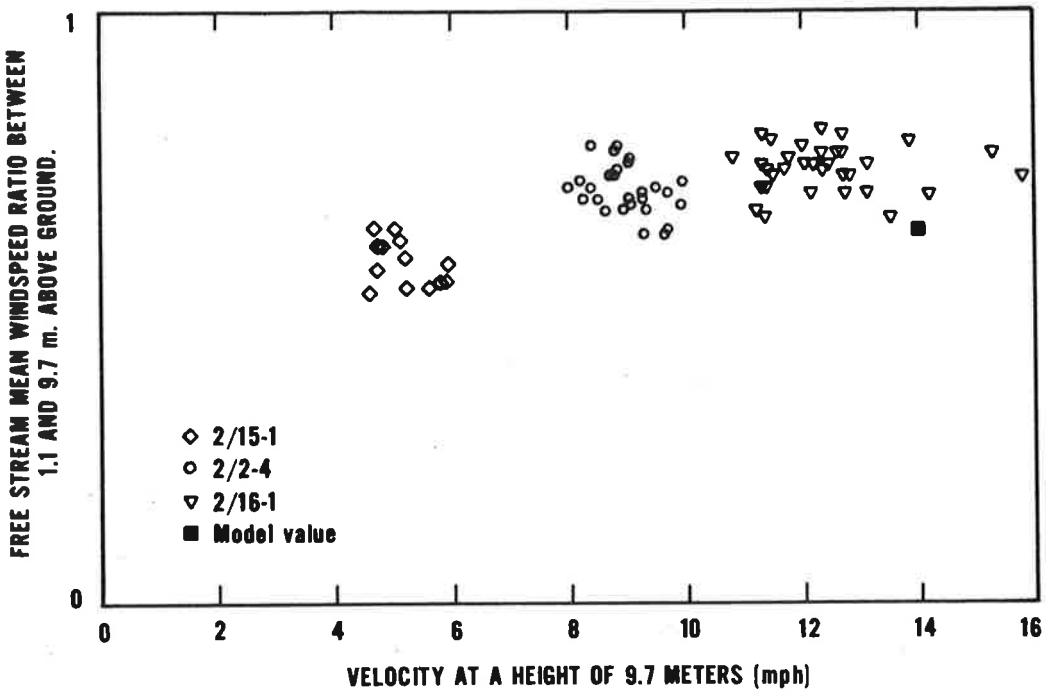

Figure 4.3 Comparison of mean windspeed variation with height

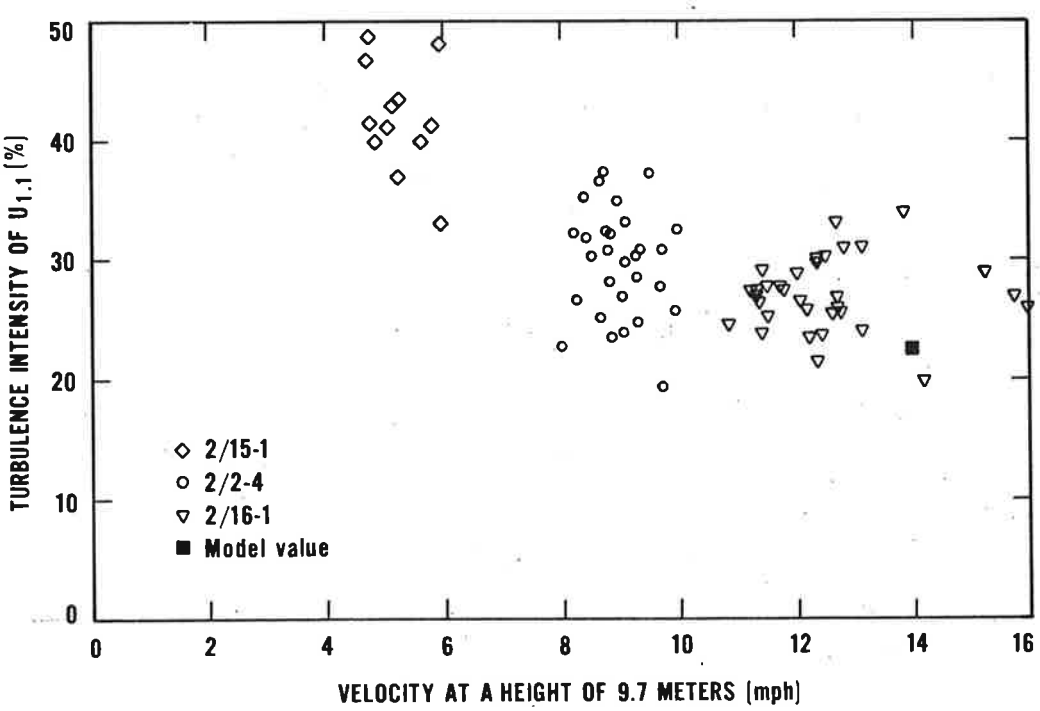

Figure 4.4 Comparison of full scale and model free stream turbulence intensities at 1.1 m. (full scale) above ground.

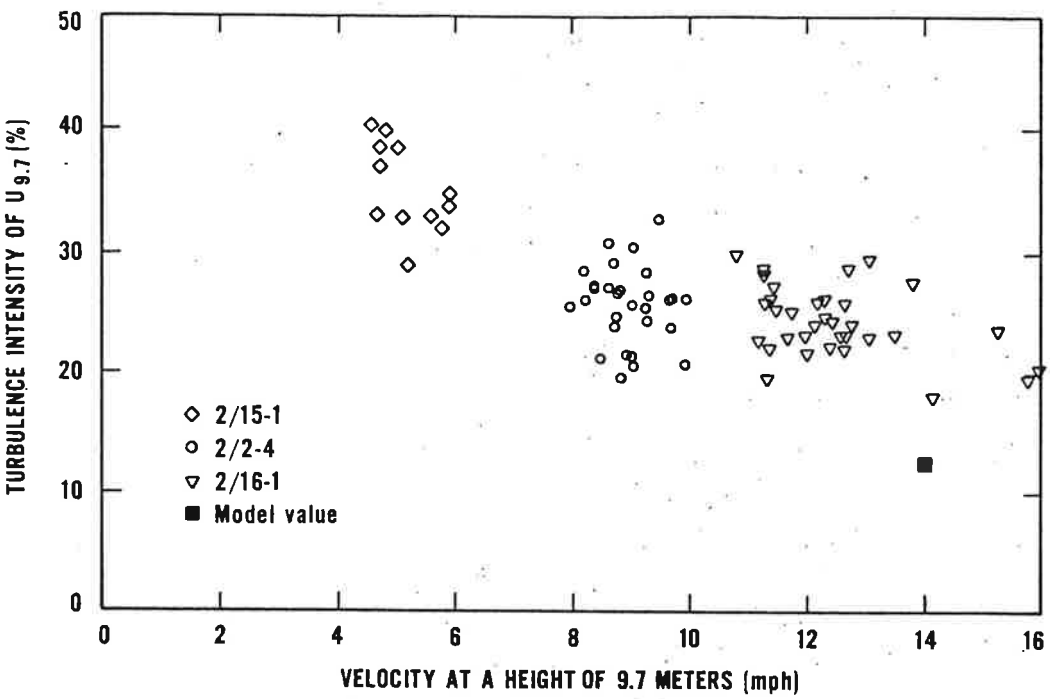

Figure 4.5 Comparison of full scale and model free stream turbulence intensities at 9.7 m. (full scale) above ground.

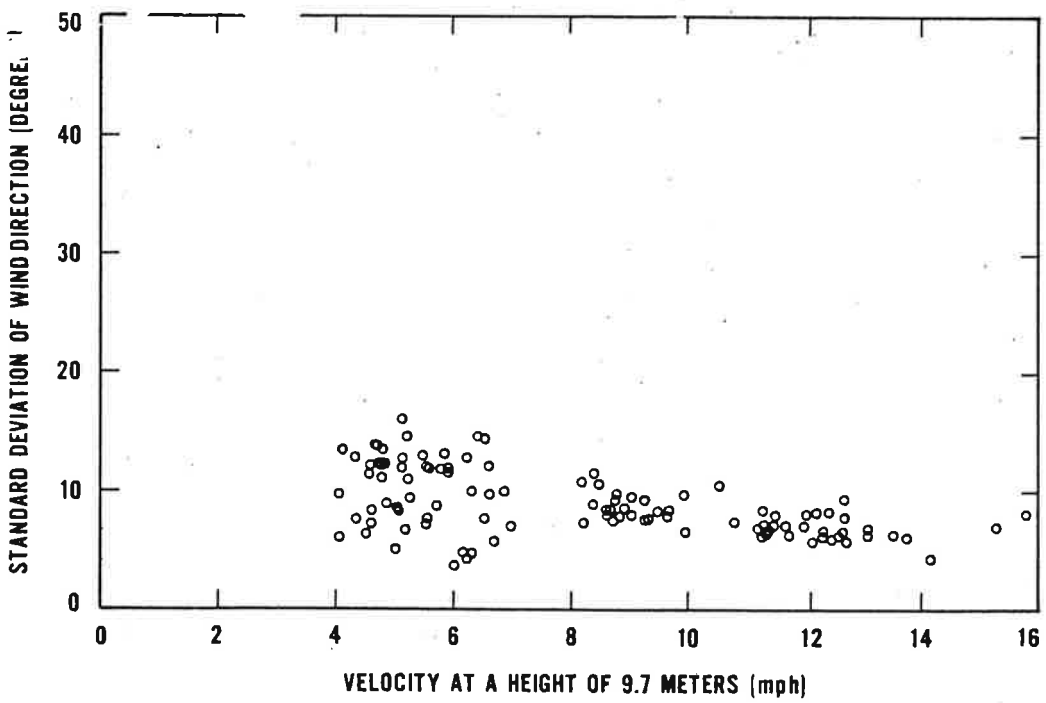

Figure 4.6 Full scale fluctuations of wind direction

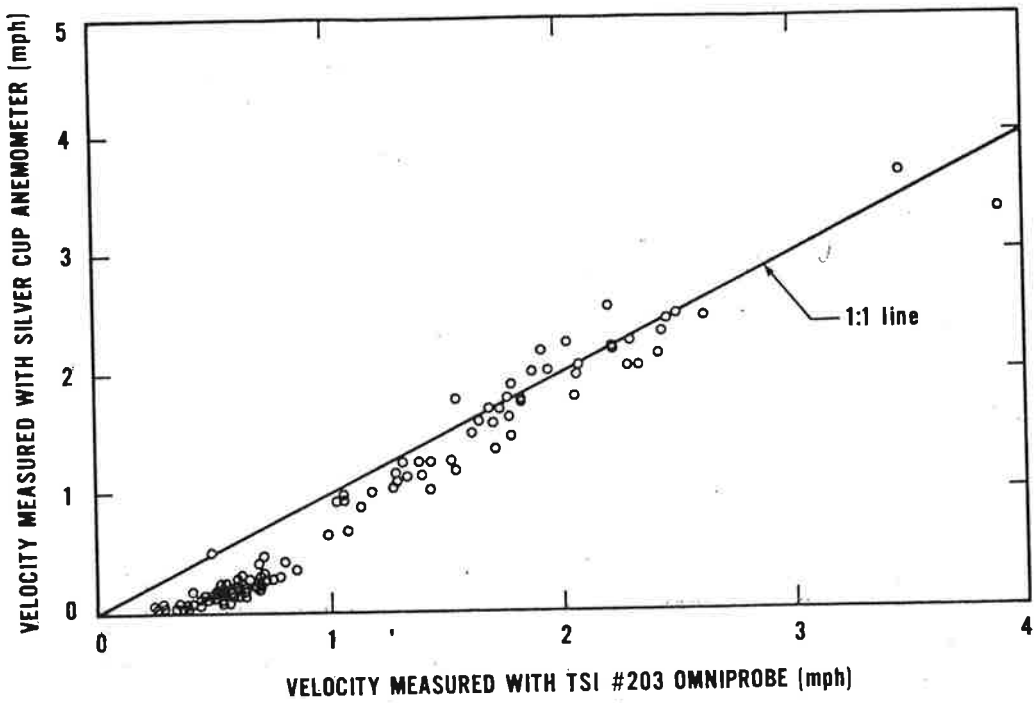

Figure 4.7 Comparison of omnidirectional probe and cup anomometer both located at position 1

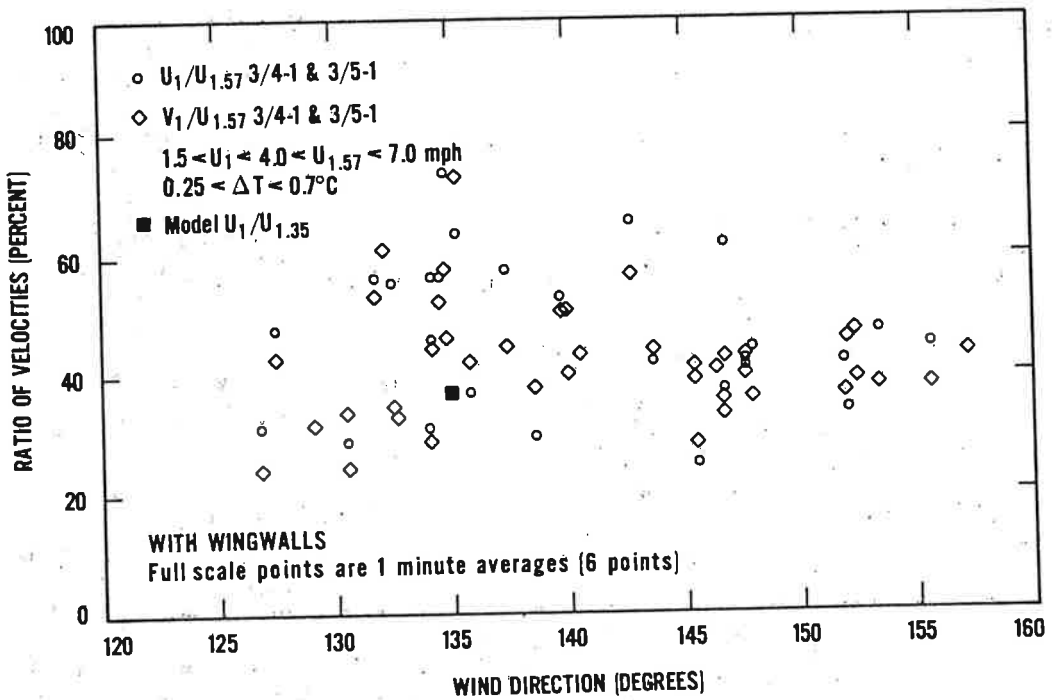

Figure 4.8 Comparison of full scale and model internal velocities at location 1