Journal of Wind Engineering and Industrial Aerodynamics, 41-44 (1992) 2353-2364
Elsevier

Analysis and wind-tunnel simulation of pedestrian-level winds in San Francisco

Bruce R. White[a]

[a]Department of Mechanical, Aeronautical and Materials Engineering, University of California, Davis, CA 95616, U.S.A.

Abstract

The city of San Francisco enacted a pedestrian-level wind ordinance as part of its city and county municipal code in 1985. The purpose of this paper is to present in engineering detail the wind tunnel testing procedure and associated analysis which allows scaling of the wind-tunnel measurements. This technique uses site specific meteorological weather data, coupled with the wind-tunnel data, to predicted full-scale wind speeds. The full-scale speeds are presented in terms of 10% exceeded equivalent wind speeds as required by the wind ordinance. Also, a description of the wind-tunnel facility in which many of the pedestrian-level wind studies are carried out is presented.

1. INTRODUCTION

The San Francisco Downtown Plan, adopted in 1985 by the city of San Francisco, established separate criteria for comfort in areas of substantial pedestrian use, for comfort in public seating areas, and for wind safety.

The wind intensity is defined in terms of equivalent wind speed. This term denotes wind speed averaged over an hour (hourly mean windspeed), modified to include the level of gustiness, or turbulence, expected on site. The equivalent wind speed as calculated assumes an unaltered wind with an inherent turbulence intensity of 15% of the hourly mean windspeed value. The turbulence intensity is defined as the root mean square (rms) of the instantaneous deviations from the value of the mean velocity, divided by the mean velocity value. When turbulence intensity at a measurement point is greater than 15%, the mean velocity is multiplied by two times the turbulence intensity plus 0.7 to create its equivalent windspeed. This equation follows from relationships developed by Hunt et al. (1976) and Jackson (1978) in which winds with different turbulence intensities were compared to each other for their effects on pedestrians.

The comfort criterion for seating areas is 7 mph (3.1 m/s) equivalent wind to be exceeded not more than 10% of the time year round between the hours of 7 a.m. and 6 p.m. The wind speed criterion is based on wind effects summarized in Penwarden (1973), Melbourne (1978), and Arens (1981). The time interval, chosen by the Department of City Planning (DCP), represents the period when most of the population is exposed to the wind; the 10% figure also was chosen by DCP. It is essentially an environmental quality decision, based on Penwarden's study (1973) of wind complaints in shopping centers. Penwarden found that substantial complaints occurred when the limit of comfortable wind speed was exceeded more than 10% of the time.

The comfort criterion for pedestrian areas is an 11 mph (4.9 m/s) equivalent wind to be exceeded not more than 10% of the time year round between the hours of 7 a.m. and 6 p.m. The wind speed part of this criterion is based on the original 11 mph (4.9 m/s) limit used by Penwarden (1973); Hunt, et al. (1976); Melbourne (1978); and others. The time interval and the 10% exceedance figure are based on the same logic as the criterion for seating areas.

0167-6105/92/$05.00 © 1992 Elsevier Science Publishers B.V. All rights reserved.

For the two comfort criteria described above, the averaging period for the mean velocity is on the order of a minute, the length of time over which U.S. Weather Bureau observers make their hourly observations. This interval is sufficiently close to the length of time that the wind actually takes to affect people's comfort that the Weather Bureau data can be used directly to satisfy these criteria.

In the Downtown Plan, the criterion for wind safety is specified in terms of true hourly wind speeds instead of the one-minute averaged wind speeds of the U.S. Weather Bureau. Based on a relationship taken from Lawson (1978), a 26-mph (12 m/s) hourly-averaged wind will be equivalent to a 3-second gust that reaches the 44 mph (20 m/s) hazard limit. Similarly, that 44 mph (20 m/s) gust is reached when the one-minute averaged speed is 36 mph (16 m/s). This 36 mph (16 m/s) value is used to test safety compliance with the Downtown Plan.

The detailed history of development of San Francisco's wind ordinance is presented by the ordinance authors in Arens et al. (1989). Included in our discussion is the underlying motivation for usage of the 10% exceeded wind-speed value, the early problems encountered with the acquisition of reasonable site-specific weather data (which still presents a problem of a lesser degree today for the hazard criterion), and the suggested correction factors to the weather data due to influence of local building effects on the anemometer data.

The Appendix presents the original wording of the wind ordinance which is taken from Section 148 of the *City and County of San Francisco Municipal Code: Planning Code Volume I*. Additional amendments to the wind ordinance also have been made (Ordinance 537-88, Approved December 12, 1988, amended by Ordinance 79-89, Approved March 24, 1989; and Ordinance 115-90, Approved April 6, 1990). The guidelines and testing procedures have remained same; however, the amendments effectively have given more latitude to city officials in granting, what this author thinks, are reasonable exceptions to proposed building designs that cannot meet the precise requirements of ordinance. Although some of the specific legal and technical requirements for compliance within the city ordinance have been relaxed, the analysis and required wind-tunnel simulation of pedestrian-level wind are still required and this is the focus of this paper.

2. WIND-TUNNEL FACILITIES

An environmental wind tunnel was built for testing natural atmospheric boundary layer flows past surface objects such as buildings and other structures. The tunnel has an overall length of 72 ft. (22 m), a test section of 4 ft. (1.2 m) wide by 6 ft. (1.8 m) high, and has an adjustable false ceiling. Wind speeds within the tunnel can be varied from 2 to 22 mph or 1 to 10 m/s.

The wind tunnel is an open-return type with the fan blades pulling the air through the tunnel as illustrated in Figure 1. The tunnel is composed of an entrance section, a flow development section, a test section with a three-dimensional remote control probe traversing system, a diffuser section, and a 75-HP DC motor.

The entrance section (see Figure 1, section A-A) is bell-mouth shaped to produce a contraction area ratio to minimize the freestream turbulence level. The contraction area is followed by a commercially available air filter which screens out airborne particles above a few microns in diameter and reduces large-scale pressure fluctuations. After the filter, a honeycomb flow straightener is used to further reduce large-scale turbulence.

The 40-foot-long (12 m) flow development section has walls that diverge to reduce the streamwise pressure gradient. The false ceiling of the section continues this process and provides zero-pressure-gradient flow. The floor is easily removable, hence different false floors with different relative roughnesses can be tested. Two roughness element models are currently being used. One consists of wooden wedges attached to the floor panels and the other consists of small rectangular wooden blocks placed on smooth floor panels. Fairings for

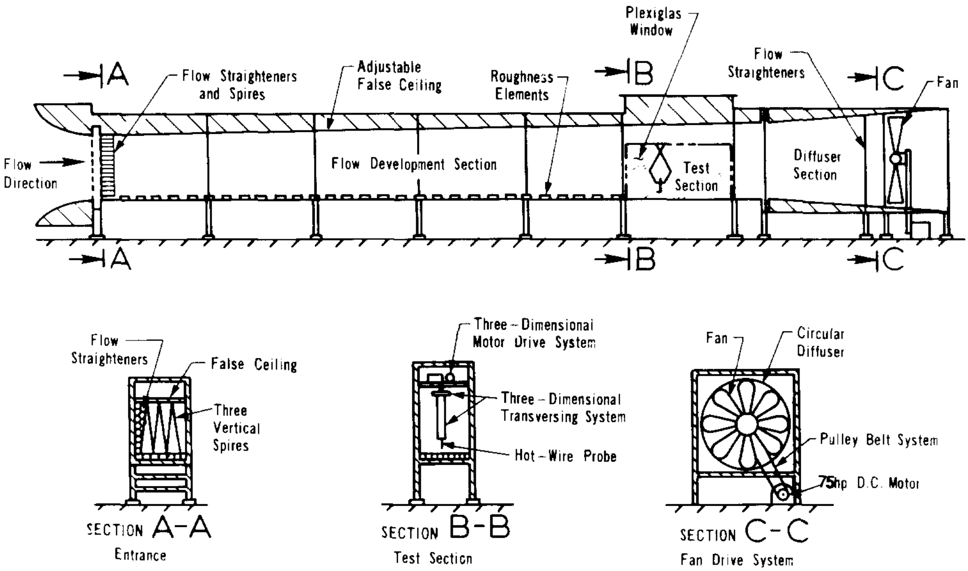

Figure 1. Schematic diagram of the UC Davis Atmospheric Boundary-Layer Wind Tunnel showing the entrance (Section A-A), the test area (Section B-B) and the diffuser-drive system (Section C-C).

smooth-wall tests are placed at the corners of the tunnel to reduce secondary flow effect. Removable spires are placed directly downstream of the flow straightener at the entrance of the flow development section.

The test section (see Figure 1, section B-B), is 12 feet (3.7 m) in streamwise length and 5.5 feet (1.7 m) high by 4 feet (1.2 m) wide in cross section and also has an adjustable ceiling to allow zero-pressure-gradient flow over its length. Access to the test section is through a framed Plexiglas door which serves as one of two vertical Plexiglas walls. Door leakage is eliminated by an O-ring seal of internally pressurized surgical tubing that is mounted between the door and its metal frame.

In the test section a three-dimensional probe traversing system can be moved over a large part of the floor area. The probe traverse mechanism is specially designed to provide precision sensor placement, small flow disturbance, and high speed in moving the sensor from point to point. All three dimensions of motion are independent and tracked by precision potentiometers rigidly coupled to the drive trains.

The diffuser section (see Figure 1 section C-C) has an expansion area ratio that provides a continuous transition from the rectangular cross section to a circular cross section for the fan.

The eight-bladed, fixed-pitch, 6-foot (1.8 m) diameter fan (see Figure 1, section C-C) is driven by a 75-HP, shunt-wound field DC motor specially designed for use with a full-wave-phase controlled power supply. The motor and fan are coupled by a dual belt and pulley drive system. The fan shroud also serves as a final diffuser section and provides more efficient pull of the air flow through the tunnel.

3. THE MODEL AND DIGITAL DATA PROCESSING TECHNIQUE

A one inch equals 50 ft. (15 m) scale (600:1) model of the area surrounding the proposed project for several thousand feet in all directions is tested in the wind tunnel. The model is usually capable of having several configurations including: the existing setting, the project setting, and as many alternatives as needed or required, each available for separate wind tunnel testing.

For each wind direction tested in the tunnel, the model area represents a minimum distance of 6000 ft. (1.8 km) in the direction of the wind (approximately 4000 ft. (1.2 km) upwind and 2000 ft. (0.6 km) downwind of the proposed site) and 2400 ft. (0.7 km) in the direction normal to the wind.

The atmospheric-boundary-layer flow over downtown areas is simulated by an upwind network of turbulence generators. The wind tunnel's false ceiling is adjusted to provide a zero-pressure-gradient downstream flow. The adjustment of the flow to zero-pressure-gradient flow is known to properly model atmospheric boundary layers near the surface of earth (Cermak et al., 1966; Cermak and Arya, 1970; Cermak, 1971, 1975 a and b). The long flow development length allows a naturally turbulent boundary layer to develop and properly model the full-scale flow.

Wind-speed measurements are usually made at 25 to 40 surface locations using a hot-wire anemometer. Hot-wire measurements made close to the surface have an inherent uncertainty of $\pm 5\%$ of the true values. Calibration measurements are made before the hot-wire experiments. The calibration is accomplished by means of a Thermo-System Incorporated (TSI) model #1126 hot-wire anemometer calibrator especially designed for low wind speeds. The calibration is accurate to within 2%. The flow above the model is adjusted to nearly the same wind speed, approximately 9 mph (3.5 m/s) for all experiments. The projected near-surface wind speeds are calculated from the hot-wire measurements.

The technique used to process the data is to digitize the analog data (this process is referred to as A to D, or A/D) and record it on the IBM personal computer. Specifically, the anemometer analog signals are first passed through an analog signal conditioning system, digitized, and processed in an IBM AT personal computer. The signals from the conditioning system are filtered by a Krohn-Hite anti-aliasing filter, model 3322, which is operated as a single-channel eighth-order low-pass filter. The filtered output signal is digitized with an IBM DACA board data acquisition system. The execution of the A/D conversion is synchronized to less than one nanosecond time shift, thus allowing digital software computer calculations to be made without loss of accuracy.

An examination of the anemometer signals with the Nicolet digital spectrum analyzer show that the turbulence frequencies typically are less than 350 Hz. Typical A/D conversion rates are 1000 samples/s for 30 seconds, which exceeded the Nyquist requirement (Bendat and Piersol, 1971; Freymuth, 1977). The 30,000 individual voltage samples are typically then averaged and the root mean square calculated for each wind speed measurement. The process of data acquisition and computer reduction takes about a minute for each measurement and is performed with an accuracy of 99.95%.

4. METEOROLOGICAL DATA AND TESTING METHODOLOGY

For each surface wind-speed measurement made in the wind tunnel it is desirable to estimate an associated full-scale wind speed. The determination of the full-scale wind speed will of course depend upon the nature of the meteorological data at the site. For San Francisco wind studies the wind ordinance requires determination of the full-scale mean wind speed exceeded 10% of the time from 7:00 a.m. to 6:00 p.m. The meteorological data used were originally taken at the weather station located on top of the old Federal Building at 50 United Plaza during the years 1945 - 1950 on an annual hourly basis for 16 equally spaced wind directions or sextodecimo wind sectors. The measurements were taken hourly and averaged over one-minute periods. Of the 16 measured wind directions, four primary wind directions comprised the greatest frequency of occurrence as well as the majority of strong wind occurrences. These wind directions were northwesterly, west northwesterly, westerly and west southwesterly which has associated of occurrence rates of 10%, 14%, 35% and 2%, respectively, for 6:00 a.m. to 8:00 p.m.[b] The remaining 12 wind directions comprised the remaining 36% frequency of occurrence. Calm conditions occurred 2% of the time.

For each of the major wind directions the individual wind-speed value that the mean exceeded 10% of the time was determined from the meteorological data. The values of the 10% exceeded speeds were 21, 25, 21 and 18 mph for northwesterly, west northwesterly, westerly and west southwesterly winds, respectively. The 12 remaining untested wind directions had an average 10% exceeded wind speed of 15 mph.

The wind-tunnel methodology used in the testing of proposed high-rise structures was decided upon by the officials of the Environmental Review Office of the City Planning Departments and the group of wind consultants who authored the Arens et al. (1989) paper. The collective decision of the group was to wind-tunnel test only three or four specific sextodecimo wind sectors of the 16 total sectors. If a proposed project has a site location south of Market Street then four wind directions would be tested: northwest, west northwest, west and west southwest. The testing of only four of sixteen wind direction may seem inadequate; however, it does account for 61% of occurrence frequency as well as accounting for the wind directions with the strongest wind-speed magnitudes. Of the untested wind sectors the 10% exceeded wind speed average is well below the 10% exceeded wind speed averages of tested wind directions given in the above paragraph. For site locations north of Market Street in the vicinity of the downtown area the testing of only three wind directions is required: northwest, west northwest and west. In these cases it was decided that the project site would be sheltered from the west southwesterly winds by the large mass of buildings in the downtown area to the west and south of any site.

The average of the measured wind ratios for the tested wind directions (at a given position and setting) was assumed to be the mean wind ratio of the untested wind directions. The justification for this procedure is that there is a symmetry-of-sorts of the wind flow around buildings and although the technique is not 100% accurate, it does provide a reasonable estimate of the average wind speed that would occur from the untested wind directions. Thus, the weighted cumulative averaged pedestrian-level 10% exceeded wind-speed calculations account for all wind directions, including those not measured in the wind tunnel.

The method used to estimate the full-scale 10% exceeded wind speed assumes the ratio of pedestrian-level wind speed to a specified reference height wind speed (both in the wind tunnel) is equal to the same ratio in full scale. The reference height used corresponds to the height of the weather station located on top of the old Federal Building, and is 132 feet high. Additionally, both the wind-speed ratios are assumed equal to power-law relationship given by Davenport (1961), i.e.,

$$\left(\frac{U_{ped.}}{U_{ref}}\right)_{\text{Full Scale}} = \left(\frac{U_{ped.}}{U_{ref}}\right)_{\text{Wind Tunnel}} = \left(\frac{z}{H_{ref}}\right)^{\alpha} \qquad (1)$$

where U_{ped} is the equivalent wind speed at pedestrian height z (approximately 6 feet), U_{ref} is equivalent wind speed at the reference height H_{ref} which is 132 feet in this case. To predict $U_{ped_{\text{Full Scale}}}$ one uses

[b] Unfortunately, the meteorological data was acquired in 3-hour intervals where the closest match to the wind ordinance time was 6:00 a.m. to 8:00 p.m. This time period was used in the analysis and scaling of wind-tunnel data. However, the usage of the 6:00 a.m. to 8:00 p.m. data is felt to be conservative since the wind data generally have greater wind speeds in the 6:00 to 8:00 p.m. time period than the early morning hour of 6:00 to 7:00 a.m., these being the hours not accounted for in the wind ordinance time period.

$$U_{ped_{Full\ Scale}} = U_{ped_{Wind\ Tunnel}}\left(\frac{U_{ref_{Full\ Scale}}}{U_{ref_{Wind\ Tunnel}}}\right), \tag{2}$$

or introducing the wind-tunnel freestream speed U_∞ yields,

$$U_{ped_{Full\ Scale}} = \left(\frac{U_{ped}}{U_\infty}\right)_{Wind\ Tunnel} \cdot U_{ref_{Full\ Scale}} \cdot \left(\frac{U_\infty}{U_{ref}}\right)_{Wind\ Tunnel} \tag{3}$$

where $(U_{ped}/U_\infty)_{Wind\ Tunnel}$ is defined as R, the wind-tunnel wind-speed ratio. Additionally, it was found that,

$$\left(\frac{U_\infty}{U_{ref}}\right)_{Wind\ Tunnel} = 2 \text{ or } \left(\frac{U_{ref}}{U_\infty}\right)_{Wind\ Tunnel} = 0.5 \tag{4}$$

from measurements taken in the U.C Davis wind tunnel with the model of the old Federal Building present in its pre-1950 setting.

This also may be compared to the full-scale situation, although the direct comparison between full-scale and wind-tunnel ratios involving freestream or geostrophic wind speed, $U_{Geostropic}$, is known not to be accurate. This is due to the Coriolis effects in full-scale; however, the comparison used in the present context for illustration purposes and justified by the fact that it is desired to assess the reasonableness of the wind-tunnel ratio value of 2. Accordingly,

$$\left(\frac{U_{ref}}{U_{Geostropic}}\right)_{Full\ Scale} = \left(\frac{z_{ref}}{\delta}\right)^{\alpha}_{Full\ Scale} \tag{5}$$

where z_{ref} is 132 feet, δ is the boundary-layer height over San Francisco, estimated at 1320 feet (10 times the reference height) and α is the power-law exponent equal to approximately 0.3. Thus,

$$\left(\frac{U_{ref}}{U_{Geostropic}}\right)_{Full\ Scale} = (0.1)^{0.3} = 0.501 \tag{6}$$

which has reasonable agreement with the wind-tunnel result of 0.5, see Equation (4).

Therefore, the $U_{ped_{Full\ Scale}}$ becomes

$$U_{ped_{Full\ Scale}} = 2RU_{ref_{Full\ Scale}} \tag{7}$$

Unfortunately, the data base from the old Federal Building was biased by the location of the measuring equipment. The anemometer was located 25 feet above the rooftop at the western end of the building, so that the Federal Building and other nearby buildings were near enough to cause wind accelerations and decelerations. These changes introduced systematic errors into the wind data. Correction factors have been developed from wind tunnel tests of a scale model of the old Federal Building and its environs (Ballanti, 1986). No post-1950 buildings of significance were included in the model so that it accurately represented the period 1945 - 1950 when the data were gathered. For each wind direction of interest, mean wind speed was obtained at the anemometer instrument location above the building while simultaneous measurements were made at the identical height of 132 feet above open ground away from the influence of buildings. Predicted wind speeds based on old Federal Building data should be multiplied by the following correction factors, CF, (the value for 'all others' is the arithmetic

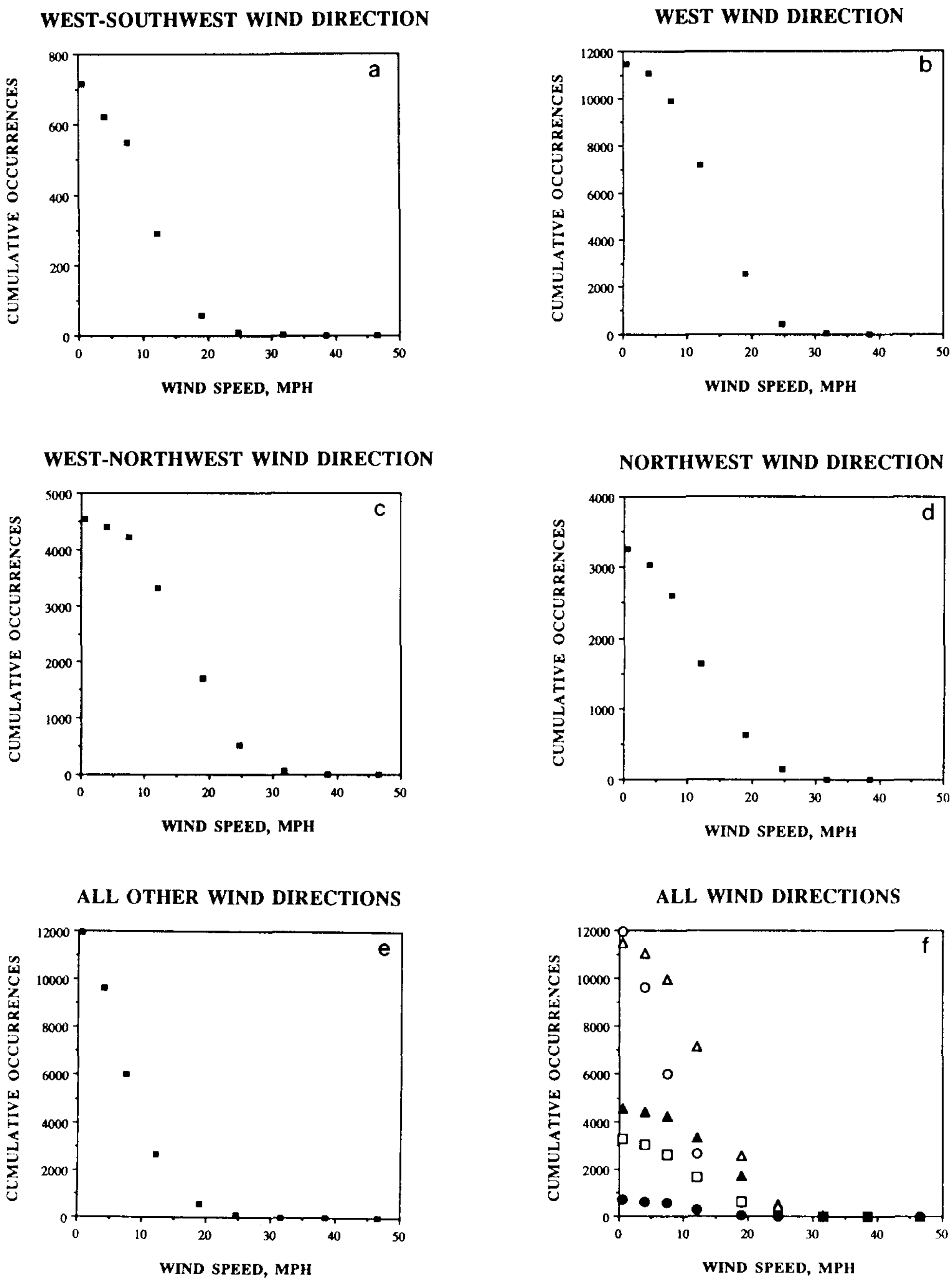

Figure 2 The cumulative number of wind occurrences from 6:00 a.m. to 8:00 p.m. as a function of hourly wind speed in mph for a) west-southwest wind, b) west wind, c) west-northwest wind, d) northwest wind, e) the 12 "untested" wind sectors, and f) total of all occurrences on the same abscissa scale for comparison purposes.

average of the first four values): northwest equals 1.02; west northwest equals 1.00; west equals 0.96; west southwest equals 0.85 and all others equal 0.96.

Therefore, the corrected full-scale pedestrian-level wind speed, $U_{ped.\ corrected_{Full\ Scale}}$, is given as,

$$U_{ped.\ corrected_{Full\ Scale}} = 2R\ CF \cdot U_{ref_{Full\ Scale}} \tag{8}$$

To determine the full-scale 10% exceeded pedestrian level wind speed, the following procedure is used. First, wind-tunnel measurements are made for the three or four wind directions (depending upon whether the site is north or south of Market Street) which produces R values for each of the measured wind directions. Equation (8) is used to scale the wind-tunnel measurements to full scale by determining (from the sextodecimo weather data) the individual full-scale 10% exceeded wind speed for each wind direction. Note, the individual full-scale wind speeds will be different since their calculations each involve wind direction measurements. This is accomplished by first selecting an initial-guess wind-speed value and then determining its per cent exceeded value. Figure 2 displays the sextodecimo Weather Bureau data for the number of occurrences as a function of directional wind speed for the northwest, west northwest, west, west southwest and "other" (i.e., untested) wind directions. Here the "other" data is a compilation of the actual untested wind directions and not an average of the tested wind directions.

From the following form of Equation (8),

$$U_{ref_{Full\ Scale}} = U_{ped_{Full\ Scale}}/(2R \cdot CF), \tag{9}$$

the full-scale speed for that wind direction may be determined from which the numerical value of associated exceeded occurrences can be determined. When all wind direction occurrences are determined, i.e., the addition of the northwest, west northwest, west, west southwest and others, a single numerical number of total occurrences for that initial guess wind speed will result. This number divided by the total of occurrences or total number of observations for all speeds will then yield the per cent exceeded value for the initial-guess wind speed. The total number of occurrences observed from the 6-year period of weather data was 32,795; thus, the procedure is repeated or iterated until the 10% exceeded number of occurrences (3280) is exactly matched. The then updated initial-value speed wind used to match the 3280 occurrences is also the full-scale 10% exceeded wind speed associated with that particular set of wind-tunnel measured R values at the single location considered.

Once the 10% exceeded wind speeds are calculated it can then be determined if the measured location met the specific criterion that applies (7-mph for public seating areas and 11-mph for a pedestrian use area). If the 10% exceeded wind speed calculation exceeds its respective criterion, the project may be modified (hopefully to improve the wind environment) and retested to determine if the modification created an improved wind condition in which the project would met the comfort criterion imposed.

This process may be repeated until the violations have been eliminated. Generally, the wind consultants and City officials determine the extent of mitigation testing required. If the City official are convinced that the only migitiation measures that would bring the project in compliance with the wind ordinance would result in an "unattractive" building, or results in other unreasonable constraints, the City official may grant an exception to the ordinance based upon Section 309 (see Appendix for precise exception wording).

5. THE HAZARD CRITERION CALCULATION

The criterion for safety or wind hazard is 26 mph (12 m/s) true hourly mean wind speed not to be reached or exceeded more than one hour per year. The frequency associated with this criterion is 0.011416% (one hour per year divided by the product of 365 times 24 hourly observations). This safety criterion is based on the widely used limit of 44 mph (20 m/s) gust of 3 second duration described in Penwarden (1973); Hunt, et al. (1976); Jackson (1978); Melbourne (1978); and others. The difference between the 26 mph (12 m/s) of the Downtown Plan and the 44 mph (20 m/s) of the limit is due to the differences in the length of averaging periods for the two values and the two different averaging periods may be related to each other through the Beaufort Scale. The mechanical forces caused by the wind at this critical limit take effect on pedestrians on the order of three seconds, while the climatological data, against which the limits are tested, are collected over longer intervals, typically one minute (for U.S. Weather Bureau data) or one hour. When that 44 mph (20 m/s) limit is considered, it must be adjusted downward to account for the greater likelihood of stronger winds occurring during the short 3-second averaging period than during the longer averaging period of the climatological data.

The same iterative procedure is used to determine if the hazard criterion is met or exceeded. As calculated in the solution procedure, the hazard criterion is 36-mph for the one-minute averages acquired from the Weather Bureau data. This criterion corresponds to 44 mph (20 m/s) averaged over a 3 second time period through a Beaufort Scale transformation. Figure 3 displays the Beaufort Scale wind speeds as a function of average time. Superposed on the graph is the San Francisco hazard criterion curve. Statistically, the criterion corresponds to no equivalent wind speed exceeding 26 mph for a single hour of the year, or 0.011416% of time.

Of recent concern is how well does the current data base of Weather Bureau wind records reflect the actual occurrence of extreme winds? It is felt that the current methodology is assessing the hazard criterion properly; however, a key element in the practical implication of method is the validity of the data base used in the calculations. Since the technique counts extreme wind occurrences, from highest values downward, to determine exceedance of the 1-minute average 36 mph equivalent wind speed, the quality of the extreme wind data must be high if the calculation is to be valid. The fact that only a six-year wind record is used is troublesome. Obviously, a data base in excess of 10 to 20 years duration would provide a statistically superior representation. This idea is illustrated by the following consideration: often times the extreme winds are 4 to 6 orders of magnitude less frequent than the mean or average wind speed values. Fortuitously, the limited six-year record used appears somewhat reasonable. Figure 4 displays the cumulative number of occurrences as a function of equivalent wind speed for the west northwest wind direction from the six-year data. Also displayed on the graph is the mean and standard derivation values of a 25-year wind record taken from the *Wind in California* book. Unfortunately, the data in the *Wind of California* book are not presented in a statistically form amenable to the current methodology, i.e., data is not subdivided into sextodecimo wind sectors.

6. SUMMARY

The methodology used in determining the 10% exceeded equivalent wind speeds, as required by the San Francisco pedestrian-level wind ordinance, is outlined. Also, the hazard criterion calculation is discussed.

The 10% exceeded equivalent wind speed calculations involve: first, measuring the equivalent wind speeds at a specified number of ground-level locations in an atmospheric-boundary-layer-type wind tunnel for three or four prominent wind directions depending upon the geographic location of the site; second, the wind-tunnel measurements are scaled through the power-law relationship to projected full-scale wind speeds; third, a correction factor calculation, due to full-scale building interference on the measuring anemometer, is applied to the wind-speed calculations; four, the total (all directions) 10% exceeded wind speed is determined from counting individual occurrences in the sextodecimo wind sectors for the measured wind directions. An average of the measured wind directions is used to determined the untested wind sectors. Accordingly, all wind directions are accounted for. This process involves an iterative procedure; five, once the 10% exceeded wind speed is determined an assessment of the appropriate pedestrian criterion can be made. If the ground-level location is found to exceed the criterion, the per cent of exceedance may be determined from the calculation output (as

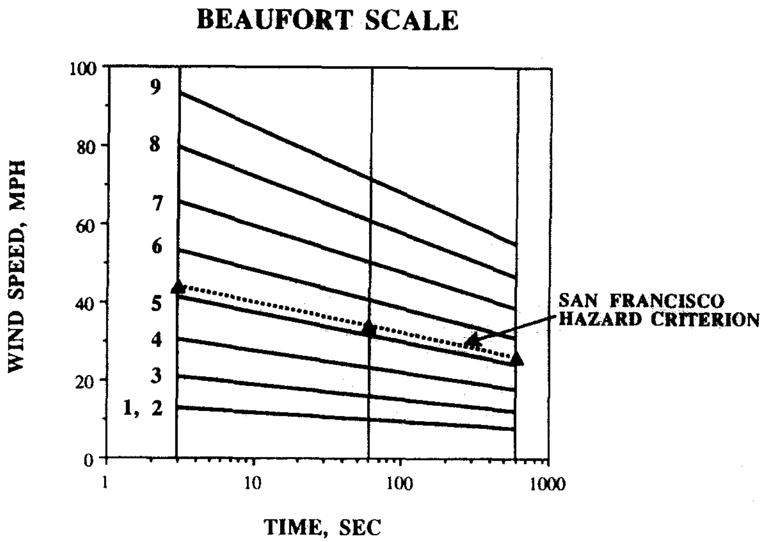

Figure 3 The Beaufort scales 1 to 9 displayed in terms of wind speed (mph) as a function of length of averaging time. Also, displayed is the San Francisco wind hazard criterion.

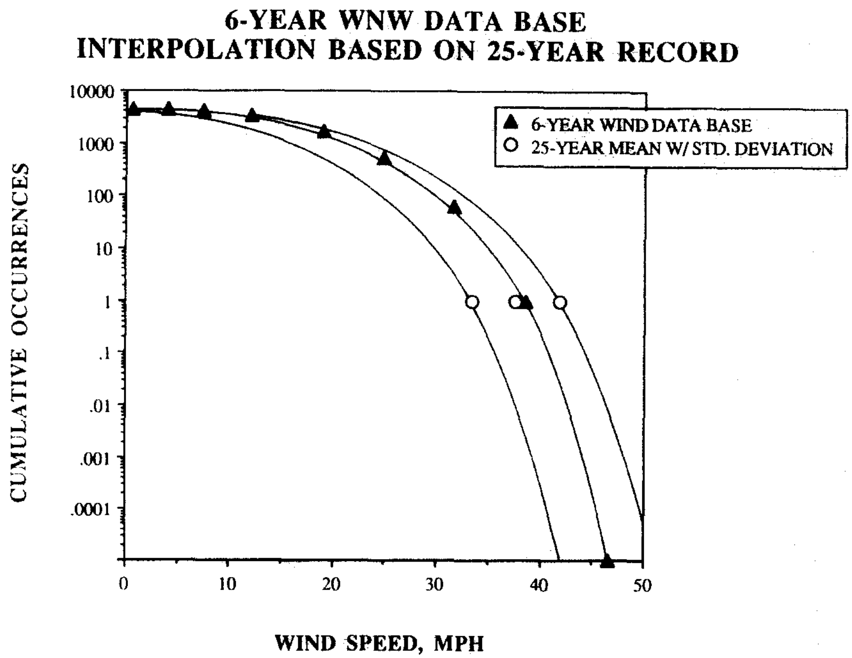

Figure 4 The cumulative number of high speed occurrences for the west northwest direction as a function of hourly wind speed in mph. Also displayed are the total mean and standard deviations wind speed values taken from the Wind in California book.

individual wind directions contributions are known). Appropriate mitigation may then be applied to the proposed building and the location retested to determine if it would met the criterion.

The calculation of the hazard criterion is similar to the 10% exceeded calculation. Some concern has been expressed over the quality of Weather Bureau data for calculation of the hazard criterion. Specifically, the short duration of data (6 year) may not provide an accurate representation of extreme wind distributions in the sextodecimo wind sectors. The calculation of the 10% exceeded equivalent wind speeds, however, is felt to be valid as data in this application do provide an adequate base.

7. ACKNOWLEDGEMENTS

The author gratefully acknowledges the discussions and technical input from J.F. Kavanagh and C.B. Bennett, both of Environmental Science Associates, Inc., San Francisco. The original conceptual development of the wind-tunnel and associated analysis is due to the efforts of C.B. Bennett and B.R. White while the compute code development is due to the efforts of C.B. Bennett and S. Guldman, formerly of Environmental Science Associates, Inc. Additionally, recent improvements to the computer code were made by J.F. Kavanagh. The author also acknowledges many helpful discussions with the original authors' of the wind ordinance: E.A. Arens, D. Ballanti, C.B. Bennett, S. Guldman and B.R. White.

8. REFERENCES

1. Arens, E. 1981 "Designing for an acceptable wind environment", Trans. Engrg. J., ASCE 107, No. TE2, 127-141.
2. Arens E., D. Ballanti, C. Bennett, S. Guldman and B. White 1989 "Developing the San Francisco wind ordinance and its guidelines of compliance", Building and Environment, 24 (4), 297 - 303.
3. Ballanti D. 1986 Private Communication.
4. Bendat, J. S., and A. Piersol 1971 *Random Data: Analysis and Measurements Procedures*, John Wiley and Sons, Inter-Science, New York, 170-213 and 286-343.
5. Cermak, J.E., V.A. Sandborn, E.J. Plate, G.H. Binder, H. Chuang, R.N. Meroney, and S. Ito 1966 "Simulation of atmospheric motion by wind-tunnel flows", Colorado State Univ. Rept. CER66JEC-VAS-EJP-GLB-HC-RMN-SI17.
6. Cermak, J.E., and S.P.S. Arya 1970 "Problems of atmospheric shear flows and their laboratory simulation", Boundary-Layer Meteorology I, 40-60.
7. Cermak, J.E. 1971 "Laboratory simulation of the atmospheric boundary layer", AIAA Journal 9:9, 1746-1754.
8. Cermak, J.E. 1975a "Application of fluid mechanics to wind engineering - A Freeman Scholar Lecture", J. of Fluids Engineering 97, 9-38.
9. Cermak, J.E. 1975b "Simulation of atmospheric boundary layers in wind tunnels", Atmospheric Technology 7, 66-71.
10. Davenport, A.G. 1961 "The application of statistical concept of wind loading of structures", Proc. Inst. Civil Engrg. 19, 449-472.
11. Freymuth, P. 1977 "Frequency responses and electronic testing for constant temperature hot-wire anemometers", J. Phys. E. Science Instruments 10, 705-710.
12. Hunt, J.C.R., E.C. Poulton, and J.C. Mumford 1976 "The effects of wind on people: new criteria based on wind tunnel experiments", Building and Environment 13, 251-260.
13. Jackson, P.S. 1978 "The evaluation on windy environments", Building and Environment 13, 251-260.
14. Lawson, T.V. 1978 "The wind content of the built environment", Journal of Industrial Aerodynamics, 7, 93 - 105.

15. Lawson, T.V., and A.D. Penwarden 1976 "The effects of wind on people in the vicinity of buildings", Proc. Fourth Intern. Conf. Wind Effects on Buildings and Structures, London, 1975, Cambridge University Press, Cambridge, U.K., 605-622.
16. Melbourne, W.H. 1978 "Criteria for environmental wind conditions", J. Indust. Aero. 3, 241-249.
17. Penwarden, A.D. 1973 "Acceptable wind speeds in towers", Build. Sci. 8-3, 259-267.
18. *Wind in California*, 1978 Bulletin No. 185, Department of Water Resources, State of California, Sacramento, California.

9. APPENDIX: CITY AND COUNTY OF SAN FRANCISCO MUNICIPAL CODE - SECTION 148 (WIND ORDINANCE)

REDUCTION OF GROUND-LEVEL WIND CURRENTS IN C-3 DISTRICTS. (a) **Requirement and Exception.** In C-3 Districts, buildings and additions to existing buildings shall be shaped, or other wind-baffling measures shall be adopted, so that the developments will not cause ground-level wind currents to exceed, more than 10 percent of the time year round, between 7:00 a.m. and 6:00 p.m., the comfort level of 11 m.p.h. equivalent wind speed in areas of substantial pedestrian use and seven m.p.h. equivalent wind speed in public seating areas.

When preexisting ambient wind speeds exceed the comfort level, or when a proposed building or addition may cause ambient wind speeds to exceed the comfort level, the building shall be designed to reduce the ambient wind speeds to meet the requirements. An exception may be granted, in accordance with the provisions of Section 309, allowing the building or addition to add to the amount of time that the comfort level is exceeded by the least practical amount if (1) it can be shown that a building or addition cannot be shaped and other wind-baffling measures cannot be adopted to meet the foregoing requirements without creating an unattractive and ungainly building form and without unduly restricting the development potential of the building site in question, and (2) it is concluded that, because of the limited amount by which the comfort level is exceeded, the limited location in which the comfort level is exceeded, or the limited time during which the comfort level is exceeded, the addition is insubstantial.

No exception shall be granted and no building or addition shall be permitted that causes equivalent wind speeds to reach or exceed the hazard level of 26 miles per hour for a single hour of the year.

(b) **Definition.** The term "equivalent wind speed" shall mean an hourly mean wind speed adjusted to incorporate the effects of gustiness or turbulence on pedestrians.

(c) **Guidelines.** Procedures and Methodologies for implementing this section shall be specified by the Office of Environmental Review of the Department of City Planning. Ordinance 414-85, Approved September 17, 1985.