TABLE OF CONTENTS

4171 (RP-816)

Wind Data for Design of Smoke Control Systems

Stephen D. Lamming, Ph.D. **James R. Salmon, Ph.D.**

ABSTRACT

This paper reports on the analysis of historical wind data from 239 stations in the United States and 146 stations in Canada to derive design wind speeds (95%, 97.5%, and 99%) for the design of smoke control systems. As part of the analysis, the data were thoroughly checked for missing observations, internal consistency, and uniformity of location and measurement height. At each location, the design speeds were extracted from cumulative distributions of the wind speed, both by an interpolation method applied to binned data and by derivation from the two-parameter Weibull distribution using binned data. Analysis of the results of both methods showed that the interpolation method produced the most accurate and stable results for stations with long data sets. On the other hand, the Weibull fit could reasonably be used in locations for which long-term data were not available.

INTRODUCTION

Fire in heavily populated buildings has always been a major concern of architects and engineers responsible for the design of such structures. While exit routes in the past have catered primarily to the "able-bodied" of the community, more modern design criteria have illustrated that there is a need to provide adequate safe egress to all persons in the event of such an occurrence. Klote (1993) notes that one proposed solution lies in the concept of providing "areas of refuge," where persons can wait in comparative safety until assisted to leave the building. Since most areas of refuge will be located near stairs or elevators for easy access to rescue personnel, the design of such areas requires information on likely wind conditions at various levels of the building. When windows break, smoke flow through the structure will be affected by the leakage function of the openings and by the variation in wind pressure on the building exterior. Such designs must, therefore, allow for pressurization air to be fed to these designated areas.

For design purposes, the *1993 ASHRAE Handbook — Fundamentals* (ASHRAE 1993) lists average wind speeds and directions for many locations in Canada, the United States, and around the world. However, the average wind speed is not an appropriate design criterion since it is generally exceeded for a significant proportion of the year. Klote (1993) recommended that designers of areas of refuge use wind speed values of two or three times the average ASHRAE value. At the other extreme, structural wind-loading design wind speeds are also not appropriate since these are defined as extreme conditions only exceeded once every 10, 50, or 100 years, as the case may be.

What is needed is a set of design data specifically for smoke control systems. Two ASHRAE technical committees, TC 5.6, Control of Fire and Smoke, and TC 4.2, Weather Data, have recommended that such design wind speeds should be those values for which the wind speed is less than, or equal to, the design value for 95%, 97.5%, and 99% of the year or which are exceeded for 438, 219, and 88 hours per annum, respectively. This paper presents some of the results from a project in which quantitative estimates were made of the design wind speeds for many stations in Canada and the United States for which good quality, long-term data are readily available.

BUILDING WIND PRESSURE

Building design is strongly influenced by the magnitude and direction of the prevailing wind. The concept of ventilation pressure has been used for many years, especially in the design of buildings to resist extreme wind events. More recently, work has concentrated on improving indoor airflow that can be augmented or impeded by natural ventilation through planned or incidental openings in the building envelope.

Stephen Lamming is associate professor in environmental technology at Sheridan College, Brampton, Ontario, and is president of Stephen Lamming Associates, Ltd., Burlington, Ontario; **Jim Salmon** is president of Zephyr North, Burlington, Ontario.

THIS PREPRINT IS FOR DISCUSSION PURPOSES ONLY, FOR INCLUSION IN ASHRAE TRANSACTIONS 1998, V. 104, Pt. 1. Not to be reprinted in whole or in part without written permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329. Opinions, findings, conclusions, or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of ASHRAE. Written questions and comments regarding this paper should be received at ASHRAE no later than **February 6, 1998.**

BACK TO PAGE ONE

The wind pressure exerted on a given surface is a function of the square of the wind velocity and is given by Bernoulli's equation (quoted in Klote 1993):

$$P_w = \frac{1}{2} C_w \rho_o V^2 \qquad (1)$$

where

P_w = wind pressure on a surface in lbf /ft^2 (N/m^2)

C_w = dimensionless pressure coefficient, generally ranging from −0.8 to +0.8

ρ_o = outside air density in lb/ft^3 (kg/m^3)

V = wind velocity in ft/s (m/s)

Therefore, the wind pressure is strongly dependent on the wind speed, as well as on the geometry of the particular structure, and will vary considerably over the building surface.

Structures are located in the near-surface portion of the atmosphere known as the boundary layer, where frictional and turbulence effects play a major role in determining the variation of wind speed with height (Figure 1, taken from ASHRAE 1993). In this boundary layer, wind speed is largely determined by the nature of the terrain over which the air is moving, the presence of obstructions, topographical influences, and atmospheric stability. On average, the variation of wind speed with height above a uniform surface is a logarithmic relationship that is very site dependent. As a general rule (ASHRAE 1993), a reasonable approximation is provided by this equation:

$$V_a = V_r \left(\frac{z_a}{z_r} \right)^n \qquad (2)$$

where

V_a = wind speed at anemometer height in mph (m/s)

V_r = wind speed at reference height in mph (m/s)

z_a = anemometer height in ft (m)

z_r = reference height, usually 33 ft (10 m) in ft (m)

n = a dimensionless exponent

Values of the exponent were taken from *ASHRAE Fundamentals* (1993) and Klote (1993) for internal consistency with other ASHRAE recommended practices (Table 1).

TABLE 1
Variation in Power Law Exponent (n) with Terrain Type

Terrain (Klote 1993)	**Exponent (n)**
Flat (grasslands or airport)	0.16
Rough (rural with trees or suburb)	0.28
Very rough (urban)	0.40

While alternative methods for height extrapolation exist, they involve parameters that depend, not only on the height of neighboring roughness elements, but also on atmospheric stability. It was felt, however, that the use of such methods would be inconsistent with Equation 2 and recommendations in *ASHRAE Fundamentals* (ASHRAE 1993). Further, it was not known beforehand what the additional accuracy provided

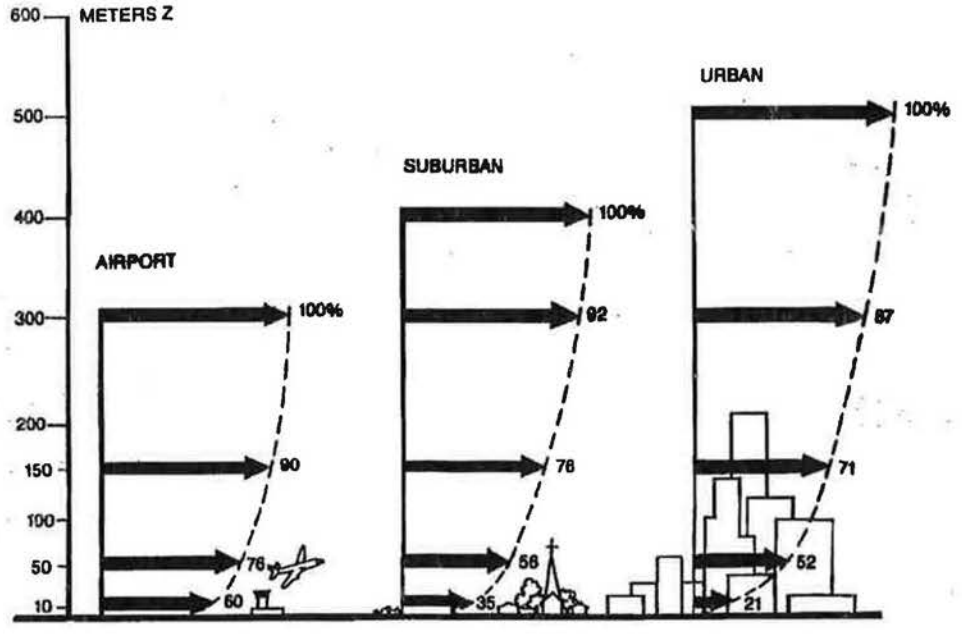


Figure 1 *Boundary layer wind flow in different terrain types.*

BACK TO PAGE ONE

by the logarithmic law and atmospheric stability approach would be and whether the added complication and processing time would be justified for this particular problem. In a study of wind data collected at nuclear power plants around the continental U.S. (Verholek 1977; Mikhail and Justus 1979), it was observed that use of the power law approach resulted in an rms error of 0.3-0.6 m/s, compared with 0.3-0.4 m/s for the more complex methodology. It was, therefore, decided to use the standard power law (Equation 2) for wind speed height conversion.

DATA SOURCES

Two primary CD-ROM data sets were used in this analysis. For stations in the United States and its territories, the database used was the Solar and Meteorological Surface Observation Network (SAMSON 1961-1990), prepared jointly by the U.S. Department of Commerce and the U.S. Department of Energy. For Canadian stations, the database was the Canadian Weather, Energy and Engineering Data Sets (CWEEDS), prepared under the direction of the Atmospheric Environment Service (AES) of Environment Canada, with support from the Canadian Federal Panel on Energy Research and Development (PERD). For stations in the database, the design speeds would be calculated for the most recent period of record for which both the anemometer location and height above ground were known and unchanged (or nearly unchanged) for a minimum acceptable duration of five years.

The SAMSON Data Set

The SAMSON database includes data from a total of 239 stations in the United States and associated territories. The database is a compilation of four separate data sets of which the most important for this project were meteorological data from the TD-3280 tape deck files at the National Climatic Data Center (NCDC). This data set is the only source of surface wind data for this project and was extracted from surface airway data collected by airport stations. Each hour's data occupies a single record, and each file contains one station-year. The data files each have a header line giving details of the station's location, elevation, and time zone. All observational records are referenced to local standard time.

Wind data are given in m/s with values of 9999. or 99.0, representing missing data. Observations are made at the end of the hour in miles-per-hour or knots and converted to SI units in the CD-ROM archives. Quality control of the data was mainly manual in the early years. Observations were usually checked for conformity with established observing and coding practices. Later checks were also made for serial consistency and against defined limits for each meteorological element. While efforts have been made to fill in data gaps for some elements by interpolation or, in the case of larger gaps, by substitution from other years, this was not possible for wind speed or direction, which were seen to be essentially discontinuous in nature.

Anemometer heights were found to vary considerably, both from station to station and over time. The most common height was 20 ft (6.1 m), with a shift in some locations to a height of 33 ft (10 m) in the 1980s. While lack of a station history file was a serious deficiency of the SAMSON archives, such information was obtained from the Local Climatological Data Annual Summaries (NOAA 1993) for most stations in the archives.

The CWEEDS Data Set

The CWEEDS files consist of compressed, formatted files of hourly weather conditions occurring at 143 Canadian locations for up to 37 years of records (1953-1989), arranged so that each file contains one station-year of data. The WYEC2 (Weather Year for Energy Calculation, Version 2) format used consists of individual records containing all weather elements for each hour of data through the year. All WYEC2 values are for local standard time, and wind speeds are archived as units of 0.1 m/s. The observation is an estimate of the one-minute mean wind speed preceding the hour for the years before 1985 and a two-minute mean wind speed thereafter.

Most of the anemometers at the stations in the CWEEDS files are mounted in a flat, open exposure such as at airport locations. As AES anemometers have not always been mounted at 10 m above ground, information on anemometer height history was provided in a separate disk file. This was combined with station location records from the Climatological Station Catalogue, Volumes 1-6 (AES 1989). In general, additional care was taken in using wind speeds before 1975. Not only were the anemometers installed at heights other than 10 m more frequently before this date, but the station history files were sometimes ambiguous as to both anemometer height and exact location. A number of nonstandard anemometer locations, such as on top of aircraft hangers or the air traffic control tower, also occurred at some locations prior to 1975.

A problem common to both data sets was that of anemometer exposure. Most anemometers were located in a flat, open area, especially at major airports, and some at extremely exposed coastal sites. Observed wind speeds at such locations are not always representative of less windy or less well exposed sites. In addition, some measurement locations are sheltered by trees or other obstructions and are not representative of more exposed locations nearby. In general, wind speeds from observing sites are only representative of other nearby sites if the height above ground and exposures are similar.

DATA PROCESSING METHODOLOGY

In order to process the large volume of available information, a suite of analytical programs was developed to provide the ability to scan the input data set and determine whether data were missing, out of range, or otherwise of doubtful quality. Scanning was done visually, using the program graphic output, and computationally, using data quality algorithms

BACK TO PAGE ONE

that verify reasonable temporal, synoptic, and statistical behavior within the data set. This two-stage process provided excellent overall data quality control.

Removal of Unit Conversion Bias

Wind speed data from the CD-ROMs were quality checked and extracted to a separate archive for those stations for which satisfactory anemometer height and location histories were known. However, in the collection and assimilation of wind data from many diverse sources, a variety of recording instruments and procedures have been utilized. In particular, wind speeds in Canada and the U.S. have traditionally been observed in miles-per-hour and knots and/or processed in these units. All processed data in the CD-ROM archives have since been converted to meters-per-second (via km/h in Canada).

These observing and processing differences cause problems for statistical analysis because the original observations were archived to the nearest integer mph or knot. Because these original data are discrete, when they are converted to other units and then rounded off to the nearest integer in the new system of units (which was typically done), gaps appear in the continuum of possible wind speeds. For example, in a conversion from integer knots to integer km/h, the only possible resultant wind speeds are 0, 2, 4, 6, 7, 9, 11, 13, 15, 17 km/h.

One problem arises when we try to examine the distribution of wind speeds or to fit a statistical function to this distribution. For example, if we placed all the wind speed data (involved in the conversion shown as an example above) in wind speed bins of 1 km/h width, there would be no data at all in a number of bins, and our representation of the distribution of the wind speeds would be biased.

To get around this problem, each wind speed datum was converted back from its archive value (m/s) to the integer value (mph or knots) that was originally measured. In this original system of units (mph or knots), a random offset was added to the back-converted value so that the modified number ranged from halfway to the previous integer value (except for zero) to halfway to the next integer value. The modified number (which, of course, would still have the same rounded integer value as it had originally) was then used as input to the whole conversion process to which it had originally been subjected. However, in this process, the decimal portion of the number was retained and no rounding off was performed. The overall effect was to create a continuum of wind speeds in the original measurement units, which converted in a reasonable way to the archived units.

It should be noted, however, that this process does not eliminate "observer bias" from the data set. This occurs because of a bias by many observers toward recording even values of wind speed, as well as values that are a multiple of 5. In other words, one sees a preponderance of data values at 2,4,5,6,8,10,12, etc., with additional weight at those points that satisfy both criteria, e.g., 10, 20. In addition, there is a bias against reporting wind speeds at 1 mph and 2 mph or knots. This is partially a result of the measurement threshold of the older anemometers and partially a result of the difficulty for the observer to discriminate between speeds at this low level. These problems have now mostly disappeared with the introduction of digital readouts and electronic data-logging systems at a number of stations.

Identification and Handling of Missing Data

After wind speed data were archived, a computer program graphed the availability of data for each station. This enabled the researchers to quickly obtain information on the usability of the record for a given station year. An example that illustrates a number of problems faced in the analysis is shown in Figure 2, for Bettles AP, AK, where the solid lines represent archived data for each hour during the year and the data gaps are immediately apparent. In particular, the data were scanned for the following:

1. **Stations with periods for which data were collected for only part of the day.** This included those stations that collected data only during daytime hours or had systematic data gaps that could conceivably introduce a bias in the design wind speeds. These were eliminated from the analysis.
2. **Station-years in which different measurement strategies were combined.** A wind measurement strategy is simply the way that wind observations are distributed in time. During the period 1965-1980, data digitization and archival procedures at most U.S. stations switched between hourly and three-hour recording periods. If wind velocity is regarded as a random variable, then in the limit of a very long period of data collection, the data sampling rate would not be expected to have a significant effect on the resulting wind speed probability distribution. While such a measurement schedule should not in itself introduce significant bias

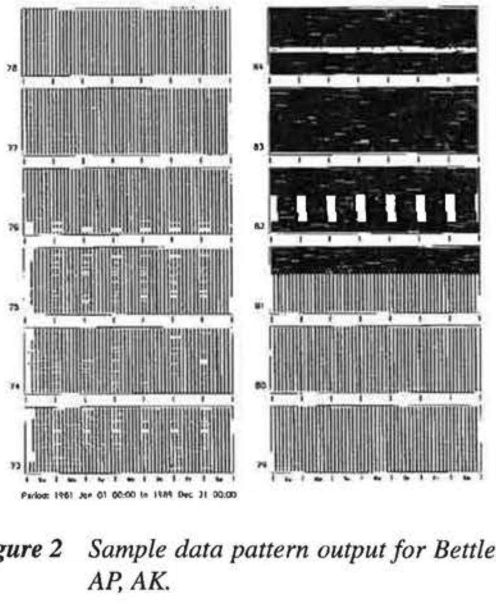


Figure 2 *Sample data pattern output for Bettles AP, AK.*

BACK TO PAGE ONE

in the data over a complete year, the archival interval for many stations was changed back to an hourly schedule midway through 1981. It was felt that a hybrid year would cause bias, and, as a result, this year was eliminated from all station records in which the mid-year changeover occurred.

3. **Station years in which significantly large amounts of data were missing.** In general, if less than 1% of the data was flagged as missing, and the data gaps occurred randomly over the year, the station-year was included in the analysis. However, the year was eliminated if missing data were concentrated over a single time period or distributed in such a manner as to potentially bias the results.

Changes in Anemometer Height

The next stage in the quality checking process was to output annual averages of wind speed in both tabular and graphical form. This enabled detection of any significant upward or downward trends in the data that might have been caused by the growth of vegetation or the construction of buildings in close proximity to the anemometer. The annual sequences were also compared with the station anemometer height and location histories to ensure that any discontinuities in the data could be explained.

To ensure comparability in the results, wind speeds were converted to a common anemometer height. For this reference height, the World Meteorological Organization (WMO) standard observation height of 33 ft (10 m) was chosen since all WMO weather stations will eventually (in theory) report at this height. The conversion method was based on Equation 2, with strict limits placed on its use. In particular, no wind data from a site with an anemometer height that differed from the reference height of 33 ft (10.0 m) by more than 13 ft (4 m) were used in the study. Essentially this restricted usable data to that from anemometer heights between 20 ft (6.1 m) and 46 ft (14.0 m). As most of the usable stations were located at airports, the "flat" value of the exponent (0.16) was most often used. Using this exponent for height adjustment generally resulted in the adjustment factors shown in Table 2.

TABLE 2
Variation in Wind Speed Correction Factor with Anemometer Height (n = 0.16)

Anemometer Height		Speed Conversion Factor
Feet	Meters	
20	6.1	1.08
30	9.1	1.02
33	10.0	1.00
40	12.2	0.97
46	14.0	0.95

Design Speed Computation

Once the data had been archived and adjusted for differences in anemometer height, the availability of a suitable period of good quality data was determined. Generally, this corresponded to a period with high data availability during which the anemometer remained at a fixed location and relatively constant elevation. If the annual averages showed a significant trend, the station record was compared with that from one or more nearby locations for the same period. If this comparison showed the trend to be unique to the station under consideration, the data were archived but were flagged as being of secondary quality. If the trend was confined to an earlier portion of the data, this portion was neglected in favor of the most recent data period, as long as such a period was greater than, or equal to, five years. The final "clean" data were then used in the design speed computations. An example of such data sets are shown in Figure 3 for (a) Brownsville, (b) Milwaukee, and (c) Port Hardy.

In order to obtain the design wind speeds required by the project, the final data set for each station was binned in intervals of 0.5 m/s (1.1 mph). The design speeds were then obtained from the cumulative frequency distribution by means of interpolation between successive bins at the required design speed level. For example, if the 14.0-to-14.5 m/s bin had a cumulative frequency of 98.9% and the next higher bin, 99.1%, we assumed that the 99% design speed was between these two bins, and a weighted interpolation between the midpoints of these bins was used to derive the appropriate design speed.

In arriving at this method of dealing with the data, a number of alternative schemes were considered. These included varying the bin width and fitting a theoretical distribution to the data. Two such distributions were examined. One of these was the standard form of the Weibull distribution function, which has been extensively used in wind studies with quite good results (Morris 1985; Lamming 1986; Ramsdell et al. 1979) and is given in Equation 3.

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{\left(\frac{-v}{c}\right)^{k}} \tag{3}$$

where

$f(v)$ = Weibull probability density function in which the probability of encountering a wind speed of v (m/s) is $f(v)$

c = Weibull scale factor (m/s) that can be related to the average wind speed through the shape factor

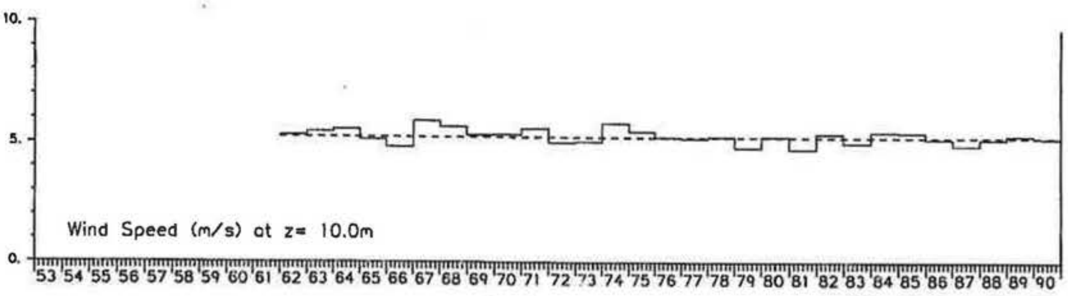
k = Weibull shape factor (dimensionless) that describes the distribution of wind speeds

The cumulative form of this function is then given by

$$F(V) = 1 - e^{\left(\frac{-v}{c}\right)^{k}} \tag{4}$$

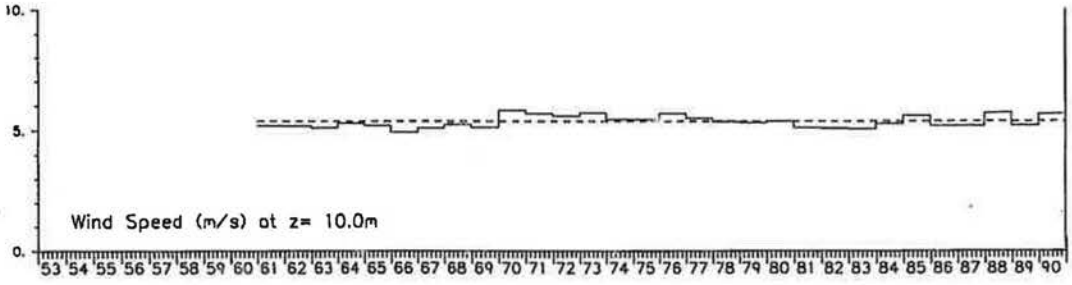
from which a least squares analysis gives the rms residual error as

BACK TO PAGE ONE



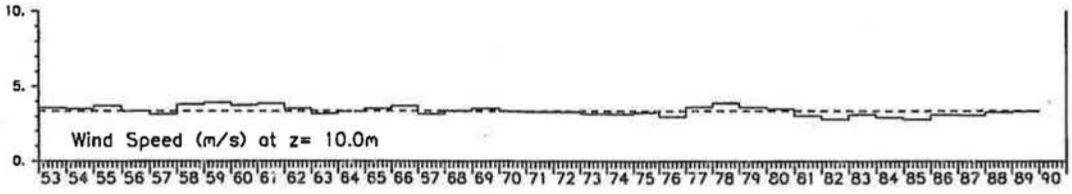
Period: 1962 Jan 01 00:00 to 1991 Jan 01 00:00
Station: Brownsville A (4)

Figure 3a *Annual wind speeds for Brownsville.*



Period: 1961 Jan 01 00:00 to 1991 Jan 01 00:00
Station: Milwaukee (10)

Figure 3b *Annual wind speeds for Milwaukee.*



Period: 1953 Jan 01 00:00 to 1990 Jan 01 00:00
Station: Port Hardy A (10)

Figure 3c *Annual wind speeds for Port Hardy.*

BACK TO PAGE ONE

TABLE 3
Comparison of Methods for Derivation of Design Speeds (m/s) for Four Stations

Design Level	Bin Size	Abbotsford BC k=1.3 c=2.8			Cheyenne WY k=2.1 c=6.8			Green Bay WI k= 2.0 c=5.3			Olympia WA k=1.6 c=3.7		
%	m/s	Intr	Wbl	Hyb	Intr	Wbl	Hyb	Intr	Wbl	Hyb	Intr	Wbl	Hyb
95.0	1.00	6.33	6.73	6.82	11.28	11.45	11.28	8.57	9.25	9.06	6.86	7.50	7.44
	0.50	6.54	6.71	6.91	11.45	11.35	11.22	8.82	9.15	8.98	7.08	7.45	7.39
	0.25	6.66	6.69	6.96	11.56	11.36	11.24	8.94	9.10	8.94	7.20	7.40	7.37
97.5	1.00	7.33	7.97	7.60	12.91	12.63	12.35	9.57	10.30	9.97	7.74	8.58	8.35
	0.50	7.57	7.92	7.74	13.09	12.51	12.29	9.81	10.15	9.86	7.95	8.48	8.27
	0.25	7.69	7.89	7.83	13.20	12.51	12.31	9.91	10.07	9.80	8.07	8.40	8.23
99.0	1.00	8.93	9.94	8.53	14.99	14.03	13.61	10.92	11.54	11.04	8.96	9.91	9.44
	0.50	9.06	9.45	8.74	15.19	13.88	13.54	11.04	11.34	10.89	9.16	9.74	9.32
	0.25	9.16	9.40	8.87	15.30	13.86	13.56	11.10	11.23	10.81	9.27	9.62	9.26

$$E^2 = \frac{1}{n}\sum_{i=1}^{n}(F_{Obs}(V_i) - F_{Calc}(V_i))^2 \qquad (5)$$

The second distribution examined was the hybrid form of the Weibull distribution, $f_H(V)$, developed by Takle and Brown (1977), which removed the effects of a large number of hours with zero wind speeds and weighted the remainder accordingly. The hybrid distribution function is given by

$$f_H(V) = F_0\delta(V) + (1 - F_0)f(V) \qquad (6)$$

where

F_0 = probability of observing zero wind speed over the time interval being considered

$\delta(V)$ = Dirac delta function

$f(V)$ = Weibull density function from Equation 3

This method merely removes those measurements of calm winds and fits the Weibull distribution to the nonzero wind speeds. The zero wind speed frequency is then reintroduced to give the proper mean and variance and to normalize the distribution. Note that for $F_0 = 0$, the equation is reduced to the usual form of the Weibull distribution.

Table 3 summarizes the results of the interpolation method (Intr) and the standard Weibull (Wbl) and hybrid Weibull (Hyb) test runs for four stations with varying wind speed conditions. In the end, it was decided to use the simple interpolation scheme on the binned data, as this provided the most stable results for all design speed levels. If wind velocity is regarded as a random variable, then, in the limit of very long data sets, one would expect that decreasing the bandwidth of the frequency bins would improve the overall estimate of the design wind speed. As can be seen from the table, there is some bin-size dependence in the speed estimates. However, the variation is generally less than 3% over a four-fold range in the size of the bins. In view of the data whitening procedure previously described, it was felt that a reduction in the bin size below 0.5 m/s might be counterproductive in terms of both overall accuracy and computational time.

It is worth noting, however, that the standard Weibull fit provides a good approximation in most cases, and consideration should be given to the use of such a parameterization for locations where there may be insufficient data for any other method of determination. The distribution at other elevations can also be adapted from parameters derived at a given reference height using the methods derived by Justus and Mikhail (1976) and reported in Doran et al. (1977). Figure 4 shows sample Weibull fits to station data for (a) high (Cape St. James, BC) and (b) low (Abilene, Tex.) wind speed locations.

Design Wind Speed Data

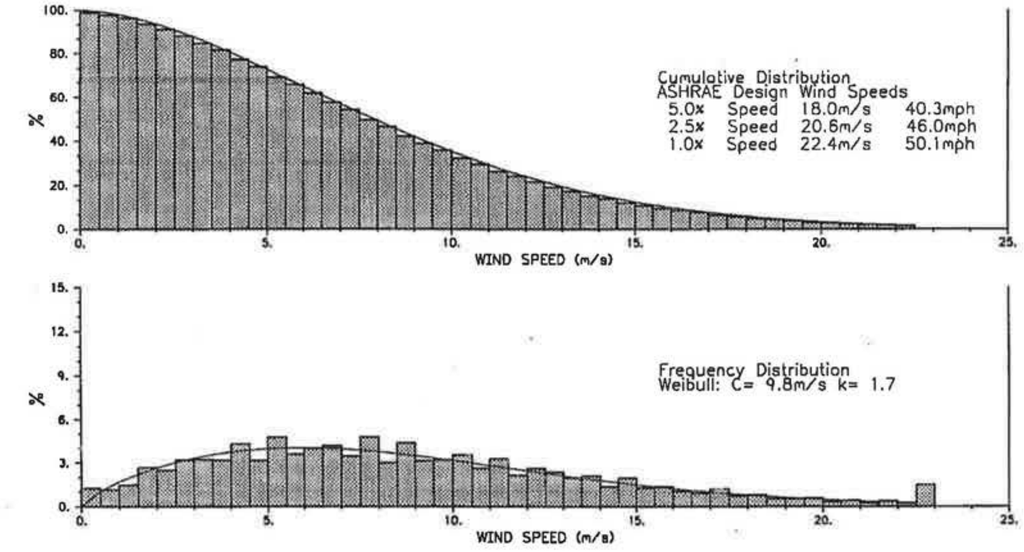
Sample design wind speeds derived using the above methodology are shown in Table 4 for nine selected stations in the United States and Canada. The complete design data set is available in the tables of Appendix B of Lamming and Salmon (1994), which summarize the required design wind speeds for all 239 U.S. and 143 Canadian locations.

CONCLUSION AND RECOMMENDATIONS

In the course of this study, it was apparent that the use of average wind speeds for the specific design purpose of locating and designing systems for areas of refuge, as set out in *ASHRAE Fundamentals*, would result in inappropriate probabilities of occurrence. The recommendation (Klote 1993) that a value of two to three times the average speed, while closer, would also have resulted in wind speed values corresponding to inappropriate probabilities in some cases. It is, therefore, clear that the data set of design wind speeds derived quantitatively in this project has extended the knowledge base for further development of the concepts of areas of refuge and related work.

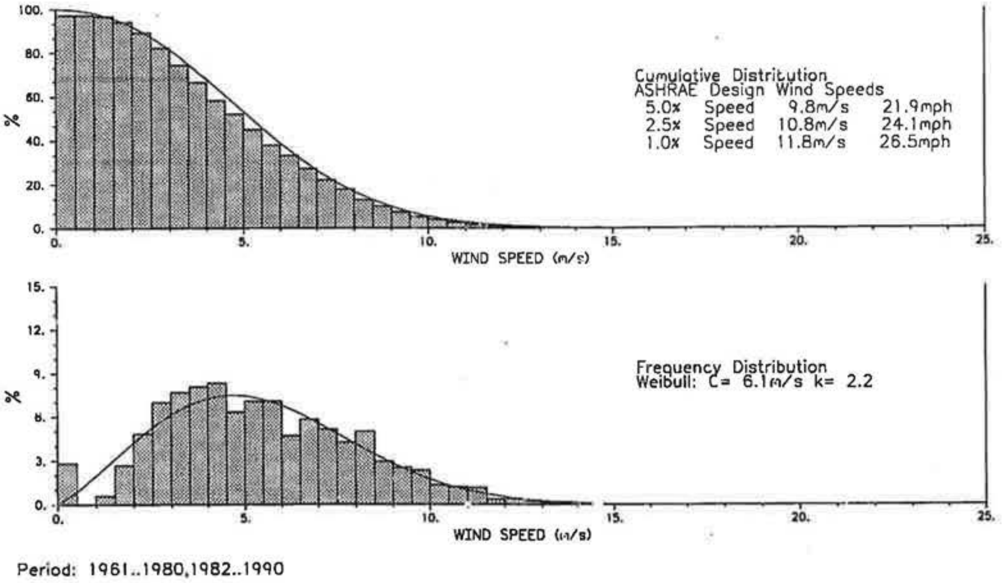
Therefore, it is recommended that the tables in chapter 24 of *ASHRAE Fundamentals* be adapted to show the design

BACK TO PAGE ONE



Period: 1957..1983,1985..1989

Figure 4a Weibull fits to data for Cape St. James.



Period: 1961..1980,1982..1990

Figure 4b Weibull fits to data for Abilene.

wind speeds derived in this project. In view of the suitability of the Weibull distribution for estimation of such design speeds, it is also recommended that a description of the distribution, and its suitability for estimation at sites with limited data, be included in the text of chapter 24.

It is further recommended that the following additional research be carried out to extend the present data set:

1. **Acquisition and processing of USAF data for Air Force stations in the United States.** Some 35 such stations are listed in the *ASHRAE Fundamentals*, Chapter 24, Table 1, and there is a good spatial spread across all states.
2. **Correction of existing station data for the effects of nearby obstacles and terrain features that could enhance or impede the airflow as "seen" by the anemometer.** In many cases, it has been found that anemometers have been sited on or close to airport buildings that would cause the measured air speed to be significantly different from what would have been observed in completely open surroundings. In addition, nearby terrain features, such as hills or valleys, can also have an effect on the data. Figure 5 shows the results of running a shelter correction model (Taylor and Salmon 1994) on a sample

BACK TO PAGE ONE

TABLE 4
Design Wind Speeds for Selected Stations in the Continental United States and Canada

State and Station Name	WBAN #	Lat. °N	Long. °W	Station Elevation (ft)	Station Elevation (m)	Years of Record Used in the Analysis	Design Speeds 95.0% 97.5% 99.0% mph	m/s
Birmingham, AL	13876	33.57	86.75	620	189	1964-90	14.9 16.8 18.8	(6.6) (7.5) (8.4)
Anchorage, AK	26451	61.17	150.20	115	35	1961-90	16.7 19.1 21.9	(7.5) (8.5) (9.8)
San Francisco, CA	23234	37.62	122.38	7	2	1961-80 1982-90	23.2 25.7 29.1	(10.4) (11.5) (13.0)
Key West, FL	12836	24.55	81.75	3	1	1961-80 1982-90	18.4 20.2 22.4	(8.2) (9.0) (10.0)
Topeka, KS	13996	39.07	95.63	875	267	1965-90	19.8 22.3 31.7	(8.9) (10.0) (11.2)
Baltimore, MD	93721	39.18	76.67	47	45	1961-68, 1970-79, 1982-90	18.5 21.0 24.2	(8.3) (9.4) (10.8)
Cape St. James, BC	25342	51.93	131.02	300	92	1957-83, 1985-89	40.3 46.0 50.1	(18.0) (20.6) (22.4)
Winnipeg, MB	14996	49.90	97.23	785	240	1953-89	22.7 25.4 29.0	(10.2) (11.4) (13.0)
Toronto, ON	94791	43.67	79.63	575	176	1965-89	19.6 22.4 25.9	(8.7) (10.0) (11.6)

station. While the correction of all station data would be a desirable option, it would also be quite time consuming and expensive even if simple correction methods (e.g., Taylor and Lee 1984) were used. It is recommended, therefore, that for each state or province, one or more "control station" data sets be maintained. These would be stations with a long period of continuous and homogeneous measurement, whose data have had all obstacle and terrain effects removed. This would then be a reference data set for theoretical design studies in each region.

3. **Completion of the research process by extending the work internationally to include those stations identified in the final table of Chapter 24 in *ASHRAE Fundamentals.***

ACKNOWLEDGMENTS

The authors very much appreciate the assistance and guidance of Mr. Robert Morris of the Atmospheric Environment Service and ASHRAE Technical Committee TC 4.2 (Weather Data) in obtaining the meteorological data for the Canadian stations.

REFERENCES

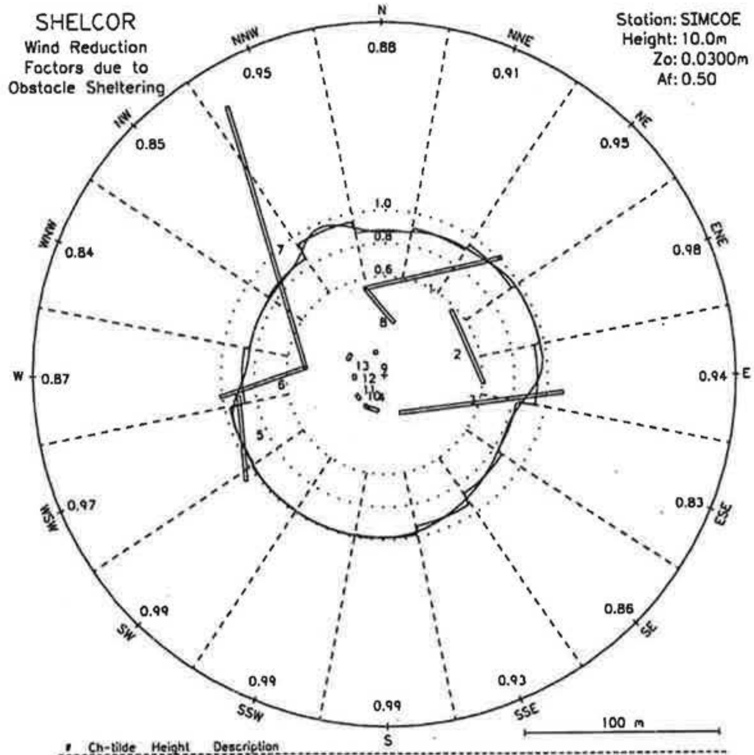
ASHRAE. 1993. *1993 ASHRAE Handbook — Fundamentals* (SI Edition). Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Atmospheric Environment Service. 1989. *Climatological station catalog, Volumes 1 - 6.* Ontario: Climatological Services Division, Atmospheric Environment Service.

Doran, J.C., J.A. Bates, P.J. Liddell, and T.D. Fox. 1977. Accuracy of wind power estimates. Battelle, Pacific Northwest Laboratories, PNL-2442. Prepared for the U.S. Department of Energy.

Justus C. G., and A. Mikhail. 1976. Height variation of wind speed and wind distribution statistics. *Geophysical Research Letters* 3:261-264.

BACK TO PAGE ONE



#	Ch-tilde	Height	Description
1	0.40	5.0m	clump of trees, mixed, 50x
2	0.25	4.0m	cubic bldg, low roof
3	0.40	8.0m	line of trees, mixed, 50x
4	0.25	3.0m	cubic shed, gable roof
5	0.30	3.0m	cubic bldgs, low roofs
6	0.64	5.5m	line of trees, evrgrn, 20x
7	0.64	5.5m	line of trees, evrgrn, 20x
8	0.72	5.0m	line of trees, evrgrn, 10x
9	0.25	3.0m	cubical shed, peaked roof
10	0.10	9.0m	single tree, decid., 70x
11	0.10	9.0m	single tree, decid., 70x
12	0.10	9.0m	single tree, decid., 70x
13	0.10	9.0m	single tree, decid., 70x

Figure 5 *Shelter Correction Model diagram for wind speed reduction by obstacles at Simcoe, Ont.*

Klote, J. H. 1993. Design of smoke control systems for areas of refuge. *ASHRAE Transactions* 90(2):793-807.

Lamming, S. D. 1986. Concepts and methods for collecting and compiling statistics on wind energy. Final Report, *Proceedings Working Group on Energy and Statistics,* United Nations Statistics Office, Rome.

Lamming, S. D., and J. Salmon. 1995. Wind data for design of smoke control systems. Final Report, ASHRAE Technical Committees TC 5.6 and TC 4.2.

Mikhail, A. S., and C. G. Justus. 1979. Height projection methods and sensitivity study. *Technical Report DOE/ET/20355-T1,* United States Department of Energy, Division of Distributed Solar Technology.

Morris, R.J. 1985. Evaluation of methods of fitting the Weibull distribution to observed wind speed distributions for wind energy applications. *Proceedings, Canadian Wind Energy Conference '85.* Dec. 9-10, 1985. Ottawa, Ontario: Canadian Wind Energy Association.

National Oceanic and Atmospheric Administration. 1993. *Local climatological data—Annual summaries for 1992.* Parts I to V. Asheville: National Climatic Data Center.

Ramsdell, J. V., S. Houston, and H. L. Wegley. 1979. Measurement strategies for estimating long-term average wind speeds. *Solar Energy* 25:495-503.

Takle, E. S., and J. M. Brown. 1978. Note of the use of Weibull statistics to characterize wind speed data. *Journal of Applied Meteorology* 11:556-559.

Taylor, P. A., and R. J. Lee. 1984. Simple guidelines for estimating wind speed variations due to small scale topographic features. *Climatological Bulletin* 18(2):3-32

Taylor, P. A., and J. R. Salmon. 1993. A model for the correction of surface wind data for sheltering by upwind obstacles. *Journal of Applied Meteorology* 32:1683-1694.

Verholek, M. G. 1977. Summary of wind data from nuclear plant sites. BNWL-2220. Richland: Pacific Northwest Laboratory.

Walmsley, J. L., J. R. Salmon, and P. A. Taylor. 1982. On the application of a model of boundary layer flow over low hills to real terrain. *Boundary Layer Meteorology* 23:17-46.