U.S. Department of Housing and Urban Development
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Monitoring of Near Ground Wind in a Built-up Suburban Environment

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Notice

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Executive Summary

Knowledge of the engineering characteristics of wind near to the ground, particularly below the standard anemometer height of 33 ft (10 m), is crucial to the efficient and safe design of low-rise buildings such as homes. These engineering characteristics include peak wind speed (profile), spatial and local variability, and turbulence which all contribute to the determination of risk-consistent wind loads on buildings. Of particular interest is the overall effect of shielding that will tend to reduce loads on smaller low-rise structures embedded within a dense built-up or wooded terrain environment. This interest in near ground wind monitoring also extends to the possibility of capturing valuable near ground wind data in a residential setting during a land-falling hurricane.

This report addresses the first phase of an effort to document the engineering characteristics of near-ground wind in a typical rough terrain (wooded/suburban) environment of an industrial park. The purpose is to explore the merits of considering shielding in wind design methodologies for homes and similar low-rise buildings in rough terrain environments and also to verify the representation of wind speed profiles in suburban terrain conditions.

The tasks included in this first phase of work are as follows:

1. Assess the existing knowledge related to the engineering characteristics of wind near to the ground including the wind velocity profile, spatial variability, turbulence, shielding, and building load (i.e. wind pressure) effects related to a typical suburban and wooded terrain condition;

2. Analyze the data collected for a few recorded wind events to provide a rough comparison to empirical representations of the wind velocity profile (i.e. the power law) including the effects of shielding and wind speed-up, spatial variability due to the arrangement and size of obstructions and open areas within the surrounding terrain, and turbulence; and,

3. Compare the empirical data collected on the characteristics of near-ground wind to that embodied in current wind engineering provisions.

To achieve the objectives of this study, an industrial park in Upper Marlboro, Maryland, has been instrumented with five near-ground wind monitoring stations having anemometers at an elevation of 10 feet (3.0 m). The five stations were located to capture a representative sample of the near-ground wind field within the built-up terrain of the industrial park. An additional monitoring station, centrally located in the industrial park, consists of two anemometers placed on a communications tower at elevations of 33 ft (10 m) and 187 ft (57 m).

The unique findings of this study are related to the variability of the near ground wind speeds (and the estimated power law coefficients) in the “exposure B” setting of the industrial park. The following significant conclusions can be made based on the length of the data record at this point:

1. On average, the estimated power-law exponent for peak gusts are in reasonable agreement with that used in the ASCE 7-95 standard for the exposure conditions of this study. However, based on the literature review, this power-law relationship, when squared to determine wind load variation with height may be conservative. (This can only be confirmed in wind tunnel studies or in full-scale building pressure measurements in unison with the wind profile measurements).

2. The average power law exponent ($1/\alpha$) of approximately 1/7 was documented based on the peak gust for each of the five near ground stations during the record period. The COV of α was between 0.35 and 0.41 for the peak gusts of the five stations.

3. The variation in estimated power law exponent can be attributed to the differences in local exposure and topographic effects experienced at the five near-ground wind stations. At a standard anemometer elevation of 33-feet, this variation could be expected to be much less as the effects of shielding and surrounding roughness conditions would be somewhat diminished.

4. The variation of wind speed between the five stations was significant, representing the range of wind conditions that would be expected in a built-up exposure. The lower wind speeds are associated with stations having a higher degree of “protection” (or shielding) from buildings or trees while the higher wind speeds were associated with parking lot exposures, possible channeling due to buildings, and effects of topography (i.e. a small knoll). Therefore, in the moderately dense conditions of the industrial park, the effect of shielding at some locations was practically offset by an opposite effect of wind speed-up at other stations. In a more dense development, more shielding would probably be realized on average.

It is recommended that the near-ground wind monitoring effort continue for an additional year to allow for an “annual extreme value” representation of the near ground wind speeds and estimated velocity profiles. Re-deployment of the wind monitoring station in a dense residential development should be considered to investigate the maximum possible condition of shielding. Also, if funding and opportunity allow, the wind monitoring stations should be deployed in an attempt to capture data from a future land-falling hurricane event in a residential setting. This would allow better correlation of near ground wind conditions with damage levels experienced by residential construction. Finally, future research should consider using this data in combination with wind-tunnel experiments to provide improved guidance for the design of residential and similar low-rise buildings in exposure B settings.

Introduction

Knowledge of the engineering characteristics of wind near to the ground, particularly below the standard anemometer height of 33 ft (10 m), is crucial to the efficient and safe design of low-rise buildings such as homes. These engineering characteristics include peak wind speed (profile), spatial and local variability, and turbulence which all contribute to the determination of risk-consistent wind loads on buildings. Of particular interest is the overall effect of shielding that will tend to reduce loads on smaller low-rise structures embedded within a dense built-up or wooded terrain environment.

Because of possible increases to and unknown variability of wind speeds in these conditions due to increased turbulence and the possibility of localized wind channeling, shielding effects have not been addressed in wind engineering provisions in the United States. There may also be some concern with localized extreme wind phenomena, such as down-bursts, that sometimes occur in unstable atmospheric conditions associated with severe thunderstorms and frontal squalls. Never-the-less, it can be expected that design wind speeds may be somewhat over-estimated very near to the ground (i.e. below the top of obstructions to wind flow) in built-up or wooded terrain. Since most of the low-rise building stock (including new and existing homes) are located in suburban terrain conditions, understanding the near ground wind characteristics in this context is potentially important to efficient, risk-consistent design. When these terrain conditions are known to exist and can be reasonably assumed to remain for the life of the structure (even during a major wind event), it is reasonable to consider the overall effects of shielding in establishing safe and realistic design loads.

This report addresses the first phase of an effort to document the engineering characteristics of near-ground wind in a typical rough terrain (wooded/suburban) environment of an industrial park. The purpose is to explore the merits of considering shielding in wind design methodologies for homes and similar low-rise buildings in rough terrain environments. In particular, the focus of this report is on the characterization of the variable nature of wind very near to the ground. Also of key interest is the comparison of actual near-ground wind data to known wind profile theories, particularly the power law representation commonly used for wind engineering purposes. Future studies, if pursued should consider wind tunnel analyses, to investigate these effects in terms of their ultimate impact on building pressures. Alternatively, this building pressure investigation could be an extension of the current full-scale monitoring of actual wind conditions.

The tasks included in this first phase of work are as follows:

1. Assess the existing knowledge related to the engineering characteristics of wind near to the ground including the wind velocity profile, spatial variability, turbulence, shielding, and building load (i.e. wind pressure) effects related to a typical suburban and wooded terrain condition;

2. Analyze the data collected for a few recorded wind events to provide a rough comparison to empirical representations of the wind velocity profile (i.e. the power law) including the effects of shielding and wind speed-up, spatial variability due to the arrangement and size of obstructions and open areas within the surrounding terrain, and turbulence; and

3. Compare the empirical data collected on the characteristics of near-ground wind to that embodied in current wind engineering provisions.

To achieve the objectives of this study, an industrial park in Upper Marlboro, Maryland, has been instrumented with five near-ground wind monitoring stations having anemometers at an elevation of 10 feet (3.0 m). The five stations were located to capture a representative sample of the near-ground wind field within the built-up terrain of the industrial park. An additional monitoring station, centrally located in the industrial park, consists of two anemometers placed on a communications tower at elevations of 33 ft (10 m) and 187 ft (57 m).

Because of timing in this initial phase of work, data from only a few weeks of monitoring were available for study. Monitoring will continue for at least one annual cycle to obtain data on additional wind events and to ascertain the effects of shielding in the context of annual extreme values. It is in this context that a wind profile based on annual extreme wind speeds, including variability in annual extremes due to shielding, will be eventually formulated. Statistical analysis of annual extreme wind speeds forms the basis of both design wind speeds in wind engineering provisions and the treatment of risk or uncertainty (i.e. the wind load factor) in reliability-based design.

It was originally proposed that the portable, near-ground wind stations would also be used to capture wind-field data from a land-falling hurricane event in a residential setting. An opportunity to test this proposal in an actual hurricane event was not possible during the 1997 hurricane season because of a lack of land-falling hurricanes on the Gulf and Atlantic seaboard. This activity is tentatively planned for future work depending on the level of funding available for such an under-taking. While logistics for such a task have been preliminarily defined, additional work is needed to ensure access to regions under a hurricane evacuation warning and to coordinate efforts with other researchers and agencies conducting similar tasks.

Problem Statement

A major goal of the project is to evaluate the validity of considering wind shielding to improve the current wind engineering approach to low-rise buildings in a typical built-up terrain environment characterized by trees and other low-rise buildings. This typical terrain environment is classified as wind exposure category ‘B’ (wooded/suburban terrain) in the American Society of Civil Engineer’s Standard 7, *Minimum Design Loads for Buildings and Other Structures* (ASCE 7-95) [1]. While the reference wind speed profile of exposure category ‘C’ (open, flat terrain) may be adjusted in ASCE 7-95 to account for various wind exposure categories, this adjustment is done without consideration of the nature of wind within the ‘interfacial layer’ in exposure B conditions. The interfacial layer, shown in Figure 1, is the layer of wind near to the ground that occurs below the ‘displacement height’ (or ‘zero-plane displacement’). The displacement height may be roughly characterized as the average height (above ground) of obstructions to the flow of wind in a dense urban or suburban setting. The displacement height decreases as the density and height of the obstructions decrease. The method of wind speed adjustment in ASCE 7-95 for terrain exposure and height follows the ‘power law’ empirical relationship as described later in this report. The power law relationship, as well as all other atmospheric boundary layer wind characterizations for engineering purposes, do not apply to the interfacial layer. However, many low-rise buildings (or at least their lower portions) exist within this interfacial layer, particularly in relatively dense urban, suburban, or wooded conditions.

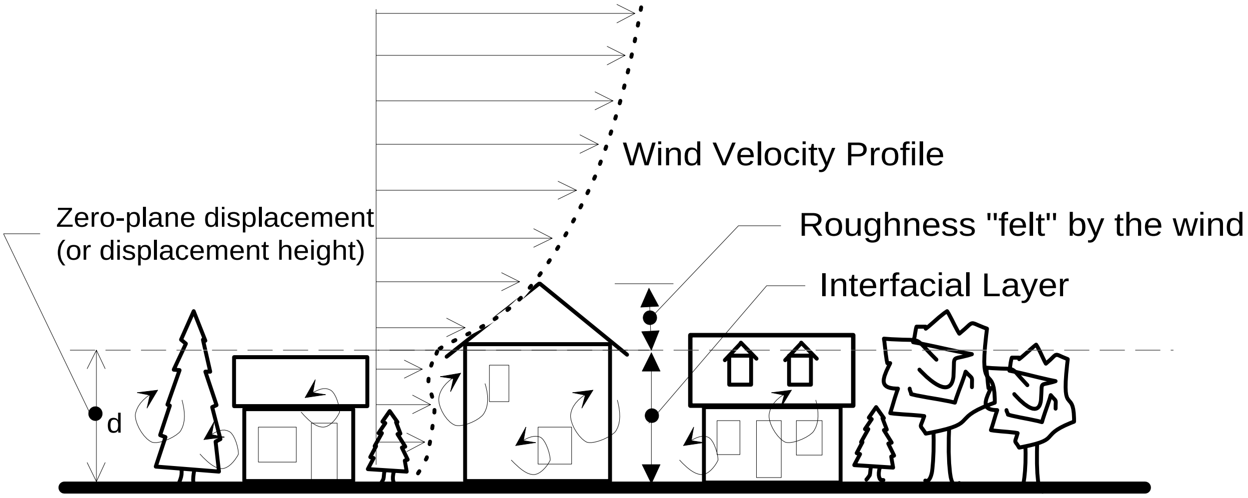

Figure 1
Interfacial Layer

The interfacial layer is characterized by lower mean wind speeds but greater turbulence. The spatial variability of the wind speed as a result of variations in very localized effects due to shielding and channeling within the interfacial layer is also a concern. The current wind engineering provisions of ASCE 7, particularly the adjustment of wind loads for surface roughness and height above-ground, only apply to conditions above the interfacial layer. Within the interfacial layer, it can be expected that the average wind speed will decrease as the density of surrounding obstructions increase. However, mechanically generated turbulence will increase and will tend to offset this wind load reduction by possible alteration of flow patterns and thus pressure zones on building surfaces. To a lesser degree, wind channeling effects may increase the magnitude of pressures in specific situations, particularly for components and cladding loads on localized, small areas of buildings. However, the net effect on building loads should be a reduction because of the dominant effect of shielding (as oppose to channeling) and the wind energy dissipation provided by numerous obstructions to wind flow in the interfacial layer of typical suburban settings.

Section 6.5.4 of the ASCE 7-95 standard specifically states that “there shall be no reductions in velocity pressures due to apparent direct shielding afforded by buildings and other structures or terrain features.” However, this does not preclude the possibility of accounting for overall shielding effects within the interfacial layer of a particular wind exposure category (i.e. exposure category B for suburban and wooded terrain). To achieve this refinement, the net load effect of mean wind speed reduction, turbulence increase, and variability of maximum wind speeds within the interfacial layer in an exposure B environment must be better understood. From this knowledge, rational solutions can be explored and developed to improve wind load provisions for low-rise buildings, particularly homes, in dense suburban or wooded terrain.

Literature Review

This literature review provides an overview of the history and state-of-the-art for characterizing wind near to the ground, particularly in rough terrain. The focus is on wind profile models in wind engineering standards, the treatment of wind variability near to the ground in rough terrain exposures, wind turbulence, and the resultant effect of these factors on a building’s wind loading. Also explored are certain meteorological conditions, such as instability of the atmosphere (i.e. negative thermal gradient), that may affect the characterization of wind near to the ground.

Historical Basis (Wind Profile)

In his article on wind velocity in relation to height above ground, Pagon begins with the statement “At the earth’s immediate surface the wind velocity must be zero” [2]. He reports on previous work by Archibald in 1885 that resulted in a power law relationship between wind speed and height above ground. The formula Archibald derived from wind speed data collected from anemometers suspended by kites at elevations as great as 1,300 ft (396 m) is:

$$\frac{V_1}{V_2} = \left(\frac{H_1}{H_2}\right)^{\frac{1}{n}}$$

Parameters V_1 and V_2 represent wind speeds at different elevations H_1 and H_2, respectively. He found that the exponent *n* varied from 5.2 to 2.75. The higher value was determined from a comparison of wind speeds at instrument heights of 1,095 ft (334 m) and 767 ft (234 m). The lower value corresponded to comparison of wind speeds at elevations of 250 ft (76.2 m) and 102 ft (31.1 m). Archibald recommended an average value of 4 for the exponent *n*. This work may represent the first appearance of the empirical ‘power law’ for determining wind speed with relationship to height above the earth. Pagon also reports on additional work by Scrase in 1930 who found that the value of the power law exponent *n* generally varied between 5 and 7.

Based on a review of the current “eddy conductivity theory”, Pagon concludes that “it is evident that the temperature gradient can have no marked effect near the ground; the turbulence here must therefore be governed by the wind velocity — which shows no seasonal variation — and by the nature of the ground. Within the first 6 ft. this seems to be entirely true.” This observation may have some bearing on the issue of the near-ground wind characteristics relative to the stability of the boundary layer atmosphere. (This issue is revisited later in the literature review).

Historical Basis of Wind Engineering

Davenport gives a comprehensive review of the state of the art of wind engineering and relevant knowledge leading up to 1960 [3]. It is interesting that a statement made by Robert F. Legget in the preface to Davenport’s report still holds true today (at least for homes) even though significant advancement in wind engineering has occurred since 1960. The statement is as follows:

> *“Improvements in the methods of designing structures must be paralleled by a more accurate assessment of the loads acting upon them, since a design can be no more accurate than the load assumptions made for the calculation.”*

Davenport’s review covers the entire spectrum of wind engineering, including the following topics:

- shape factors (i.e. surface pressure coefficients for buildings),
- boundary layer velocity profiles,
- design wind velocities,
- structure of the natural wind,
- wind speed averaging periods for structural design purposes,
- the validity of wind tunnel results,
- shielding effects, and
- the dynamic effects of wind.

An attempt is made to focus on those topics related to the primary subject matter of this report. However, as mentioned previously, many inter-related factors in defining the structure of wind, such as turbulence and atmospheric stability, affect the determination of an appropriate wind profile model and thus wind loads for engineering purposes.

Davenport reports that various empirical, semi-empirical, and theoretical formulae have been derived to represent the variation of wind velocity with height [3]. Three of the more familiar forms are the spiral, logarithmic, and exponential (i.e. power law) profiles. For structural purposes, the power law profile has been used most widely because of its simplicity. The basic form of the power law was stated as follows:

$$V_z = k \times z^{\frac{1}{\alpha}}$$

where V_z is the velocity at height z above ground and k and $1/\alpha$ are constants. The exponent $1/\alpha$ is reported to increase by an increase in either roughness or stability. The power law is also reported as being applicable from a height of roughly 33 ft (10 m) to the gradient height which covers the range of heights of interest to structural engineers.[1] The gradient height is the distance above the earth's surface – roughly 1,000 to 2,000 feet (305 m to 610 m) above which the wind velocity can be assumed constant and no longer affected by the roughness of the earth's surface.

Numerous empirical measurements of the wind profile are reported which Davenport uses to give confirmation of the power law [3]. The exponent of the power law is seen to vary between roughly 1/9 and 1 depending only on the surface roughness characteristics. Two of the data sources were from winds recorded during Hurricanes "Carol" and "Edna" (1954) over flat country with scrub trees. The power law closely fit the recorded wind speed profile with exponents of 1/3.4 and 1/3.3 for one-minute averaging times. The height of the measurements ranged from about 40 ft (12.2 m) to 400 ft (122 m) and the one-minute average wind speeds were 40 to 50 mph (22.4 m/s) and 70 to 100 mph (31.3 to 44.7 m/s) at the respective heights.

Davenport appropriately qualifies this assessment of the power law profile by stating that the data refer specifically to mean velocity profiles prevailing above a height of 30 ft (9.1 m) in strong winds, over flat ground surface at lapse rates which, if not explicitly stated, by the nature of the storms studied could not have differed greatly from the adiabatic. The lapse rate is used to measure the stability of a storm and it is simply the rate of temperature variation with height. In storm winds of long duration in which turbulence causes thorough mixing the lapse rate near the ground is invariably close to the adiabatic which corresponds to a state of neutral stability (i.e. little variation in temperature with height). Observations of mature large-scale storms, whether of the tropical (i.e. hurricane) or extra tropical variety, were reported as evidence. However, Davenport finds exceptions in severe local storms such as thunderstorms and frontal squalls which are notably unstable, air near the ground being warmer than aloft. Davenport reports on a couple measurements that give evidence of virtually no change in wind speed with height in conditions of extreme instability with measured power law exponents of 0.02 (1/50) or less. Davenport recognizes that the issue of atmospheric stability has been given scant attention with respect to its possible importance in the accurate evaluation of wind velocities. (Again, this issue is addressed later in the literature review.)

Davenport also reports on a secondary effect that wind speed has on the profile in that the value of the surface friction increases slightly with wind velocity [3]. (This phenomena is confirmed in this report on the basis of 3-second gust measurements and is also reported in other sources covered later in the literature review.) From reported investigations of five-minute mean velocities at heights up to 410 ft (125 m) for nine storms, it was found that the exponent of the power law profile increased by approximately 0.02 for every 10-mph (4.5 m/s) increase in surface wind velocity. At 50 mph (22.4 m/s) the value was found to be 0.27 (1/3.7) and the

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[1] It is interesting to note that the range of heights of interest in the structural design of homes is less than 33 ft (10 m).

extrapolated value at 80 mph (35.8 m/s) was 0.33 (1/3.0). It was reported that these profiles fit the experimental records extremely well with a standard deviation of 1.26 mph (0.6 m/s).

Bearing in mind the influence of the wind velocity on the rate of increase of wind velocity with height and the extent of data available for various terrain conditions, Davenport suggested power law coefficients corresponding to qualitative descriptions of the surface roughness as shown in Table 1.

TABLE 1
POWER LAW EXPONENTS
FOR VARIOUS DESCRIPTIONS OF TERRAIN
BY DAVENPORT (1960) [3]

Description of the Terrain	**Power Law Exponent, $1/\alpha$**	**Gradient Height, z_g**
For open country, flat coastal belts, small islands situated in large bodies of water, prairie grasslands, tundra, etc.	1 / 7 (0.14)	900 ft (274 m)
For wooded countryside, parkland, towns, outskirts of large cities, rough coastal belts	1 / 3.5 (0.29)	1,300 ft (396 m)
For centres of large cities	1 / 2.5 (0.40)	1,700 ft (518 m)

Davenport again qualifies the applicability of these exponents with the following statement:

> *"These figures refer to the mean wind velocity over level ground, to large-scale severe storms (which exhibit nearly neutral stability) and to heights between about 30 ft (9.1 m) and the height at which the gradient velocity is first attained. If there are areas in which the highest probable velocities occur during severe local storms such as thunderstorms and frontal squalls (which does not seem likely) no increase in velocity with height would seem appropriate."*

Davenport reports on studies at the National Physical Laboratories related to shielding effects [3]. The work is quoted as follows:

> *"It is clear that for general design purposes it would not be practical to treat each case separately and allow for shielding effects of existing surrounding buildings, partly because this would be an unnecessarily complicated procedure but mainly because the conditions might be varied after the building was erected. On the other hand, the results of the tests show that in a built-up area, even with buildings quite large distances apart, there is a substantial shielding effect and it is unnecessary therefore to allow for the fully exposed loading…"*

Davenport gives some caution that, if lower wind speeds are considered due to overall effects of shielding in a built-up environment, a larger negative shape coefficient should also be considered for roofs because downwind structures may experience negative pressures over all surfaces. In all other circumstances the shape coefficients in the unshielded condition yield the maximum pressures. Davenport further states that the concern with reductions to account for shielding is accounted for in the profiles recommended in Table 1 for cities and towns.

A study of hurricane winds at Lake Okeechobee (Florida) by the U.S. Corps of Engineers was also reported by Davenport where the data suggested that the rate of increase of wind speeds with elevation over water increased with wind speed [3]. This indicated that the surface roughness was increased due to wind generated waves. This result may have influenced Davenport's decision to not include a separate category for coastal exposure in Table 1. It is also interesting to note that a recent study regarding ocean roughness due to wind generated waves during hurricanes indicates that the ocean surface is similar in roughness to a flat, open terrain condition [4].

Davenport also discusses the current knowledge and experimentation regarding gust action and gust coefficients [3]. He concluded that there was no rational theory for the development of a gust coefficient in wind design codes at that time. However, from the data and reports available, the following relevant findings were reported.

Gustiness (i.e. the range over which velocities fluctuate) decreases with height. Data was shown for a suburban profile (power law exponent of 1/4.75) in which the gustiness is reported at various elevations by stating the recorded mean and standard deviations of the wind records. Mean velocities are for a 100-second average of one-hundred velocity measurements having a 1-second averaging time. The results are reported in Table 2.

TABLE 2
VARIATION IN GUSTINESS WITH HEIGHT
IN A TERRAIN CHARACTERIZED BY A POWER LAW
EXPONENT OF 1/4.75

Height	**Mean Velocities (mph) [avg. of 100 1-sec.velocity readings]**	**Standard Deviation (mph)**
58 ft (17.7 m)	43.7 mph (m/s)	4.45 mph (m/s)
88 ft (26.8 m)	47.5 mph (m/s)	3.51 mph (m/s)
118 ft (36.0 m)	50.7 mph (m/s)	2.55 mph (m/s)

The data show that 66 percent of the one-second velocities were less than the mean plus one standard deviation which corresponds to a power law profile with an exponent of 1/7. It is also shown that 95 percent of all one-second velocities were less than the mean plus two standard deviations which corresponds to a power law exponent of 1/11.8.

Davenport reports on a few available studies that show the effect of the size of a surface or building on the gust loading experienced [3]. As logic would suggest, the smaller surfaces or buildings experience in general a greater load impact from gusts. Therefore, gust size in relation to surface area, building size and shape, and response was noted by Davenport as an important area for future research.

Davenport provides a very detailed review of the current practice for wind tunnel studies and the development of shape coefficients (surface pressure coefficients) [3]. Only those issues that are applicable to low-rise structures are reported here. Davenport states that wind tunnel studies are generally valid when three conditions are fulfilled:

1. geometrical similarity between the model and prototype;
2. equality of Reynolds numbers; and
3. kinematic similarity in the approaching flows.

Davenport notes that the first condition presents no problem and that on sharp-edged structures, the separation of wind flow is initiated at the edges of the building. Therefore, the flow patterns and hence the pressures are largely independent of Reynolds number (i.e. velocity x characteristic dimension / kinematic viscosity of fluid) and surface roughness, but not of the upstream velocity profile. He notes that this is not the case for cylindrical or more aerodynamic shapes. He also reports that exceptions to this statement can be found when the vortex layer approaches tangency to one of the surfaces and high suctions are generated. This situation can be attained on relatively flat roofs (i.e. less than about 20 degree slope, but most pronounced near 20 degrees) and for wind incident upon the walls of a structure at small angles. Davenport also notes that the presence of the ground surface exerts a considerable stabilizing effect on the pressure distributions which, except just to the lee of the separation point, are for all practical purposes static if the flow is steady.

Davenport reports at the time of his writing that in only one or two tests has kinematic similarity been partially achieved in a wind tunnel. (This is not true today). The kinematic properties of the natural wind which require simulation in a wind tunnel are, basically, the increase of mean velocity with height and the turbulence. A study is cited in which it is shown that the practical rule for using the 1/7th power law to adjust the wind pressure on a structure at any height is clearly conservative (based on an 80 mph velocity at a reference height of 40 ft). This practical rule is:

$$q \propto H^{\frac{2}{7}}$$

where q is the wind pressure, H is the height on the building, and the 2/7 exponent is the square of the 1/7th power law to transform the velocity profile to a wind pressure profile since wind pressure is a function of the square of the wind velocity. The wind tunnel model data for full-scale heights less than 100 ft (30.5 m) was fitted to the following representation of the power law:

$$q \propto H^{\frac{1}{1.33}}$$

It is obvious that this representation of the wind pressures results in a significantly greater decrease in loads than the practical rule stated previously. However, it is noted that the 1/7th power law more appropriately represented the wind velocity with height in the study. (It is interesting to note that the more conservative 1/7th power law rule is still in use today in wind design provisions of at least one model building code in the United States.) Davenport suggests that the proposed velocity pressure distribution should be considered in conjunction with other experiments in which the effect of turbulence on the pressure distribution is also studied.

It is noted that very few studies had been published regarding tests under turbulent flow. However, those reported demonstrated significant disparity between wind tunnel tests with laminar flow and actual full-scale measurements in the natural wind. One study indicated that windward pressures were slightly less than in laminar flow and the reductions in the leeward pressure considerably less (up to 50 percent). Full-scale measurements in the natural wind yielded similar reductions in comparison to modeled tests in laminar flow. As a whole, this and similar studies show that the pressure does not increase with height at the same rate as the measured velocity pressure. This observation agrees with the 1/1.33 power law relationship for pressure stated earlier.

Regarding shape coefficients, Davenport reports on gross inadequacies in the then current provisions of the National Building Code of Canada and other similar codes. He also recommends the use of the Swiss standards which provide distinct shape coefficients for various regions on specific structural forms, including homes. (Upon inspection of the Swiss standard translation in the appendix of Davenport’s report, it is apparent that the Swiss standard was a fairly advanced wind design approach for its time, even though it was based on the use of laminar flow wind tunnels.)

Davenport closes his review with several recommendations for future research and improvements to wind engineering provisions. While many of the recommended actions have seen great advancement (particularly with the rise of the ‘boundary layer wind tunnel’), some of the issues such as shielding have seen little progress in the development of improved wind design methods for buildings in the United States.

Canopy Flow (Wind in the Interfacial Layer)

Most of the research to date on wind flow in the interfacial layer has been done in the context of agricultural applications, not wind engineering of buildings. The complex movement of wind in the interfacial layer for built environments may be considered similar to “canopy flow” which refers to wind movements within the environment of a plant canopy (i.e. trees, crops, etc.). However, differences at the level of extreme winds of structural engineering interest must be considered. Therefore, in this section of the literature review, several studies regarding canopy flow are discussed with a focus on the aspects that may have relevance to the topic of this report. While the analytical descriptions of canopy flow may be unacceptable for engineering purposes from a standpoint of complexity, they can be useful in developing a simplified theory or factor to address shielding in the interfacial layer of a built or suburban environment. At a minimum, these studies provide insights into the nature of wind flow in this complex, near ground environment.

Cionco reports on the use of an exponential function for the prediction of the wind velocity profile for canopy flow [5]. Canopy flow is the nature of wind movement within the canopy of various types of plants and other sources of mechanical retardation of wind speed very near the earth's surface. The form of the exponential function is as follows:

$$u = u_H \exp\left[a\left(\frac{z}{H} - 1 \right) \right] ,$$

where u = horizontal wind speed at any height z within the canopy; u_H = horizontal wind speed at the top of the canopy; H = average height of the canopy elements, and *a* is a constant known as the 'attenuation coefficient'. By solving the above equation for *a*, the following equation is derived:

$$a = \left[\ln \frac{u}{u_H} \right] \Big/ \left[\left(\frac{z}{H} - 1 \right) \right]$$

The *a-value* can be easily calculated from wind profile data by means of a least-squares method. Cionco reports that the attenuation coefficient is a "conservative measure of the response of air flow to the various types of vegetation."

Cionco gives several fitted values of the attenuation coefficient for natural and artificial canopies from previously reported data. It is apparent from the data that the *a-value* increases with increasing complexity and density of the canopy. It is affected by element density (including the amount of foliage on plants), flexibility or rigidity, and general structure within the canopy. Table 3 provides a few solutions for the attenuation coefficient that may have some relevance to wind profiles for structural design purposes rather than agricultural applications such as predicting evapo-transpiration rates.

TABLE 3
SELECT LEAST-SQUARES SOLUTIONS FOR THE ATTENUATION COEFFICIENT [5]

Canopy	$\bar{a}$ -Value
Larch Trees	1.00
Wooden Pegs	0.79
Citrus Orchard	0.44
Bushel Baskets	0.36

While these measured *a-values* are representative of relatively low wind speeds (i.e. less than 11 mph (5 m/s)), the concept of using an exponential profile may have bearing for estimation of wind speeds in the interfacial layer of a built-up environment, one dominated by trees, buildings, or a mixture of both. In his conclusions, Cionco mentions that the higher a-values (i.e. dense canopy) tend to increase with increasing wind speed while the lower ones are constant.

Oliver and Mayhead report on anemometer readings taken during a strong gale which blew down some of the trees in an even-aged 52 ft (16 m) stand of pine trees [6]. Gusts at the top of the canopy attained 39.1 mph (17.5 m/s). They report that the wind profiles agreed well with the theoretical logarithmic profile above the canopy and the exponential profile below. It is also reported that the zero plane displacement and roughness length values were similar to those at lower wind speeds. The zero plane displacement (or displacement height) is the distance above the ground surface that the logarithmic law profile (and thus the power law profile also) is displaced due to surface roughness. Therefore, it is dependent on the height, spacing, shape, and complexity of the elements creating the surface roughness effect.

The logarithmic profile used to approximate the wind profile above the canopy is as follows:

$$u_z = \frac{u_*}{k} \log_e \left(\frac{z-d}{z_o} \right)$$

where,

u_z = wind speed (m/s) at height z (m)
d = zero plane displacement (m)
z = height above ground (m)
z_o = roughness length (m)
k = universal (von Karman) constant = 0.41
u_* = friction velocity (m/s).

While the logarithmic profile only applies under ‘neutral’ conditions, i.e. when there is little gradient of temperature, the strong winds were believed to make the temperature gradient very small so that the equation should fit fairly well above the canopy. A plot of wind speed (u_z) against $\log_e$(z-d) produced a straight line representing a good fit. The roughness length, z_o, was found at the intercept of the straight line with the height axis (i.e. at u = 0) to be 0.97m which agreed with earlier data from normal wind conditions. The slope of the straight line yielded a surface friction velocity, u*, of about 1.6 m/s for the gale. Thus, the logarithmic law provided an adequate fit above the canopy height.

Below the canopy height, the exponential profile was used to approximate the wind flow using the equation (same as reported previously, but with a change in notation in this particular study):

$$u_z = u_h e^{-\alpha(1-z/h)}$$

where,

h = height of top of tree canopy (m)
u_h = wind speed (m/s) at height h
e = base of natural logarithms
α = constant ('attenuation coefficient')
other symbols as before.

The above equation can be approximated by:

$$u_z = u_h\left[1+\alpha\left(1-z/h\right)\right]^{-2}$$

The actual wind profile recorded during the gale was plotted with the exponential profile for various α-values (same as previous *a*-values). An α-value of 2.5 fit the data best on average for heights within the canopy greater than about 60 percent of the canopy top elevation, h. A α-value of 2.0 provided a conservative estimate of the wind profile (i.e. over-estimate of the actual wind speed) in the canopy layer for heights down to about 50 percent of the canopy height, h. The fit was not exact, particularly below a height of about 0.5h where the exponential profile under-estimated the actual wind speeds by about 30 percent on average. However, the general shape of the exponential profile did follow the shape of the actual profile reasonably well. The logarithmic profile may be generalized to couple with the exponential profile at a point of inflection near the canopy top elevation, h. Thus, the generalized wind profile has a concave shape above the canopy and a convex shape within the canopy as would be required by the two theoretical profiles.

Turbulence measurements in a simulated plant canopy were made in a wind tunnel by Seginer, et al. [7]. The results agreed with an exponential wind profile and showed constant turbulence intensity along the height of the canopy. Turbulence intensity increased only at an internal boundary layer which extended to a height of about 10 percent of the canopy height. The turbulence intensity was about 0.47 on average within the canopy and increased to a maximum of about 0.52 at the base in the lower 10 percent of the canopy height. Turbulence intensity is simply the coefficient of variation (standard deviation/mean) of the wind speed. The wind tunnel experimental data agreed well with field studies by others and confirmed the exponential profile and the constant stream-wise turbulence within the canopy.

Modern Wind Engineering

Numerous analytical and wind tunnel studies have been conducted since the time of Davenport's comprehensive review of wind engineering and research needs in 1960 as addressed earlier in this literature review [3]. Covering the breadth of these studies and the current state-of-the-art of wind engineering in general is beyond the scope of this paper. There are at least two texts which can serve that role very effectively [8],[9]. The commentary and provisions of the ASCE 7-95 standard reflects the state-of-the-art in the United States, which is the topic of the next section of this report [1]. Therefore, the scope of this part of the literature review will focus on a recent study that gives a comprehensive treatment of wind engineering as it relates to low-rise buildings and the development of modern design codes for these types of buildings [10]. Also presented are a few more recent studies related to the wind profile near to the ground.

Ho's wind tunnel experiments and analytical work comprise the most comprehensive study found in the literature of near-ground wind effects in isolated and built-up building conditions in suburban and open exposure wind profiles [10]. Ho's compilation of references and treatment of numerous wind engineering topics can be considered as representing the state-of-the-art of modern wind engineering for low-rise buildings.

In Ho's study, 20 different low-rise building sizes and shapes were investigated in random arrangements in numerous wind tunnel experiments. The variability in building loads due to random shielding, the exposure environment, building shape, directionality effects, and wind climate were explored using a combination of experimental data, *Monte Carlo Simulation*, and analytical methods. Ho's work was capped by a reliability analysis of the thousands of data sets of wind tunnel data to form a comprehensive basis for suggested building code provisions regarding wind loads on low-rise buildings, including the effects of shielding in a single exposure category code format.

The particular features of Ho's work that are relevant to this study include:

1. a review of analytical characterizations of the wind;
2. a review of the treatment of wind profiles in building codes;
3. wind tunnel experiments on the effects of immediate surroundings; and
4. wind tunnel studies on the effects of upstream exposures.

Ho uses the 'ESDU model' (also known as the 'Deaves and Harris theory') to provide an analytical characterization of the wind profile in his studies. This more complicated model is described in Ho's work and it reduces to the logarithmic law for heights less than about 30 m. Also reported is a simplified model based on a paper by Davenport in 1984 with the following equation for the mean wind speed profile derived as shown in Ho's thesis:

$$\frac{V_z}{V_g} = 0.285\left(\frac{fz_o}{V_g}\right)^{0.07} \ln\left(\frac{z}{z_o}\right)$$

where

V_z = wind speed at height z
V_g = wind speed at the gradient height
$\frac{fz_o}{V_g}$ = the dimensionless Rossby Number (f is the Coriolis parameter)
z = height above the zero displacement plane
z_o = the surface roughness length

The fluctuating component of wind in the longitudinal (stream-wise) direction can be approximated by $\sigma_u = 2.5\, u_*$, where σ_u is the standard deviation of wind velocity and u_* is the surface friction velocity. From this relationship and using the logarithmic law, the following expression for turbulence intensity is derived:

$$I_u = \frac{\sigma_u}{V_z} = \left[\ln\left(\frac{z}{z_o} \right) \right]^{-1}$$

where

I_u = turbulence intensity in the longitudinal direction
σ_u = standard deviation of the wind speed in the longitudinal direction
V_z = mean wind speed at height z
z = height above the zero plane displacement height
z_o = surface roughness length

It is noted that this equation provides and easy method to assess the surface roughness length from measurements of turbulence intensity (above the displacement height).

Ho reports that the exposure factor in the National Building Code of Canada (NBCC) is represented by a gust pressure profile, normalized at a 10 m height. Since it is believed that the gust pressure for different exposures is “similar”, the NBCC uses only a single definition of exposure factor for its simple method. In keeping with this simple approach, the power law expression is used to approximate the gust pressure profile as follows:

$$C_e = \left(\frac{H}{10} \right)^{0.2}$$

where,

C_e = the exposure factor
H = height above ground

The power law exponent of 0.2 (or 1/5th) for gust pressure (i.e. gust load) is derived from the square of the 1/10th power law for wind velocity following the NBCC’s single standard exposure classification for all terrain conditions.

Ho recognizes that while the 1/5th power law for gust pressure is seen to be a good descriptor of the pressure variation for open exposure conditions, it is a poor [conservative] estimator for rougher exposure conditions [10]. For small building heights (i.e. less than 5 to 10 meters) in rougher terrain such as suburban areas, Ho displays charts that indicate wind loads may be easily over-estimated by as much as 150 to 200 percent due to the single power law exponent (i.e. 0.2) associated with a single terrain roughness category. (It is for this reason that the ASCE 7-95 has retained different power law descriptions or exponents for various basic terrain categories.)

Ho also reports on the effects of building loads as affected by open and suburban exposure and the immediate surrounding conditions of 'isolated' (i.e. no adjacent buildings or obstructions) and 'built-up' (i.e. random configurations of adjacent low-rise buildings similar in height and size). He notes in his thesis that most engineering codes are based on wind tunnel modeling of the isolated, open exposure condition and that this condition is not realistic for most low-rise structures. Ho's wind tunnel studies regarding upwind exposure and shielding from immediate surroundings can be summarized as follows:

1. The 'built-up' condition results in a consistent average reduction in local peak loads of about 25 percent (with COV of 0.6) relative to the 'isolated' condition (a factor of about 0.75 with a COV of about 0.2).

2. The suburban exposure condition results in a consistent average reduction in local peak loads of about 40 percent relative to the open exposure condition.

These findings were noted as being consistent with previous studies conducted by Stathopoulos in the 1970s [11].

Ho also studies the population of low-rise industrial buildings in North America and finds that there is about a 0.74 probability of any given building being located in suburban terrain and a 0.10 probability that it will be in urban terrain. The remaining structures would fall in rural (wooded or open) terrain conditions (0.16 probability). Within the suburban setting, Ho also determined that there was a 1/3rd probability that the building would be near the edge of the built-up area. While probabilities for homes in these surrounding and exposure conditions would differ, it stands to reason that most homes would be in the category of a suburban exposure with built-up or wooded surroundings.

After a significant exercise in reducing the wind tunnel data using analytical methods and principles of reliability-based design, Ho concludes his thesis with a simplified and a more exact method for determining building loads for code purposes. It should be noted, that while the format used was based on a single wind exposure category, the effects of wind directionality and shielding in rough surroundings was incorporated in the reliability-based analysis of the design wind loads. Wind directionality accounts for the probability of a wind coming from the worst-case direction to produce the maximum load effect on a building. This effect is a necessary consideration in reliability-based design since wind codes are based on wind tunnel data that 'envelopes' the building to determining the maximum surface pressures that occur from wind coming from all possible directions.

The wind profile for engineering purposes has been characterized most commonly by the power law because of its simplicity, as reported earlier in this literature review. Other popular models include the logarithmic law (also reported earlier) and the ‘Deaves and Harris’ model. These models are covered in detail in the previously mentioned texts [8], [9]. Therefore, the following papers are presented based on some unique contributions to the topic of this paper, particularly the wind profile and its use for determining near ground wind speeds.

One problem with all of the current wind profile models used for engineering purposes is that they do not necessarily provide reasonable agreement with actual wind behavior below the displacement height. The displacement height is taken as the depth of the ‘still’ air trapped among the roughness elements of the surface as described by Sutton in 1949 [12]. It is also described as the average height of roughness above a smooth reference plane (i.e. ground) in conditions of large, closely-packed surface roughness (i.e. towns and cities). Therefore, to apply the logarithmic law (and the power law for that matter), it is necessary to raise the profile from the ground surface by a height, D, the displacement height. The displacement height depends on the characteristics of the surroundings (i.e. size, shape, spatial density, and height of obstructions on the earth’s surface). With this recognized, the form the logarithmic law is properly stated by Ab+ew as [12]:

$$U = \frac{U_*}{k} \ln \frac{(Z - D)}{Z_o}$$

where

U = mean velocity measured at height Z
U_* = surface shear velocity
Z = height of velocity measurement from a reference surface
Z_o = aerodynamic roughness, and
k = von Karman’s constant (0.4 under neutral conditions).

To implement the logarithmic law, U_*, D, and Z_o need to be empirically quantified from wind data for a particular site, estimated by visual judgment, or determined by proven analytical methods. The parameter Z_o has been empirically determined for various descriptive terrain categories such that visual estimates can be made for engineering purposes based on an individual site’s surroundings. This approach is used with the power law exponent in the ASCE 7-95 standard [1]. Abtew gives a list of several analytical methods of estimating Z_o by various researchers and presents an improved method. Of potential importance to this study was the method derived to estimate the displacement height, D. Abtew’s findings are summarized in Table 4 for relevant roughness conditions.

TABLE 4
ESTIMATES OF DISPLACEMENT HEIGHT (D)
AND AERODYNAMIC ROUGHNESS (Z_O)
FOR VARIOUS SHAPES [12]

Roughness, object	**Shape**	**D**	**Z_o**
Broad leaf trees (avg. of open and closed pack)	Sphere	(0.71R + X)0.85	0.13(H-D)
Ridges with touching bases	Triangular	0.5H	0.065H
Evergreen trees (avg. of open and closed pack)	Upper-half triangular	(0.5H + X)0.85	0.13(H-D)
Buildings	Rectangular	HF_c	0.13(H-D)

H is maximum height of the object
F_c is fraction of the total surface covered by roughness elements
D is the displacement height
Z_o is the surface roughness length
R is the radius of curvature of plant top
X is the distance from ground to the center of curvature of the roughness elements

Because the estimates in Table 4 produce an excellent fit with independent data sets and cover a wide range in roughness heights, it is suggested that the prediction procedure is general in nature [12].

As reported in Simiu's and Scanlan's text on wind effects [8], the following model is suggested by Helliwell to determine reasonable values of the displacement height (or 'zero plane displacement') in cities with densely packed buildings:

$$z_d = \overline{H} - \frac{z_o}{k}$$

where $\overline{H}$ is the general roof-top level and other parameters as before.

As reported by Cook [8], work by 'ESDU' has produced the following relationship to predict the zero plane displacement height for urban or woodland areas:

$$d = H - 4.3z_o(1 - a)$$

where H is the average height of the roughness elements, the individual hedges or buildings; and where a is the plan-area density of the roughness elements – the area occupied by buildings divided by the total site area. Values of d which are typical of the three roughest categories in the UK are: d =2 m for z_o = 0.1m; d = 10 m for z_o = 0.3 m; and d = 25 m for z_o = 0.8 m [8, p208,210],. It should be noted that the value displacement height for a typical residential suburban terrain with spotted trees and closely spaced single-family homes (z_o = 0.3 m) would be 33 ft (10 m) – at or above the roof height of most one- and two-story homes.

While defining the displacement height allows the logarithmic law to properly model the wind profile, it does not provide a mechanism to determine the wind profile below the displacement height (see the previous section of this literature review on ‘canopy flow’). This same concept of a displacement height also applies to the power law model. The solution in most wind engineering provisions has been to ignore the existence of the displacement height. The benefits in terms of simplicity are recognized. However, if the displacement height is greater than about 20 to 30 feet, the wind speeds and building loads on small homes may be over-estimated on average by use of a wind profile characterization that only applies above the displacement height. This concern is particularly valid for one- and two-story commercial or residential structures in typical dense suburban and wooded terrain conditions. Also included would be the design of numerous other structures such as signs, industrial facilities, and agricultural buildings.

In a paper by Bailey and Sforza, wind data from 18 meteorological towers across the state of New York are analyzed [13]. Roughness lengths range from 1.13 m to 0.02 m. It is shown that there is no significant variation in the power law exponent, α, as a function of magnitude of atmospheric instability. (It should be noted that in this paper the power law exponent is given as α, not $1/\alpha$ as is common in engineering uses). A moderate increase in α occurs for the neutral case and increases dramatically with increasing stability of the atmosphere. It is also interesting that the standard deviation of α is about 0.05 for unstable conditions, 0.08 for neutral conditions, and increases as the stability class increases (also as the mean value of α increases).

The stability of the atmosphere near to the ground is commonly defined by the rate and sign of air temperature change with height, also referred to as the lapse rate. For neutral (or adiabatic) conditions, the lapse rate is generally between -1.5 and -0.5^{o}C/100m. The atmosphere becomes increasingly unstable as the lapse rate takes on larger negative values (i.e., colder air above warmer air). An extremely unstable atmosphere is one with a negative lapse rate greater than -1.9^{o}C/100m. Conversely, the atmosphere becomes more stable as the lapse rate becomes positive and increases in magnitude. A lapse rate of greater than 4^{o}C/100m is considered extremely stable.

Bailey and Sforza also found that the power law exponent increased dramatically as wind speeds increased to about 25 mph (11 m/s) where the power law exponent value began to level off. This gives confirmation that mechanical mixing of the air (due to turbulence generated by the rough surface of the earth) in higher winds essentially counteracts the effects of atmospheric instability seen at lower wind speeds as reported above. This is also in agreement with Davenport’s review of wind engineering in 1960 (covered previously) where it was found that the power law exponent continues to increase with increasing wind speed because of increased surface friction [3]. It is also relevant to the observation in Pagon’s article in 1935 (also covered earlier) where it was stated that the temperature gradient has “no marked effect near the ground” [2].

In summary, this finding in the literature provides strong evidence that the issue of instability of the atmosphere is offset by larger magnitude wind speeds when near to the earth’s surface. Design wind speeds are sufficient to give mixing of the near ground wind (creating essentially neutral conditions) and they are based on wind measurements at a standard anemometer height of 10m (including any annual extreme wind events than may have occurred with unstable atmospheric conditions, i.e. frontal squalls). Therefore, atmospheric stability is generally an issue at wind speeds well below design level wind speeds. This finding is particularly relevant to the design of low-rise buildings and confirms that the use of a wind profile based on neutral atmospheric conditions is an appropriate model for engineering purposes, if not conservative. For example, the choice of power law exponent (if based on lower than design wind speeds) can result in conservative wind speed estimates for terrain roughness categories as recognized by Davenport [3]. Also, if design wind speeds were entirely governed by unstable events such as frontal squalls or severe thunderstorms, the use of a power law coefficient based on neutral atmospheric conditions would be conservative. This is particularly true for heights above the standard anemometer height since wind speeds could become essentially uniform at some height much lower than the standard gradient height which is based on surface roughness and the assumption of neutral stability in the atmosphere. This suppressed gradient height would need to be considered when converting wind speeds recorded in meteorological standard exposure conditions (i.e. exposure C in ASCE 7-95) to other terrain conditions. For heights below the standard anemometer height of 33 ft (10 m), the effect of the lower gradient height (if representative of the extreme wind speeds at return periods of interest to engineering) may result in a larger rate of decrease in wind speed below the standard anemometer height.

In fact, as reported in Simiu's and Scanlan's text on wind effects (based on wind studies by Thom in 1968), about one-third of the extreme wind records in the United States are associated with thunderstorms [8, p81]. It is also reported that during such events, the wind speeds vary with height in accordance with the logarithmic law (and thus the power law) at heights up to 100 m. Above 100 m, the variation of wind speed with height is negligible [8,p80-81]. Finally, analytical methods of modeling the effects of atmospheric stability on the wind profile estimation by the logarithmic law show that, at design level winds, the effects of atmospheric instability are negligible [8,p50-51].

Summary of Key Findings in the Literature

From the literature review, the following key findings are summarized regarding the subject matter of this report:

1. The affect of atmospheric instability on the wind profile is not a major concern for design level wind speeds (i.e. greater than about 25 mph (11 m/s)) and low-rise buildings, particularly since design wind speeds are based on annual extreme values at heights near to the ground (i.e. well below 100 m).

2. As wind speed increases, surface friction also increases which creates added resistance to the flow of wind near the earth's surface (i.e. the power law exponent increases with wind speed) [13]. This was also noted in one of the studies of canopy flow [5]. It is further confirmed by peak 10-min and 1-min average wind profiles presented later in this study.

3. While turbulence increases with nearness to the earth's surface, it is more nearly uniform with height in the interfacial layer (i.e. below the displacement height).

4. No wind profile model exists to handle the global or overall wind load effects of shielding for low buildings (i.e. homes) in typical suburban environments.

5. Based on recent wind tunnel studies of random, built-up suburban settings (with both open and suburban wind profiles modeled), shielding was found to reduce peak pressures on all building surfaces (corner, edge, and interior zones of roof and wall surfaces) by a mean factor of 0.75 (with a COV of 0.2).

It should be noted that no studies were found in the literature that had objectives or data similar to this study of near ground wind. Particularly, there were no field studies addressing the variable nature of wind in the interfacial layer of a suburban environment to compliment the limited number of wind tunnel studies on this topic.

Review of ASCE 7-95

The ASCE 7-95 standard is the only consensus standard for wind loading of structures in the United States and it is widely referenced in the U.S. model building codes. Therefore, it is considered the primary application of any practical findings from this study. As such, this review of the wind provisions of ASCE 7-95 is intended to give a state-of-the-art assessment of this standard and to identify areas where findings from this work may contribute toward more advanced provisions. Again, the particular interest is with low-rise buildings (i.e. homes) in the near-ground wind environment of a suburban exposure.

The first step in determining a wind load on the building is to determine the “velocity pressure” for the particular site’s wind climate and the appropriate height above ground.
The velocity pressure in ASCE 7-95 is calculated as follows [1,p17]:

$$q_z = 0.00256 K_z K_{zt} V^2 I \qquad \text{(Eq-1)}$$

where,

q_z = velocity pressure (lb/ft^2)
K_z = velocity pressure exposure coefficient at height z above ground
K_{zt} = topographic factor
V = basic wind speed in miles per hour associated with a 3-second gust measurement at an elevation of 33 ft (10 m) having an annual probability of exceedance of 0.02 (i.e. 50-yr mean return period)
I = importance factor (1.0 for homes).

The velocity pressure is determined for a specific elevation on the building or at the mean roof height depending on the surface pressure of interest and its location on the building relative to wind direction (i.e. windward or leeward surface). The appropriate surface pressure coefficient and gust effect factor are then multiplied by the velocity pressure, q, to determine the wind pressure (load). Two general forms of the wind pressure calculation are as follows:

$$p = q_h (G)(C_p) \qquad \text{(Eq 2a)}$$

or,

$$p = q_h (GC_p) \qquad \text{(Eq 2b)}$$

where,

p = design surface pressure on the building (psf)
q_h = velocity pressure from Eq 1 with K_z determined at the mean roof height, h.
G = gust effect factor
C_p = surface pressure coefficient
GC_p = combined gust effect factor and surface pressure coefficient

The form in Equations 2a and 2b is essentially a matter of choice in code development as determined somewhat by the format of the wind tunnel data used. Equation 2a is the form used by ASCE to calculate loads on the main wind force resisting system (MWFRS) of buildings. The MWFRS loads are a combination of local loads over multiple building surfaces or across distinct pressure regions that are resisted by the structural system or frame of a building. Components and cladding (C&C) loads (or local loads) are higher than MWFRS loads and increase as the area considered on the building surface becomes smaller. In general, elements or assemblies with larger tributary areas will have lower loads (due to time and spatial averaging effects in turbulent wind flow) and those with smaller tributary areas will experience higher design loads per unit area. For example, a shear wall in a building will be designed using the MWFRS loads because it resists loads from wind pressures on the windward side of the building and suction pressures on the leeward side. Similarly a gable roof truss and its uplift connections will be designed as a MWFRS; however, individual panel members in the top chord of the truss should be designed as a component with C&C wind loads. Finally, attachment of wall sheathing, roof sheathing, windows and doors (i.e. building envelop components) should obviously be designed using C&C loads.

The gust effect factor, G, the surface pressure coefficient, C_p, and thus the GC_p coefficients are all somewhat dependent on the wind exposure (terrain roughness) condition. This dependence is linked to the turbulence effects on the size and location of various C_p regions on the building surface. Gustiness (which is a measure of larger scale turbulence or ‘eddies’) effects the value of G depending on the response characteristics of the structure relative to the size and frequency of the gusts. The building response characteristics are determined by the rigidity (or flexibility), dampening, size, and shape of the structure. Therefore, the terrain roughness affects the surface pressure coefficients and the gust effect factor as well as the boundary layer wind profile. However, for certain rigid, small structures, these effects may be minimal [3],[8,p155-168].

Since the GC_p coefficients in ASCE 7-95 are based on wind tunnel studies of isolated buildings in modeled exposure C (open terrain) conditions, this inter-relationship is important to address. These inter-relationships demonstrate the complexities of making modifications to any one parameter in any wind load provision without also considering the effects on other related parameters, particularly when the design methodology is to apply generally to all buildings. The recent and extensive wind tunnel modeling by Ho of various low-rise buildings in suburban and open exposure wind flows with built-up and isolated surroundings has provided many answers to these inter-relationships for typical low-rise buildings [10].

The estimation of mean wind speed profile is important because it provides the mechanism to adjust for wind exposure (i.e. terrain roughness) conditions different from that used to develop the design wind speed map in ASCE 7-95 [1]. The wind map is based on a probabilistic analysis of wind records from weather stations that are generally representative of or corrected for a wind exposure category ‘C’ (open/flat terrain) condition at an elevation of 33 ft (10m) [14]. Therefore, for buildings typically at other conditions than this reference elevation and exposure category, an adjustment must be made. This adjustment is made by the “velocity pressure exposure coefficient”, K_z, in the ASCE 7-95 standard.

The velocity pressure exposure coefficient, K_z, in ASCE 7-95 is derived from the power law wind profile model which was reported earlier in the literature review. The power law model is further modified for use in ASCE 7-95 to derive the “velocity pressure exposure coefficient”, K_z . As stated previously, K_z is used as a multiplier to adjust the wind load from the base map conditions of exposure ‘C’ at an elevation of 33 ft (10 m) above ground to other exposure conditions and elevations (see Equation 1). This modification of the power law velocity profile is based on the relationship of wind load to the square of the wind velocity (i.e. $p \propto V^2$). The value of K_z is determined from the following equation as given by equation C3a in ASCE 7-95 [1,p152]:

$$K_z = 2.01\left(\frac{z}{z_g}\right)^{\frac{2}{\alpha}} \text{ for 15 ft} \le z \le zg$$

or

$$K_z = 2.01\left(\frac{15}{z_g}\right)^{\frac{2}{\alpha}} \text{ for } z < 15 \text{ ft}$$

where,

z = height above ground, z [ft] (not above the zero plane displacement height)
z_g = the gradient height [ft] (see Table 5)
α = power law exponent

Thus, the equation for K_z and its resultant value for a particular elevation and exposure condition, provides a means to adjust the wind load calculated from the design wind map basis of exposure 'C' (open, flat terrain) at an elevation of 33 ft (10 m) above the ground.

It should be noted that the power law profile is not displaced to the zero plane displacement height in the rough terrain exposure categories (i.e. A and B). Therefore, it will provide generally conservative estimates below a height of about 30 ft for densely developed suburban or well-forested terrain (see literature review) [9, p210]. As shown in Table 5, the values for α have changed from previous versions of the ASCE 7 standard [1][14]. The changes have resulted in an increase in the exposure A and B wind loads and slight decreases in exposure D wind loads relative to previous versions of ASCE 7. These changes are reflected by new K_z values in Table 6-3 of ASCE 7-95 based on Equation 3 above. As noted in the commentary of ASCE 7-95, the primary reason is related to changes in the wind speed profile associated with a change from fastest-mile to 3-second gust wind speeds. The gradient heights have remained unchanged.

TABLE 5
HISTORY OF THE POWER LAW EXPONENT, α, IN THE ASCE 7 STANDARD [1],[14]

Exposure Category	α (ASCE 7-95)[1]	α (ASCE 7-93)[2]	Z_g [ft (m)]
A	5.0	3.0	1,500 (457)
B	7.0	4.5	1,200 (366)
C	9.5	7.0	900 (274)
D	11.5	10.0	700 (213)

[1] For use with a 3-second gust wind speeds.
[2] For use with a fastest-mile wind speeds.

In summary the following findings related to the review of ASCE 7-95 are relevant to the objectives and intended application of this study:

1. the effects of displacement height are not considered when applying the power law model to adjust wind loads with height above ground in rough terrain conditions (i.e. exposures A and B); and
2. overall shielding effects are not considered for structures below the displacement height in rough terrain conditions.

These two findings have the tendency to result in over-estimates of loads relative to the intended levels of risk for low-rise buildings, particularly one- and two-story homes in dense suburban or wooded terrain. In other words, there is a significant positive bias (e.g. loads are higher than actual) in the standard for these types of structures in a fairly typical terrain condition – exposure B for suburban or wooded conditions. Part of this problem may be attributed to the physical relationship of exposure B to a condition representative of a low density of development or forestation. This problem can be solved by an additional exposure classification representing conditions between exposures A and B in the ASCE 7 standard. This would not require additional research and simply requires a decision of those participating in the updating of the ASCE 7 standard as to the merits of an additional exposure category.

Wind Monitoring Approach

To achieve the objectives of this study, an industrial park in Upper Marlboro, Maryland, has been instrumented with five near-ground wind monitoring stations having anemometers at an elevation of about 10 feet (3.0 m). A typical near-ground wind station is shown in Figure 2. The five stations were located to capture a representative sample of the near-ground wind field within the built-up terrain of the industrial park. An additional monitoring station, centrally located in the industrial park, consists of two anemometers placed on a communications tower at elevations of 33 ft (10 m) and 187 ft (57 m). These two anemometers are shown in Figures 3a and 3b. Because of possible shielding and acceleration of wind for certain directions of wind, the data reported in this study for the 33-ft tower anemometer are only given for wind directions well outside the 60-degree sector of the tower frame. The anemometer at the top of the tower is located approximately 1-foot above the top rail. Its elevation above the tower was limited by FAA regulations governing the height of this particular tower.

Figure 2 - Portable near-ground wind station with a anemometer at a 10-ft (3-m) height above ground.

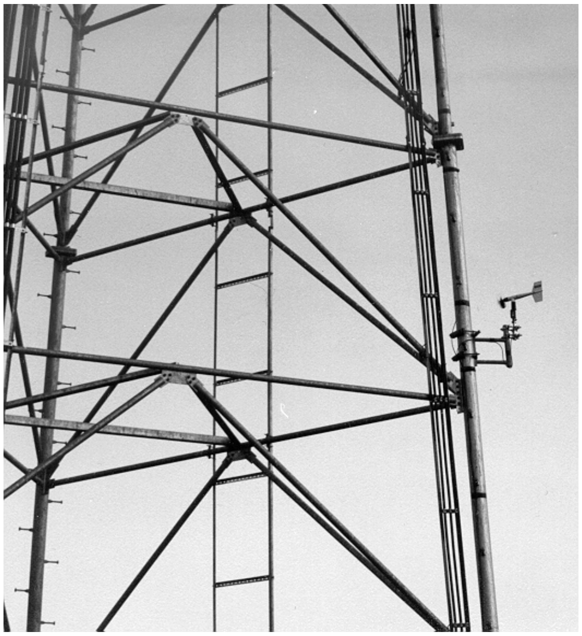

Figure 3a - Lower tower anemometer at a 33-ft (10-m) height above ground.

Figure 3b - Upper tower anemometer at a 187-ft (57 m) height above ground.

The layout of these six stations in the industrial park is shown in the aerial photograph of Figure 4. (The tower is labeled as station #2.) As seen in the aerial photograph, the industrial park is situated in an exposure category ‘B’ environment as described by ASCE 7-95 [1]. As such, the surrounding land has both small open fields with trees on the boundaries (eastern direction) and is predominantly characterized by deciduous trees in the other directions. Within the industrial park, the buildings are typically 20 ft (6.1 m) to 30 ft (9.1 m) in height. There are also numerous parking lots and several undeveloped lots with trees, brush, and open grassy fields. The terrain is relatively flat with gently rolling hills. These conditions are similar to that found in many residential and commercial developments with a moderate density of structures.

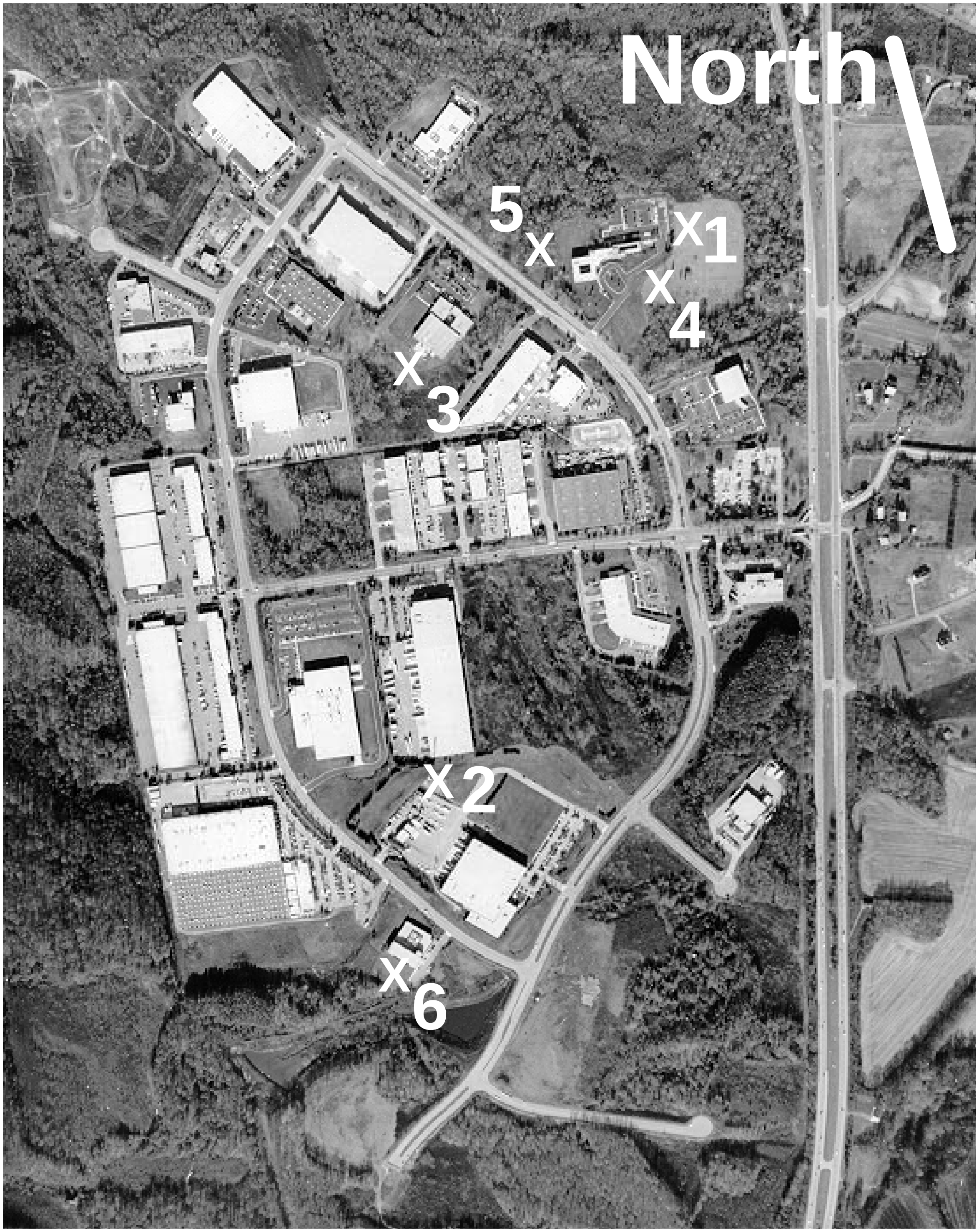

Figure 4 - Aerial photograph of 10-ft (3-m) height wind monitoring stations with an approximate scale of 1:8400. The tower station with anemometers at 33-ft (10-m) and 187-ft (57 m) heights is labeled as #2.

The portable near-ground wind stations have been deployed in a manner to capture different types of localized exposures within the industrial park. It is expected that, depending on wind direction, some stations will experience shielding and other possible instances of wind channeling. This realistic condition will provide highly variable readings for any given wind event across all of the wind stations, as would be expected in the interfacial layer of a suburban and wooded terrain. One of the stations (#1 in Figure 4) is located on a small knoll and may experience wind speed up due to topography for winds coming from the Northeast and Southwest. Conversely, another station (#5 in Figure 4) is located in a wooded area with a slight depression in elevation. The remaining near-ground wind stations are located in "open areas" with highly variable surroundings of buildings, parking lots, grassy lawns/fields, and woods. A detailed description of each near-ground monitoring station's exposure is found in Table A-1 and the photographs of Appendix A.

Four of the 10-ft (3-m) near-ground stations and the tower station were instrumented with R.M. Young Wind Monitor (model 05103) directional vane anemometers and a Campbell Scientific CR-10 data-logger. This anemometer was selected because of its durability and combined ability to monitor wind speed and direction. The propeller has a threshold wind speed sensitivity of 2 mph (0.89 m/s) and a directional sensitivity of 2.2 mph (0.98 m/s) for a 10 degree displacement. One of the near-ground stations was instrumented with a Met One (model 034A-L) cup-type anemometer and a separate wind direction vane. The Met One has a wind speed threshold of 0.9 mph (0.04 m/s) and is not sensitive to wind directional changes as are vane-type anemometers. Since it was originally proposed that the portable, near-ground wind stations would also be used to capture wind-field data from a land-falling hurricane event in a residential setting, the more durable R.M. Young Wind Monitor anemometers were used on most stations.

Every monitoring station was programmed to record the following information:

- maximum gust
- time of maximum gust
- direction of maximum gust
- mean wind speed (M)
- mean direction of mean wind
- standard deviation of mean wind speed (S)
- turbulence intensity in the 10-minute and 1-minute time interval of maximum gust (S/M)

Site conditions are monitored every one-second. The raw data is aggregated into one minute, five-minute, ten minute, and one-hour intervals unless the peak gust falls below 10 mph. When this occurs, only hourly data is recorded for reasons of efficiency in data storage and analysis.

Results

Selected Wind Events

This report examines near ground wind data from March 19 through April 1, 1998. During this interval wind conditions were variable but no major storms or mesocyclones occurred. The wind record is summarized for each of the five ground wind stations in the hourly maximum gust trace of Figure 5. Figure 5 shows the mean of the five ground stations' hourly maximum gust and includes the hourly maximum gust of the 33 and 187 foot tower stations. Key data for each event and anemometer (station) is summarized in Table 1 including the following information:

- peak wind speed for each anemometer (peak gust and maximum 1-minute, 10-minute, and hourly means),
- wind direction at peak gust and mean wind speeds,
- turbulence intensity (TI) at time of peak gust (1-minute and 10-minute interval),
- gust factor (GF) for each anemometer (ratio gust to 1-minute and 10-minute mean wind speed), and
- estimated power law exponent, α, for each station and each wind speed duration based on 187-ft (57-m) measurements and either the 33-ft (10-m) tower or the five near ground 10-ft (3-m) measurements.

It should be noted in this study that the power law exponent is expressed as 1/α instead of α. Therefore, the values for α represent the denominator of the power law exponent as used in the ASCE 7 standard [1].

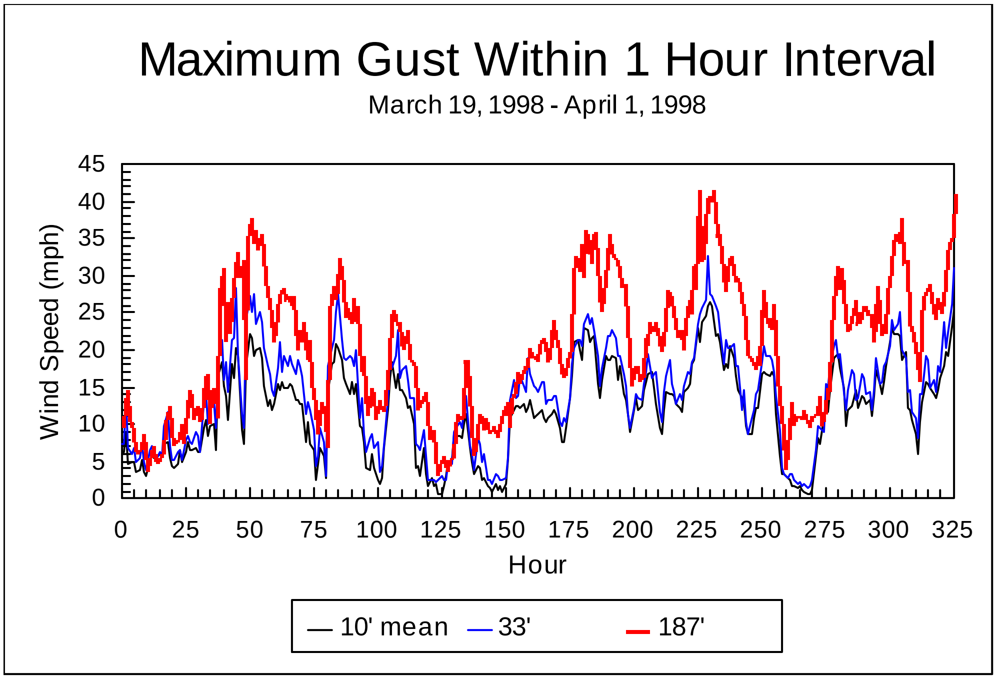

Figure 5 - Maximum hourly gust trace for ground stations

TABLE 6
SUMMARY DATA FOR ALL WIND EVENTS DURING THE PERIOD OF RECORD

Station	Peak Gust (mph)[2]	Peak 1 Min Mean (mph)[2]	1 Min TI	1 Min GF	Peak 10 Min Mean (mph)	10 Min TI	10 Min GF	α[1] gust	α[1] 1 min	α[1] 10 min
1	25.7 (NW)	18.0 (SW)	0.20	1.43	13.6 (SW)	0.25	1.89	6.12	4.93	4.89
3	27.2 (S)	18.6 (S)	0.23	1.47	12.6 (E)	0.34	2.17	6.95	5.22	4.33
4	32.2 (SW)	22.8 (SW)	0.14	1.41	17.6 (SW)	0.23	1.82	11.65	8.16	8.65
5	22.4 (S)	12.6 (S)	0.24	1.78	8.6 (S)	0.35	2.63	4.75	3.08	2.77
6	27.8 (S)	17.2 (SW)	0.25	1.61	11.8 (SW)	0.36	2.38	7.37	4.57	3.96
10' Mean	27.1	17.9	0.21	1.54	12.9	0.31	1.96	7.37[1] (6.87)	5.19[1] (4.85)	4.92[1] (4.47)
10' COV	0.13	0.20	0.21	0.10	0.25	0.20	0.21	0.35[1] (0.41)	0.36[1] (0.45)	0.45[1] (0.53)
33'	32.7 (S)	21.8 (SW)	0.17	1.5	14.6 (SW)	0.31	2.22	N/A	N/A	N/A
187'	41.4 (SW)	32.6 (SW)	0.10	1.27	24.8 (E)	0.20	1.67	N/A	N/A	N/A

[1] Based on the mean and standard deviation of the α for each of the five near ground stations. Values in parenthesis are based on the mean and standard deviation of wind speed for the five near ground stations.

[2] 1mph = 0.447 m/s.

As seen from the data, the near ground 3-second gust wind speeds varied from 22.4 mph to 32.2 mph with a COV of 0.13. When mean 1-minute and 10-minute near ground wind speeds are examined, the wind speed decreases and the COV increases as the average time interval increases, as would be expected. The turbulence intensity (TI) also varied from 0.14 to 0.25 for the 1-minute mean and 0.23 to 0.36 for the 10-minute mean. The COV of TI was similar for both average time intervals (0.21 and 0.20).

The value of α for each station is based on the maximum wind speed recorded throughout the entire reporting period. The calculation utilizes the difference in wind speeds between the 187' and 10' stations. Since α is being used for engineering calculations this approach represents an "extreme-value" by using only data from peak wind speeds which occurred on different times or days and wind direction between the recording stations. If the data were recorded for an entire year, the reported α-values would represent an annual extreme value.

Power Law Wind Profile

The measured power law exponent, $1/\alpha$, is shown in Figures 6 through 11 for all of the wind events combined. Separate plots are provided for estimates of the power law exponent based on the peak gust and the 1-minute, 10-minute, and hourly mean wind speeds. The plots are based on measurements between the 187-ft (57 m) tower anemometer and the mean of the 5 near ground stations, as well as the 33-ft (10-m) tower anemometer.

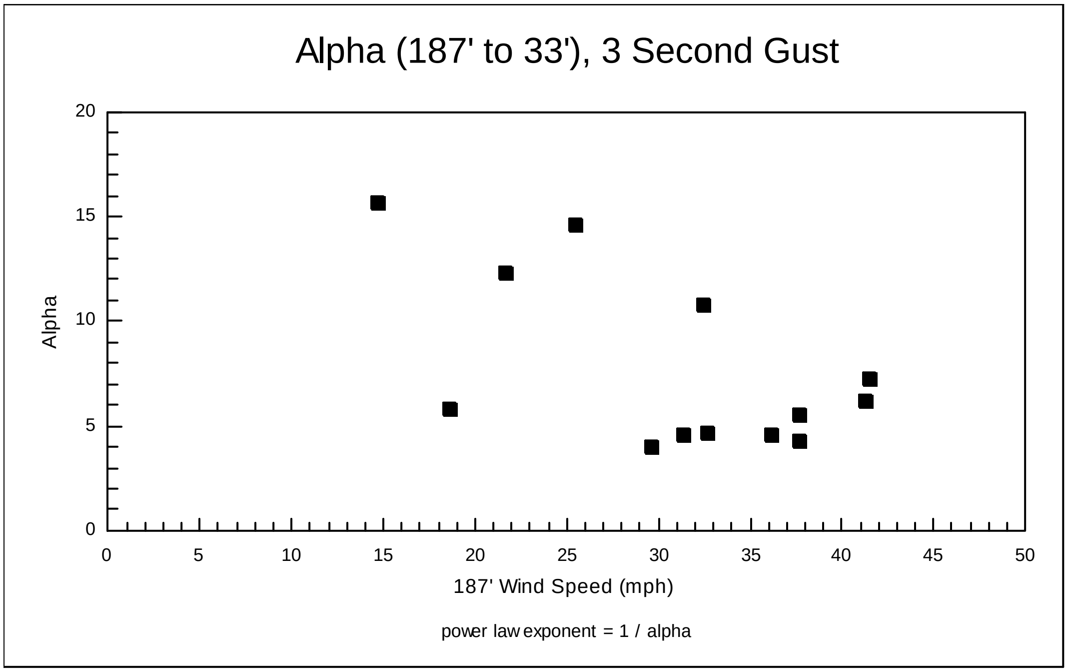

Figure 6 - Plot of estimated α for daily peak gust wind measurements based on 187-ft (57-m) tower anemometer and 33-ft (10-m) tower anemometer.

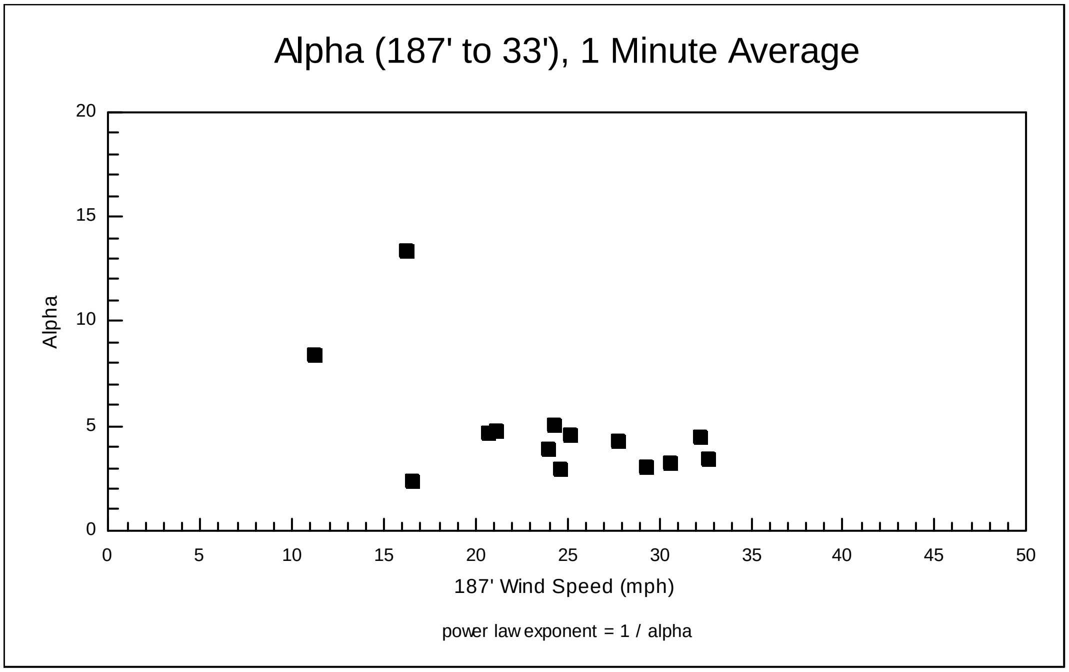

Figure 7 - Plot of estimated α for daily maximum 1-minute mean wind measurements based on 187-ft (57-m) tower anemometer and 33-ft (10-m) tower anemometer.

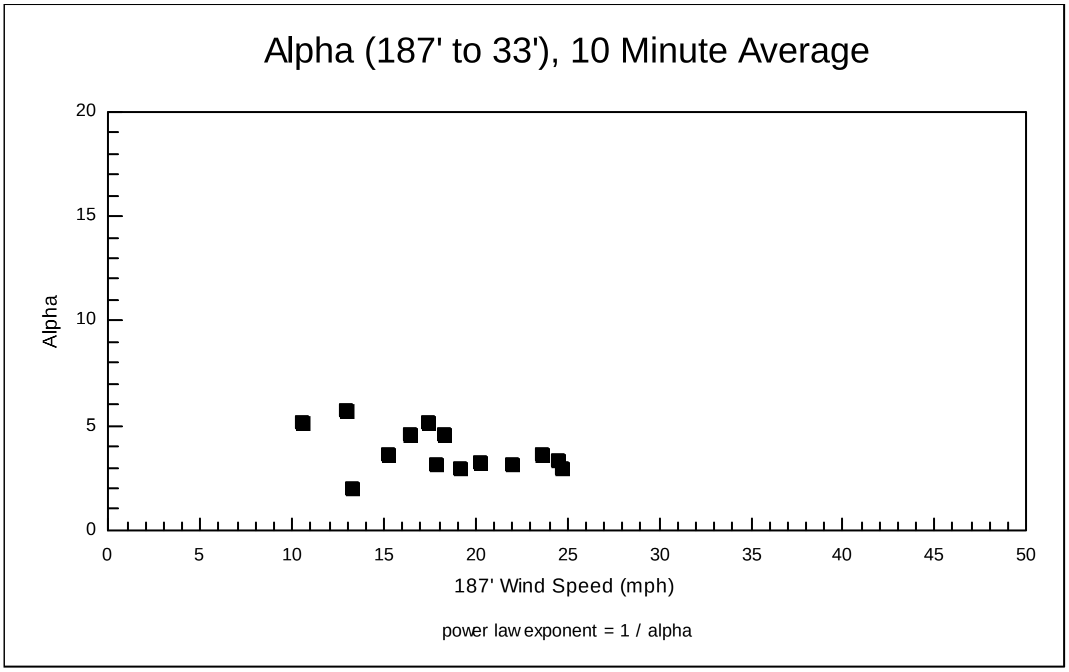

Figure 8 - Plot of estimated α for daily maximum 10-minute mean wind measurements based on 187-ft (57-m) tower anemometer and 33-ft (10-m) tower anemometer.

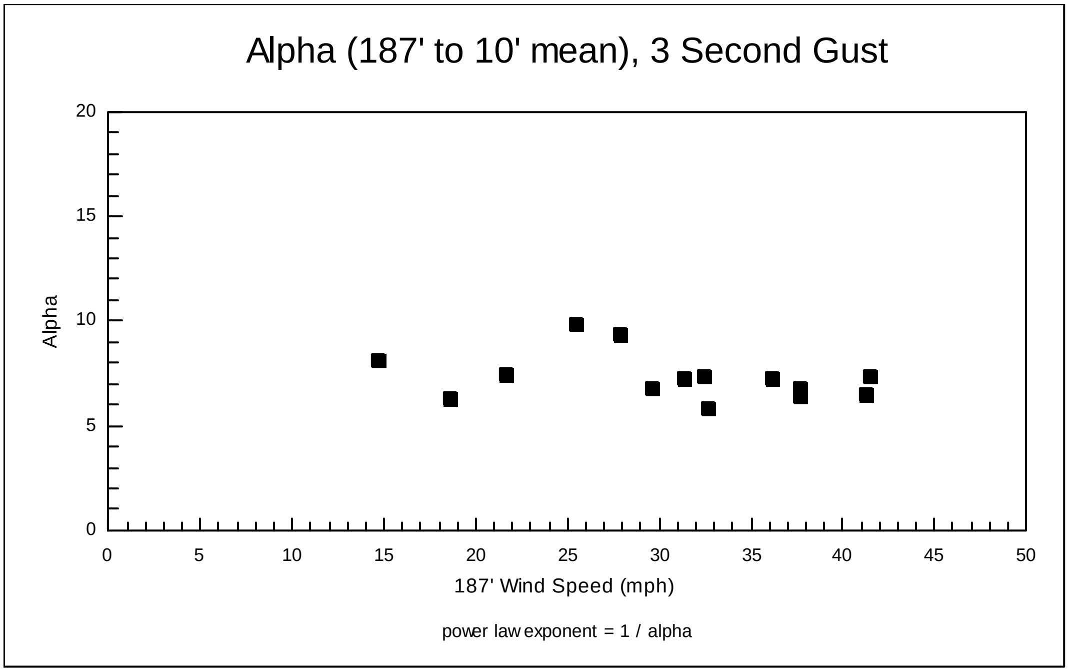

Figure 9 - Plot of estimated α for daily peak gust wind measurements based on 187-ft (57-m) tower anemometer and 10-ft (3-m) tower anemometer.

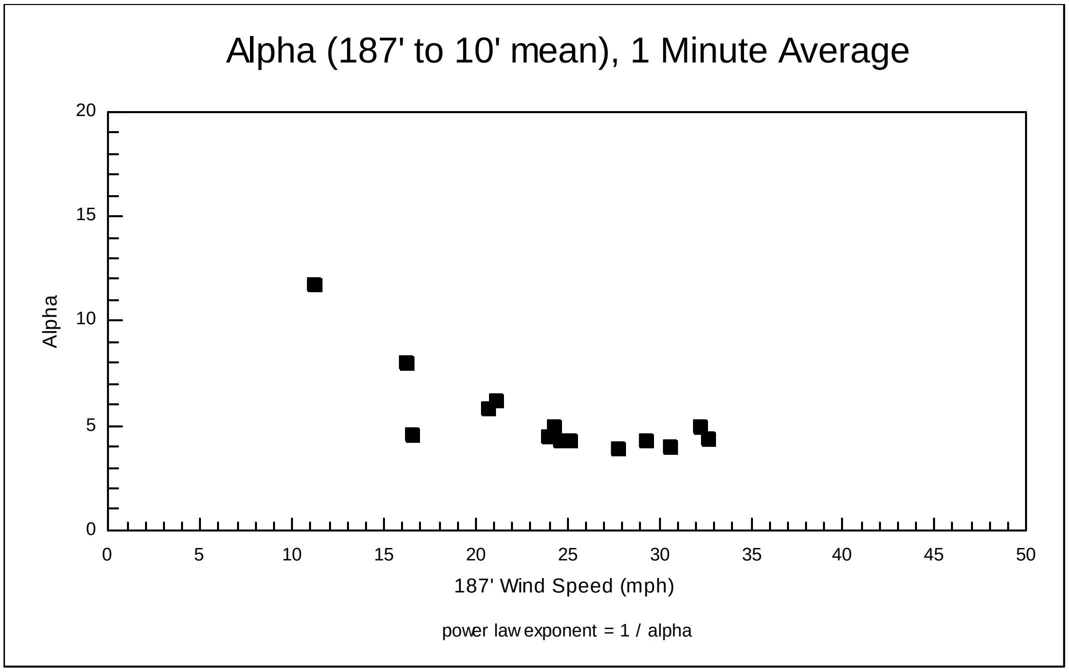

Figure 10 - Plot of estimated α for daily maximum 1-minute mean wind measurements based on 187-ft (57-m) tower anemometer and 10-ft (3-m) tower anemometer.

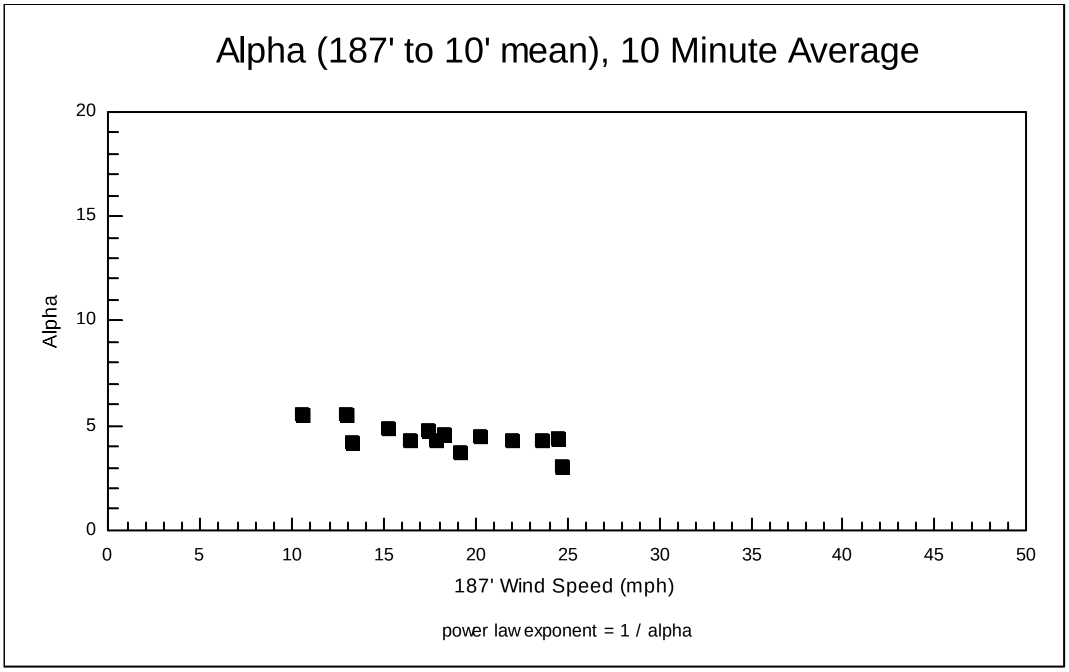

Figure 11 - Plot of estimated α for daily maximum 10-minute mean wind measurements based on 187-ft (57-m) tower anemometer and 10-ft (3-m) tower anemometer.

As seen Figures 6 through 11 the estimated power law exponent (1/d) varied according to wind speed. However, this trend is most evident for the 1-minute and 10-minute mean wind speeds where the α decreased in value (power law exponent increased) as wind speed increased. At the lower wind speeds (e.g. less than 20 mph), this effect is mostly attributed to thermal effects; however, at higher wind speeds the decrease may be a result of some dependence of surface friction on wind velocity (as noted in the literature survey). As wind speeds increase further, the rate of change of the exponent decreases to a more constant rate where it is governed primarily by increased surface friction as a result of the kinematic viscosity of the faster moving, well mixed (i.e. neutral stability) air. More data at higher wind speeds will provide greater insights into the rate of change of α at higher (i.e. design level) wind conditions for 3-second gust wind speeds. The α scatter is more severe when determined from the 187' to 33' data. When α is plotted from 187' to 10' data the values are more clustered. As additional data is recorded and higher daily wind events encountered the relationship of α to wind speed for exposure B conditions will be more clearly defined. The COV of α was plotted as a function of wind speed (Figures 12 through 14). These figures reveal that the COV of α increases slightly with wind speed for the 3 second gust basis and decreases with increasing wind speed for the 1-minute and 10-minute mean wind speeds. These trends will be better defined when more data is collected over the course of a year.

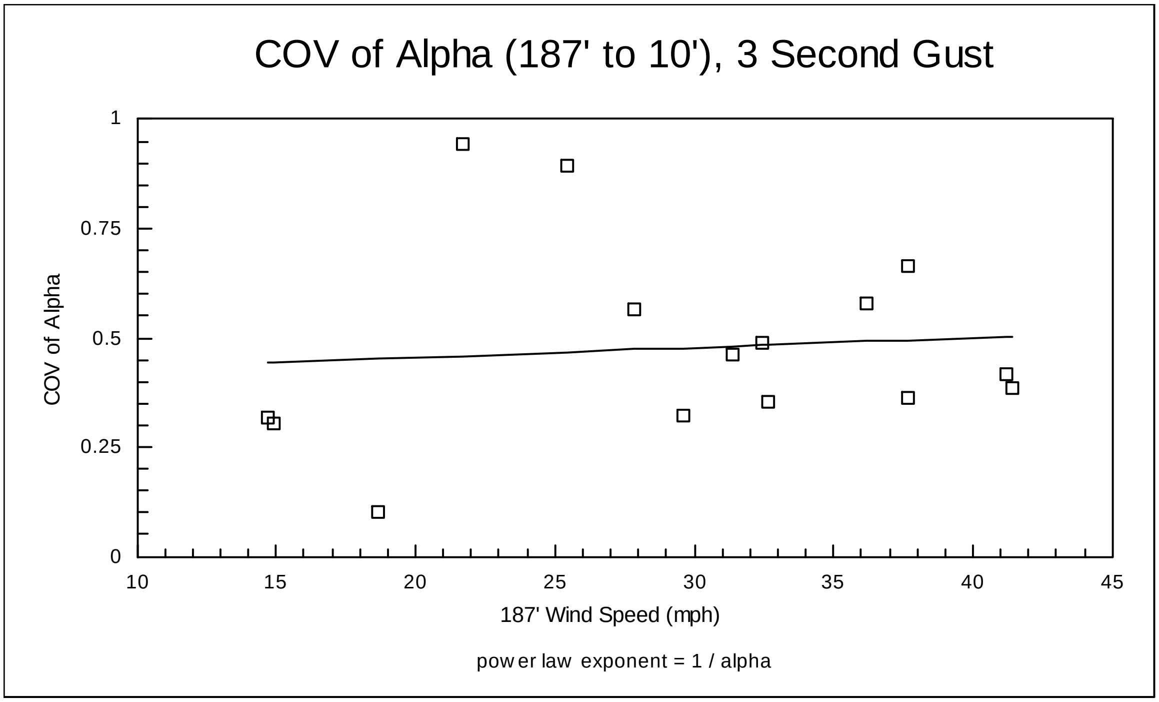

Figure 12 - Plot of COV of α for daily peak gust wind measurements based on the 187-ft (57-m) tower anemometer and the 10-ft (3-m) near-ground anemometers.

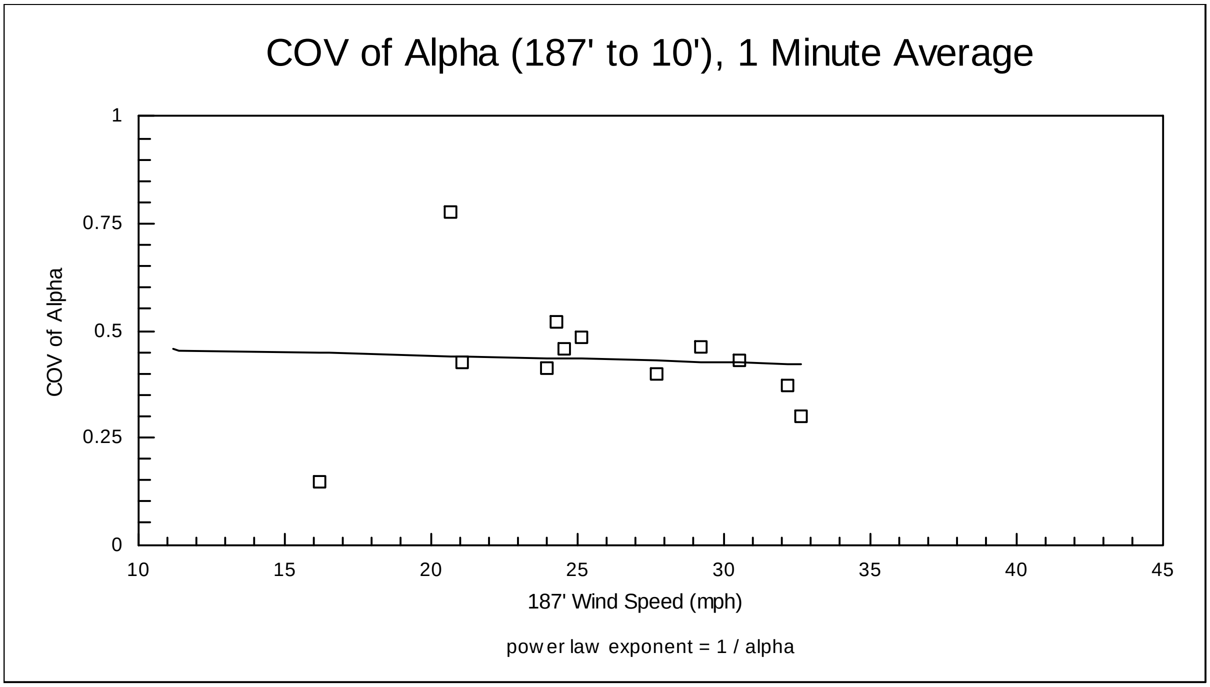

Figure 13 - Plot of COV of α for daily maximum 1-minute mean wind measurements based on 187-ft (57-m) tower anemometer and the 10-ft (3-m) near-ground anemometers.

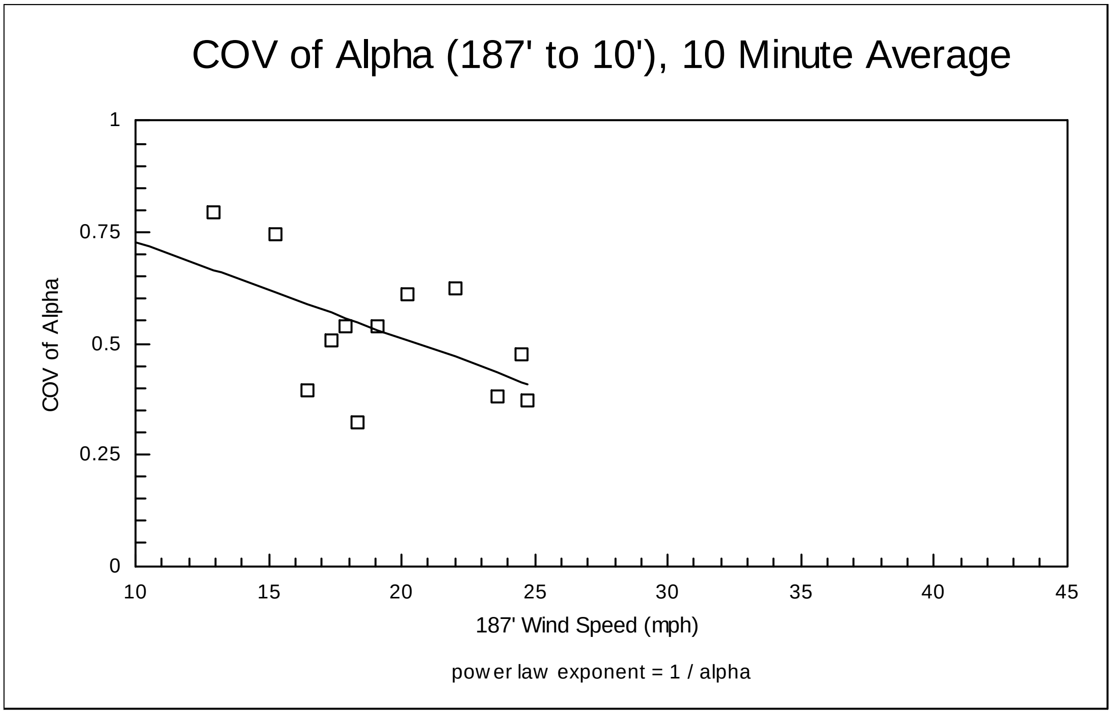

Figure 14 - Plot of COV of α for daily maximum 10-minute mean wind measurements based on 187-ft (57-m) tower anemometer and the 10-ft (3-m) near-ground anemometers.

Based on a commonly assumed gradient height of 1,200 ft (366 m) for suburban or wooded terrain [1] and calibrating to the 187-ft (57-m) tower anemometer readings, the power law wind velocity profile plots are shown for each of the 10-foot near ground anemometers in Figures 15 through 17. Also shown on the plots is the actual 33-ft (10-m) tower anemometer reading (peak gust, 1-minute, or 10-minute average as indicated). The theoretical profiles are shown for peak gusts and maximum 1-minute and 10-minute means for the reporting period. The calculated α coefficients used to derive the wind profiles for each station are found in the legend for each figure. The relatively high α value for near-ground station 4 is attributed to a topographic effect for the wind direction at the time of the peak gust record. It should be noted that these profiles are not intended to represent the actual wind profile but are provided for comparison sake in roughly evaluating the use of the power law representation of the wind profile for engineering purposes.

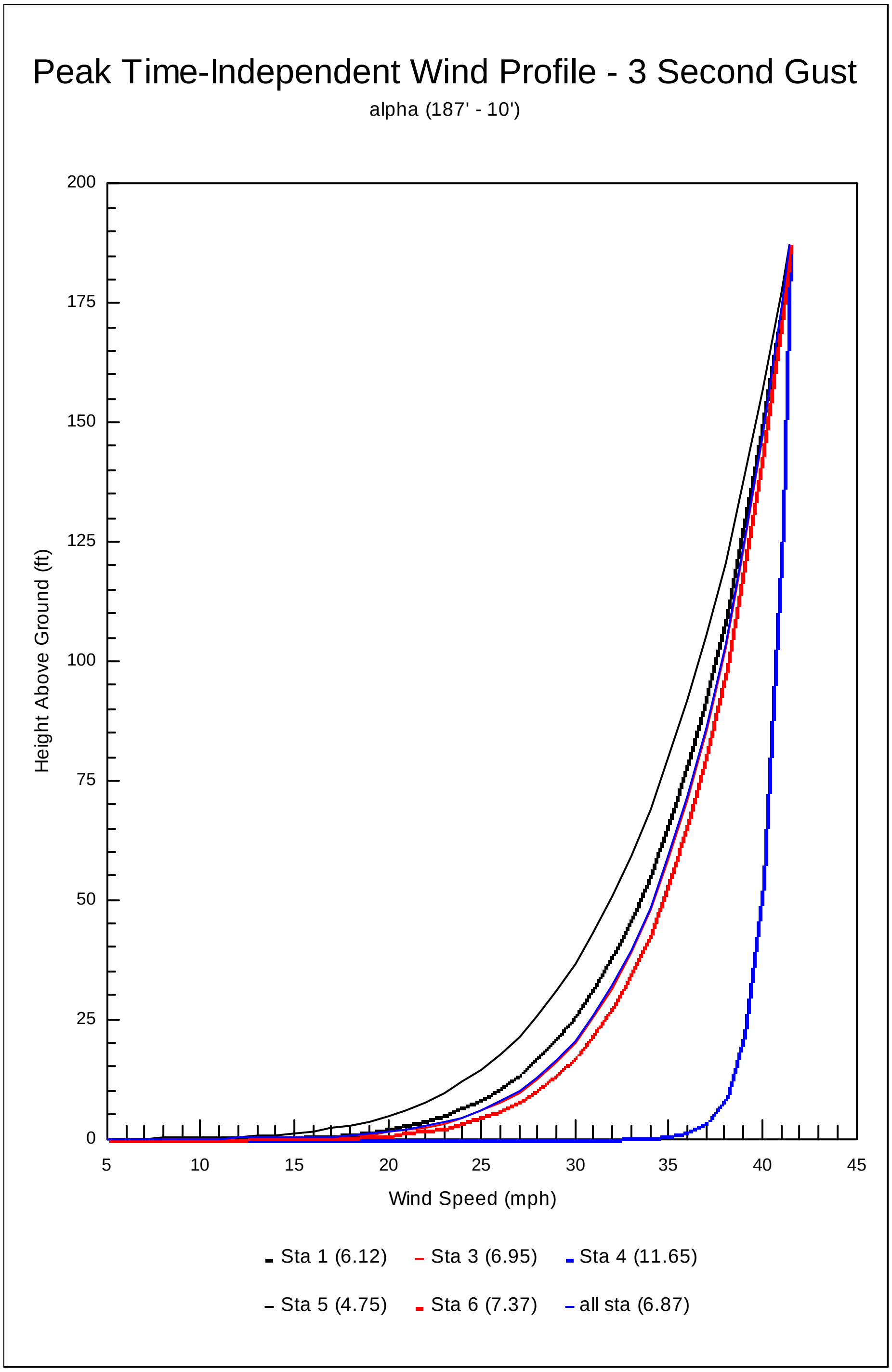

Figure 15 - Power law profile for peak gust wind speeds based on the 187-ft (57-m) tower data and an assumed gradient height of 1,200 ft (366 m).

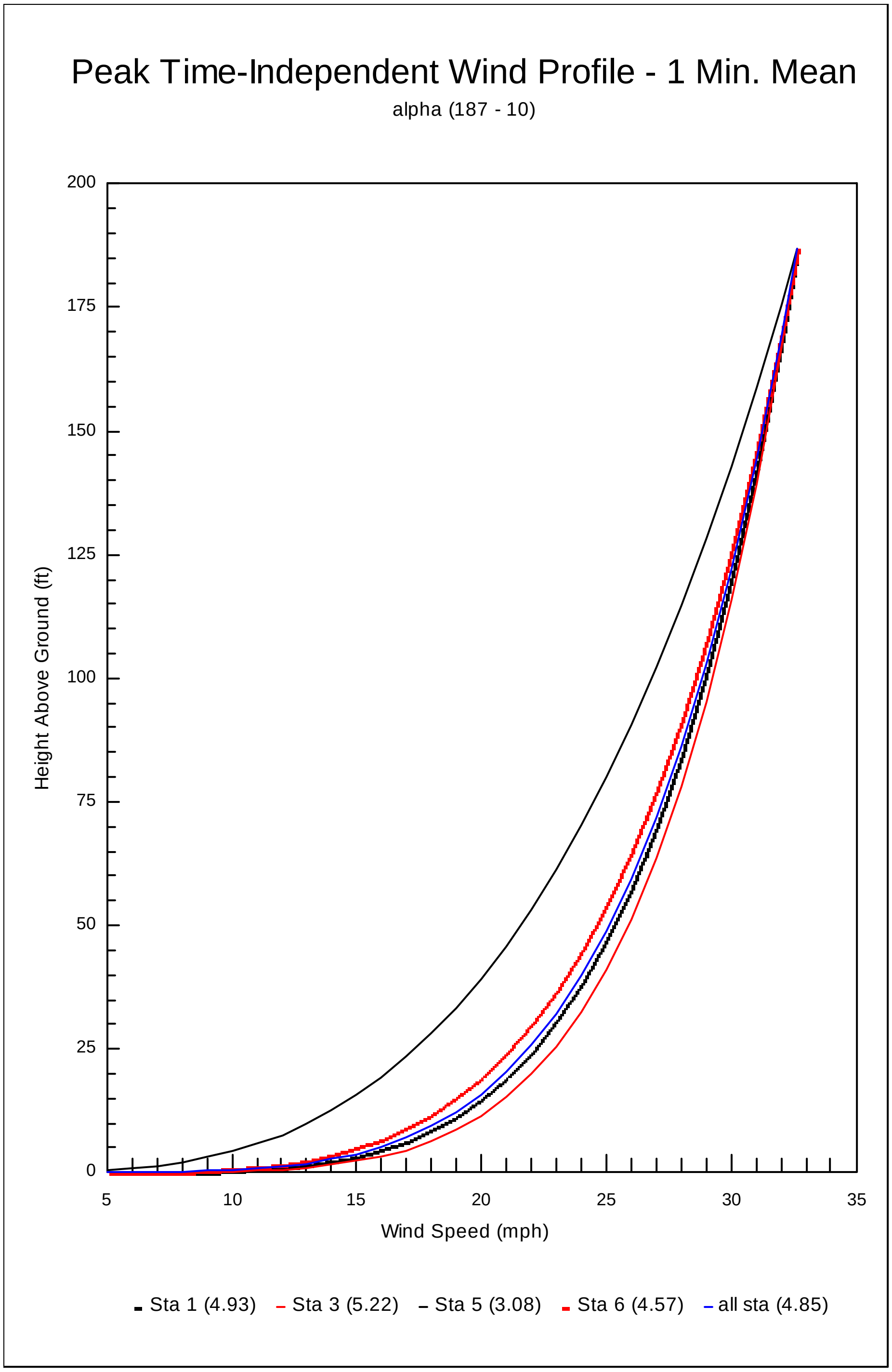

Figure 16 - Power law profile for maximum 1-minute mean wind speeds based on the 187-ft (57-m) tower data and an assumed gradient height of 1,200 ft (366 m).

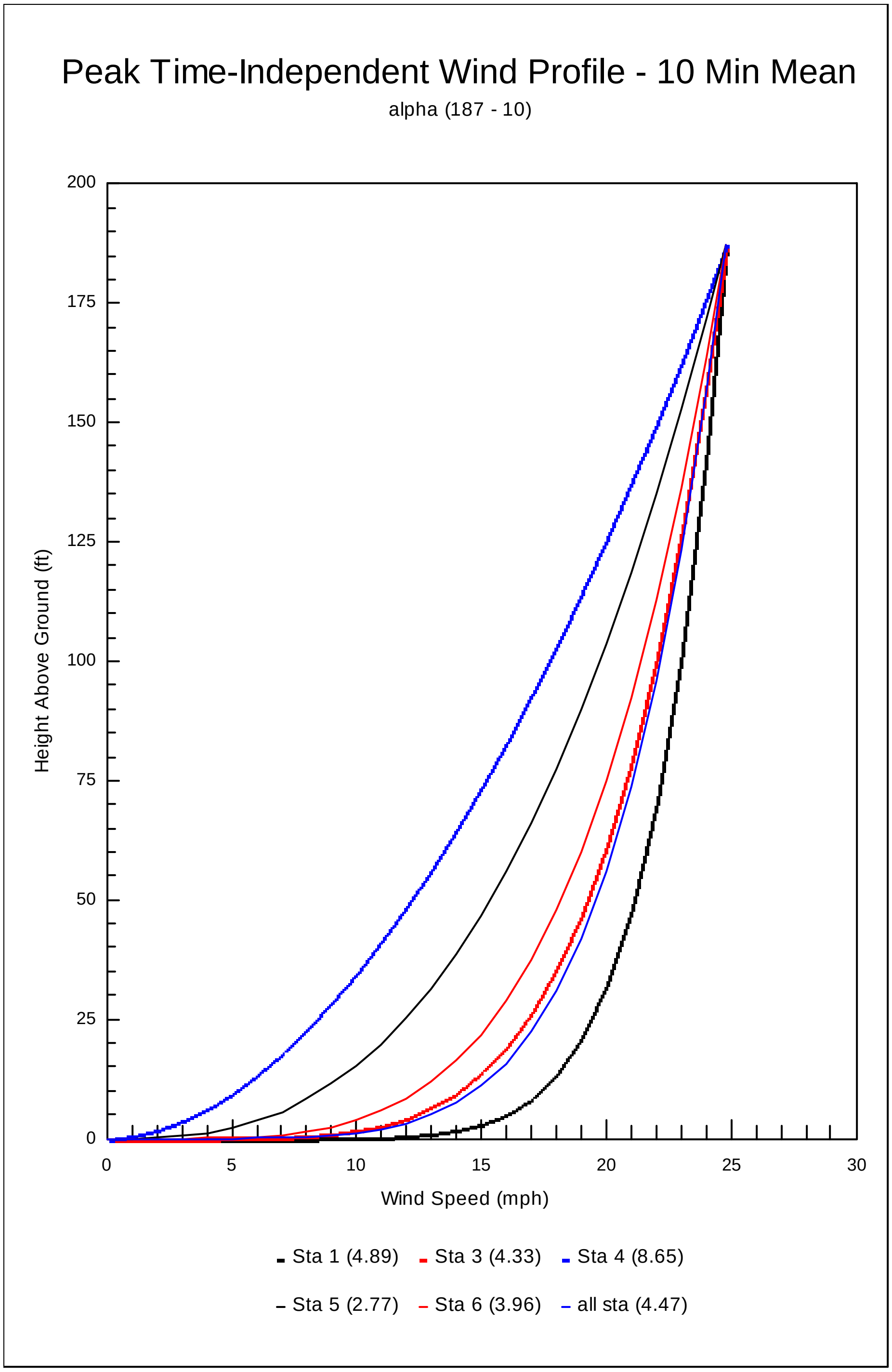

Figure 17 - Power law profile for maximum 10-minute mean wind speeds based on the 187-ft (57-m) tower data and an assumed gradient height of 1,200 ft (366 m).

Turbulence Intensity Profile

Turbulence profiles at the time of each station's peak gust wind speed for 1-minute and 10-minute periods are seen in Figures 18 and 19. In general the profiles have the expected shape of increasing turbulence with decreasing height above ground. This trend occurs with much less intensity for station 4 for both time intervals and for station 1 with the 10-minute interval (see Table 6). These differences may be due to localized terrain effects as these stations in general have the least obstructions and represent more open terrain (approaching a category C exposure).

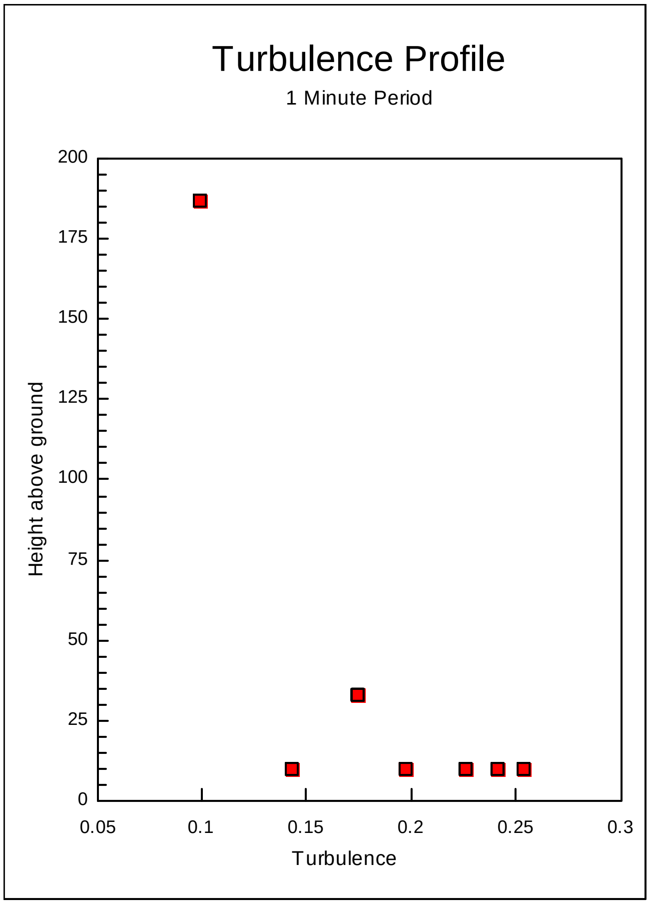

Figure 18 - Turbulence intensity profile for a 1-minute period at the time of each station's peak gust record.

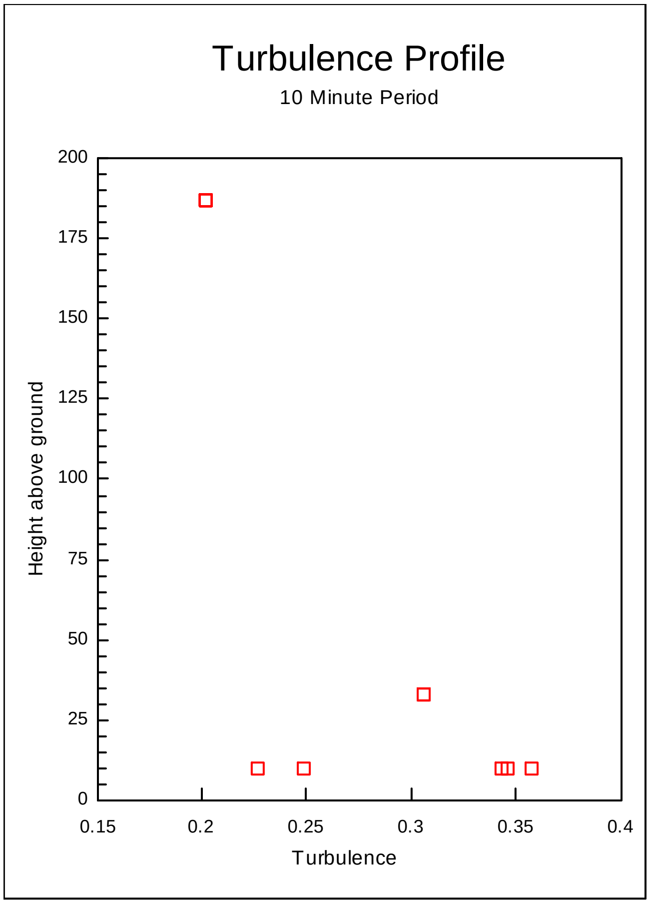

Figure 19 - Turbulence intensity profile for a 10-minute period at the time of each station's peak gust record.

Conclusions

In general, the limited length of record (14 days) available at the time of this report should considered by the reader, particularly since the maximum gust wind speed was about 42 mph for the 187-foot tower. However, the findings are consistent with similar data presented in the literature review section with respect to expected trends of wind speed gradient as a function of wind speed and elevation. Turbulence intensity also followed expected trends.

The unique findings of this study are related to the variability of the near ground wind speeds (and the estimated power law coefficients) in the "exposure B" setting of the industrial park. The following significant conclusions can be made based on the length of the data record at this point:

1. On average, the estimated power-law exponent for peak gusts are in reasonable agreement with that used in the ASCE 7-95 standard for the exposure conditions of this study. However, based on the literature review, this power-law relationship, when squared to determine wind load variation with height may be conservative. (This can only be confirmed in wind tunnel studies or in full-scale building pressure measurements in unison with the wind profile measurements).

2. The average power law exponent ($1/\alpha$) of approximately 1/7 was documented based on the peak gust for each of the five near ground stations during the record period. The COV of α was between 0.35 and 0.41 for the peak gusts of each of the five stations.

3. The variation in estimated power law exponent can be attributed to the differences in local exposure experienced at the five near-ground wind stations. At a standard anemometer elevation of 33-feet, this variation could be expected to be much less as the effects of shielding and surrounding roughness conditions would be somewhat diminished.

4. The variation of wind speed between the five stations was significant, representing the range of wind conditions that would be expected in a built-up exposure. The lower wind speeds are associated with stations with a higher degree of "protection" (or shielding) from buildings or trees while the higher wind speeds where associated with parking lot exposures, possible channeling due to buildings, and effect of topography (i.e. small knoll). Therefore, in the moderately dense conditions of the industrial park, the effect of shielding at some locations was practically offset by an opposite effect of wind speed-up at other stations. In a more dense development, more shielding would probably be realized on average.

Recommendations

It is recommended that the near-ground wind monitoring effort continue for an additional year to allow for an “annual extreme value” representation of the near ground wind speeds and estimated profiles. Based on the current data, the future data is expected to confirm the ASCE 7 wind profile (power law exponent) used for exposure B. However, the information on the spatial variability of the peak wind speeds will be useful in answering concerns regarding wind channeling effects, open area effects, and potential shielding effects in an exposure B setting. Re-deployment of the wind monitoring station in a dense residential development should be considered to investigate the maximum possible condition of shielding. Also, if funding and opportunity allow, the wind monitoring stations should be deployed in an attempt to capture data from a land falling hurricane event in a residential setting. This would allow better correlation of near ground wind conditions with damage levels experienced by residential construction. Finally, future research should focus on using this data in combination with wind-tunnel experiments to provide improved guidance for the design of residential and similar low-rise buildings in exposure B settings.

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APPENDIX
GROUND STATION TERRAIN DESCRIPTIONS

Table A-1 - Characteristics of Monitoring Locations

Direction	Station 1		Station 3		Station 4		Station 5		Station 6	
	Description	Dist.	Description	Dist.	Description	Dist.	Description	Dist.	Description	Dist.
Height (z)	9.9’		10.75’		10.1’		10.8’		10.1’	
North	lawn	0’-133’	grass	0’-350’	4' scrub	0’-44’	clearing	0’-12’	lawn	0’-156’
	4' tall scrub	133’-158’	scattered trees	135’	lawn	44’-70’	wooded	12’	35' building	156’
	wooded	>158’	wooded, 30’ building	>600’	8' hill	70’-100’				
					lawn, pavement	100’-228’				
					35' building	228’				
Northeast	grass	0’-150’	grass, pavement	0’-200’	15' grass slope	0’-221’	clearing	0’-12’	lawn	0’-122’
	4' tall scrub	150’-218’	25' high building	200’	10' shrubs	221’-291’	wooded	12’	35' building	122’
	wooded	>218’			grass	291’-557’				
					4' scrub	557’-627’				
					wooded	>627’				
East	grass	0’-310’	grass, pavement	0’-113’	grass	0’-400’	clearing	0’-12’	lawn, pavement	0’-134’
	wooded	>310’	4' scrub	113’-250’	wooded	>400’	wooded	12’	hedge	134’
			15' shrubs, 25’ building	>250’			30’building	>600’	downslope to wooded	140’
Southeast	grass	0’-442’	grass	0’-37’	4' scrub	0’-84’	clearing	0’-12’	lawn	0’-51’
	wooded	>442’	4' scrub	37’-257’	wooded	>84’	wooded	>12’	10' shrubs	>51’
			25' building	257’						
South	grass	0’-221’	Grass	0’-51’	4' scrub	0’-84’	clearing	0’-12’	downslope to wooded	0’
	10' shrubs	221’-261’	4' scrub	51’	wooded	>84’	wooded	12’		
	grass	261’-447’	30’ building	>300’			30’ building	>600’		
	wooded, 30’ building	>447’								
Southwest	lawn, pavement	0’-93’	grass	0’-58’	3' hill	0’-40’	clearing	0’-12’	grass	0’-30’
	dumpsters, shrubs	93’-128’	4' scrub	58’-104’	6' hill	40’-80’	wooded	12’	4' scrub	30’-76’
	3' lawn hill	128’-221’	wooded	> 104’	lawn, pavement	80’-300’			downslope to wooded	>76’
	lawn, pavement	221’-454’	30’ building	>300’	30' building	300’				
	shrubs	454’								
West	3' lawn hill	0’-23’	grass	0’-42’	3' hill	0’-27’	clearing	0’-12’	grass	0’-100’
	pavement	23’-263’	4' scrub	42’-83’	6' hill	27’-74’	wooded	12’	15' hill	100’-193’
	30’ building	>93’	wooded	>83’	lawn, shrubs	74’-260’				
	lawn	263’-510’	30’ building	>600’	30’ building	>260’				
	wooded	>510’								
Northwest	lawn, pavement	0’-214’	grass	0’-278’	lawn	0’-33’	clearing	0’-12’	lawn	0’-112’
	4' tall scrub	214’-228’	wooded	278’	10' lawn hill	33’-70’	wooded	12’	15' hill	112’-205’
	wooded	>228’	30’ building	>600’	pavement, lawn	70’-131’				
					10' shrubs	131’-164’				
					pavement, lawn	164’-				

Direction	Station 1		Station 3		Station 4		Station 5		Station 6	
	Description	Dist.	Description	Dist.	Description	Dist.	Description	Dist.	Description	Dist.
						234’				
					35' building	234’				

STATION 1

Figure A-1 - View Looking Northwest (Station 1)

Figure A-2 - View Looking Northeast (Station 1)

Figure A-3 - View Looking East (Station 1)

Figure A-4 - View Looking Southeast (Station 1)

Figure A-5 - View Looking South (Station 1)

Figure A-6 - View Looking Southwest (Station 1)

Figure A-7 – View Looking West (Station 1)

Figure A-8 – View Looking Northwest (Station 1)

STATION 3

Figure A-9 - View Looking North (Station 3)

Figure A-10 - View Looking Northeast (Station 3)

FigureA-11 - View Looking East (Station 3)

Figure A-12 - View Looking Southeast (Station 3)

Figure A-13 - View Looking South
(Station 3)

Figure A-14 - View Looking Southwest
(Station 3)

FigureA-15 - View Looking West
(Station 3)

Figure A-16 - View Looking Northwest
(Station 3)

STATION 4

Figure A-17 - View Looking North (Station 4)

Figure A-18 - View Looking Northeast (Station 4)

Figure A-19 - View Looking East (Station 4)

Figure A-20 - View Looking Southeast (Station 4)

Figure A-21 - View Looking South (Station 4)

Figure A-22 - View Looking Southwest (Station 4)

Figure A-23 - View Looking West (Station 4)

Figure A-24 - View Looking Northwest (Station 4)

STATION 5

Figure A-25 - View Looking North (Station 5)

Figure A-26 - View Looking Northeast (Station 5)

Figure A-27 - View Looking East (Station 5)

Figure A-28 - View Looking Southeast (Station 5)

Figure A-29 - View Looking South (Station 5)

Figure A-30 - View Looking Southwest (Station 5)

Figure A-31 - View Looking West (Station 5)

Figure A-32 - View Looking Northwest (Station 5)

STATION 6

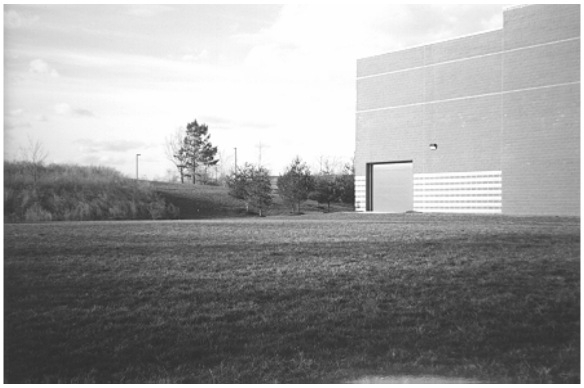

Figure A-33 - View Looking North (Station 6)

Figure A-34 - View Looking Northeast (Station 6)

Figure A-35 - View Looking East (Station 6)

Figure A-36 - View Looking Southeast (Station 6)

Figure A-37 - View Looking South (Station 6)

Figure A-38 - View Looking Southwest (Station 6)

Figure A-39 - View Looking West (Station 6)

Figure A-36 - View Looking Northwest (Station 6)