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INHERENT UNCERTAINTIES IN METEOROLOGICAL PARAMETERS
FOR WIND TURBINE DESIGN

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One of the major difficulties associated with meteorological measurements is the inability to duplicate the experimental conditions from one day to the next. This lack of consistency is compounded by the stochastic nature of many of the meteorological variables of interest. Moreover, simple relationships derived in one location may be significantly altered by topographical or synoptic differences encountered at another. The effect of such factors is a degree of inherent uncertainty if an attempt is made to describe the atmosphere in terms of "universal" laws. In this paper some of these uncertainties and their causes are examined, examples are presented and some implications for wind turbine design are suggested.

The basic design process for a wind turbine typically takes into account a number of wind characteristics. First, some estimates of wind speeds and their frequency of occurrence are needed. This information may be summarized in a probability distribution function of wind speed. However, such information may only be available at a single height, and it then may be necessary to use an extrapolation technique to relate winds at one height to those at another. Finally, the effects of unsteady winds must be taken into account, so some information on turbulence is required as well.

When the basic wind characteristics of interest have been identified, some standard reference work or handbook may be used to quantify these features. Using these values as a design basis, and incorporating some reasonable safety factors where appropriate, the machines may then be built and tested. Mass production and marketing of the turbines follow, based on the expectation that the failure rate will be small, at least in the near future.

This process might work--or it might not. Presumably there are no inherent, fatal design flaws in the current generation of wind turbines and there is a reasonable expectation of success. Nonetheless, it is useful to keep in mind that the wind is temperamental and may often refuse to abide by the laws summarized in standard reference works. It is therefore important that machines not be unduly sensitive to deviations from "expected" wind behavior.

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Let us look at some of these laws and see how and where they were derived. The effects of statistical variability, terrain and thermal influences on these laws can then be considered.

If one is interested in how the wind varies over the course of a year, a probability distribution function is needed. One that is often used is the Weibull distribution,

$$p(V) = \left(\frac{k}{c}\right) \left(\frac{V}{c}\right)^{k-1} \exp \left[- \left(\frac{V}{c}\right)^k \right] \quad [1]$$

Here, c is a scale parameter proportional to the mean wind speed and k is another scale factor that determines the width of the distribution about the mean.

If one wishes to know how this distribution varies with height, a logical starting point is to look at the change in wind speed occurring during a single hour rather than over a whole year. The variation of the wind speed with height depends on a number of factors. If one has a cloudy day, uniform upwind terrain for a distance of a couple of miles or more, and flat terrain, and if one is only interested in the first 30-50 m of the atmosphere above the surface (possibly 100 m if all goes well) then the velocity profile is given by

$$\bar{U}(z) = A \ln \frac{z}{z_0} \quad [2]$$

\bar{U} is the average speed at a height z , A is a constant and z_0 is another constant called the roughness length; it is determined by the nature of the upwind surface. An atmosphere that obeys this relationship is said to behave as a neutral atmosphere.

If preferred, one can pick two heights, z_1 and z_2 , and express the ratio of speeds at these two heights in the form shown below.

$$\frac{\bar{U}(z_2)}{\bar{U}(z_1)} = \left(\frac{z_2}{z_1}\right)^\alpha \quad [3]$$

This is the power law form, and α is the power law exponent. For z_0 in the range of 1-20 cm (smooth to moderately rough terrain), the log formula predicts that α will lie in the range 0.12-0.19 for $z_1 = 20$ m and $z_2 = 100$ m. Clearly, if the log law is correct, the power law exponent will have to vary as z_1 and z_2 vary.

Finally, the distribution of turbulent energy over various frequencies is given by an expression from Kaimal et al. [1] and Frost et al. [2]

$$\frac{n S(n)}{\sigma_u^2} = \frac{0.164 (n z / 0.0144 \bar{U})}{1 + 0.164 \left(\frac{n z}{0.0144 \bar{U}} \right)^{5/3}} \quad [4]$$

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$S(n)$ is the power spectral density for longitudinal turbulence, σ_u^2 is the variance of the fluctuating wind, proportional to the total energy of the fluctuations, and n is the frequency. The intensity of turbulence is σ_u/\bar{U} . For $z_0 = 1-20$ cm, $\sigma_u/\bar{U} \sim 0.11-0.22$ between 20 and 100 m.

The Weibull distribution seems to work more or less well in a variety of situations. The other formulas are for "ideal" cases, but they may not be a faithful representation of conditions that a turbine must live with. There are at least three causes of this--terrain differences, differences in the thermal structure of the atmosphere, and the random nature of the wind. There are often other causes as well, but considerations of these for the remainder of the paper will suffice.

Consider the wind speed distribution at a single height. Justus et al. [3] have done a study of distributions taken from 140 sites in the continental United States. In this study they obtained estimates of the expected statistical spread of Weibull distributions. Some results are shown in Figure 1.

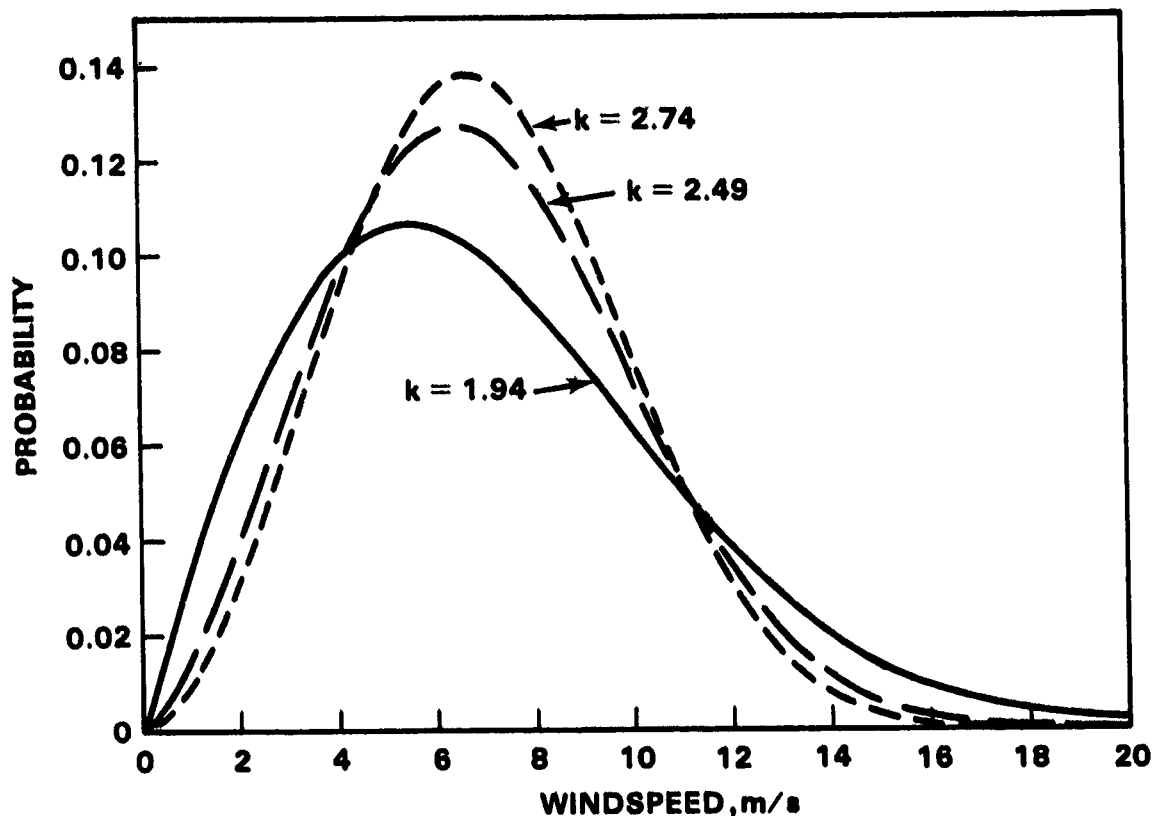


FIGURE 1. WEIBULL WIND SPEED PROBABILITY DISTRIBUTIONS FOR 7 M/S MEAN WIND SPEED AND THREE VALUES OF k

Assume the annual average wind speed is 7 m/s (about 16 mph). Then the mean distribution looks like the curve marked $k = 2.49$ in the figure.

However, one can expect 10% of the cases to look more peaked than the $k = 2.74$ curve and 10% to look flatter than the $k = 1.94$ curve. If one does a simple calculation, one can show that the available power, proportional to V^3 , is 32% higher for the $k = 1.94$ curve than for the $k = 2.74$ curve. The actual difference in extracted power, of course, might be less.

Thus far the assumption has been that the mean wind speed is actually 7 m/s. However, Corotis [4] has shown that if measurements are taken for a year to attain an annual average speed, there is a 30% chance that next year's annual average speed will differ from this year's by 10% or more. This is an inescapable result of the stochastic nature of the wind.

Now assume one has the wind speed distribution at one height and wishes to extrapolate it to another height. Justus and Mikhail [5] have also proposed a set of formulas that will do this. Figure 2 shows how well one of them works.

Here the ratio of extrapolated to measured c values, at some upper level, is plotted on the y axis as a function of the c values at the lower level, plotted on the x axis. Recall that c is essentially a measure of the mean wind speed. This plot then gives an estimate of how well one can extrapolate the mean wind speed from one level to another on an annual basis. A value of one for the ratio would be perfect. One can see that the formula works well in the mean, but there is a considerable amount of scatter. The data were taken from measurements at nuclear power plant sites, and wind turbines might well be located in terrain with far more complexity. In such cases the scatter could be worse. The implications for estimates of potential energy capture are serious. If c is overestimated, the energy will be, too; from the figure, errors of 20% are seen to be quite common.

Thus far, only statistical variations have been considered. What happens when other factors such as terrain or the thermal structure of the atmosphere are explicitly taken into account? Under "ideal" conditions one gets a neutral atmosphere and the wind speed increases with the logarithm of the height. A condition for this is that the terrain upwind of the measuring point be uniform and flat. Under many circumstances, however, the turbine site is unlikely to be particularly level or uncluttered. It should not come as a surprise, then, if the wind characteristics at turbine sites differ widely from those at "ideal" sites.

Consider a plot of the distribution of power law exponents that are obtained at a flat site. Recall that the power law exponent depends on the heights at which the wind speeds are measured. It also depends on the roughness length and the thermal structure of the atmosphere. Figure 3 shows some results obtained at Meade, Kansas for moderately strong wind cases, i.e., 8 m/s or larger at a height of about 10 m. There is a peak at a value of α a little larger than 0.1, about what one might expect from the previous discussion.

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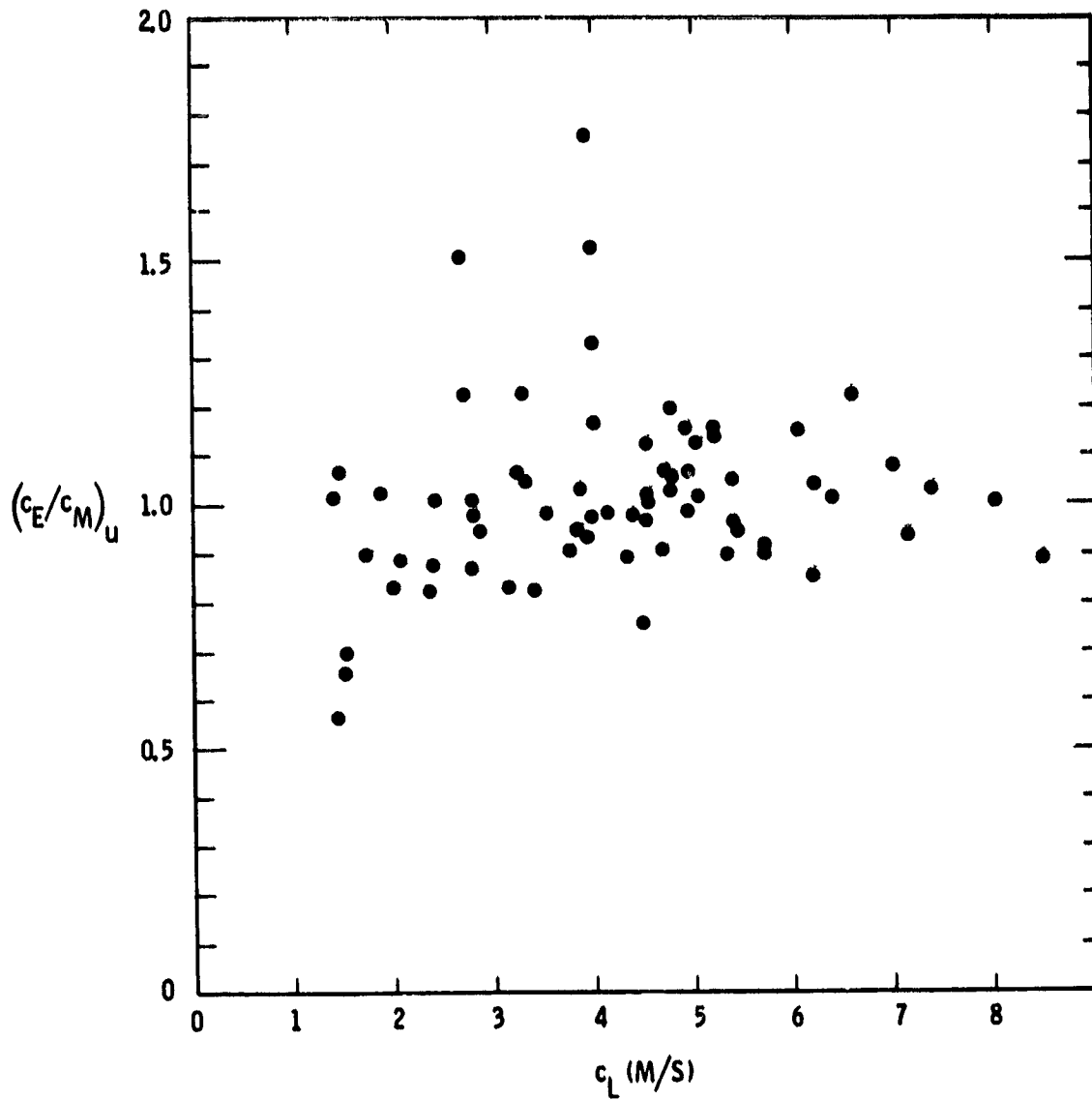


FIGURE 2. RATIOS OF EXTRAPOLATED TO MEASURED VALUES OF c AT UPPER LEVELS VERSUS MEASURED VALUES OF c AT LOWER LEVELS

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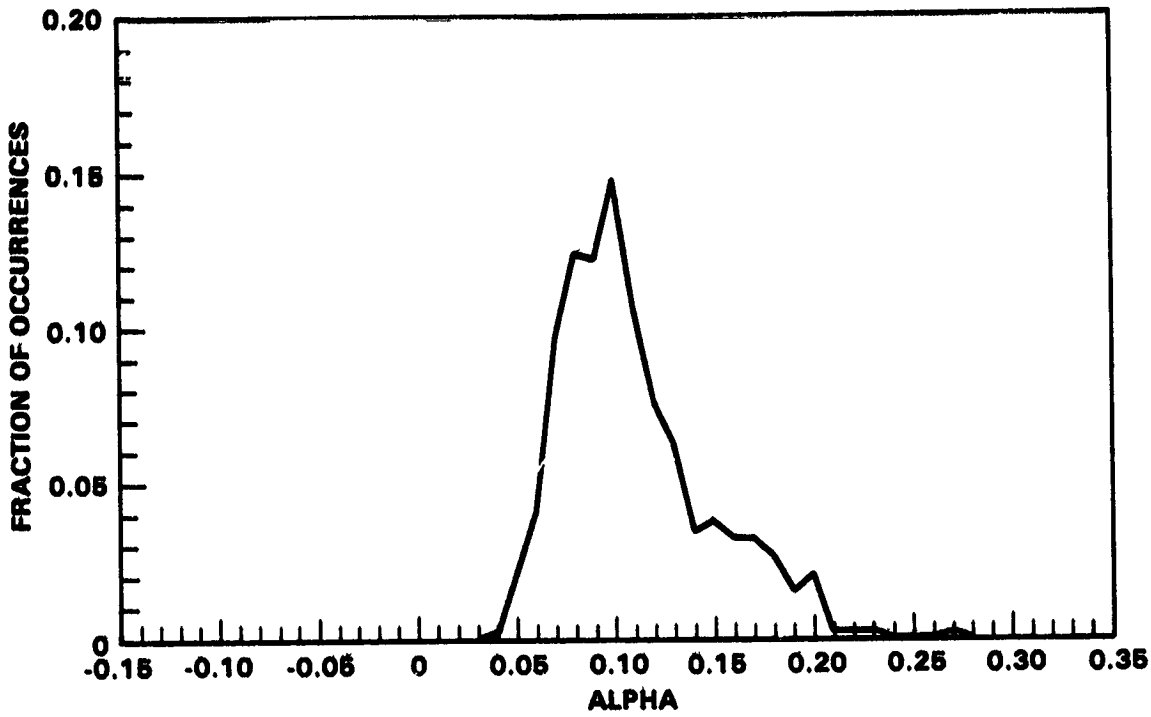


FIGURE 3. WIND SHEAR EXPONENT FREQUENCY DISTRIBUTION NEAR MEADE, KANSAS

Now consider results from a second site, Wells, Nevada.

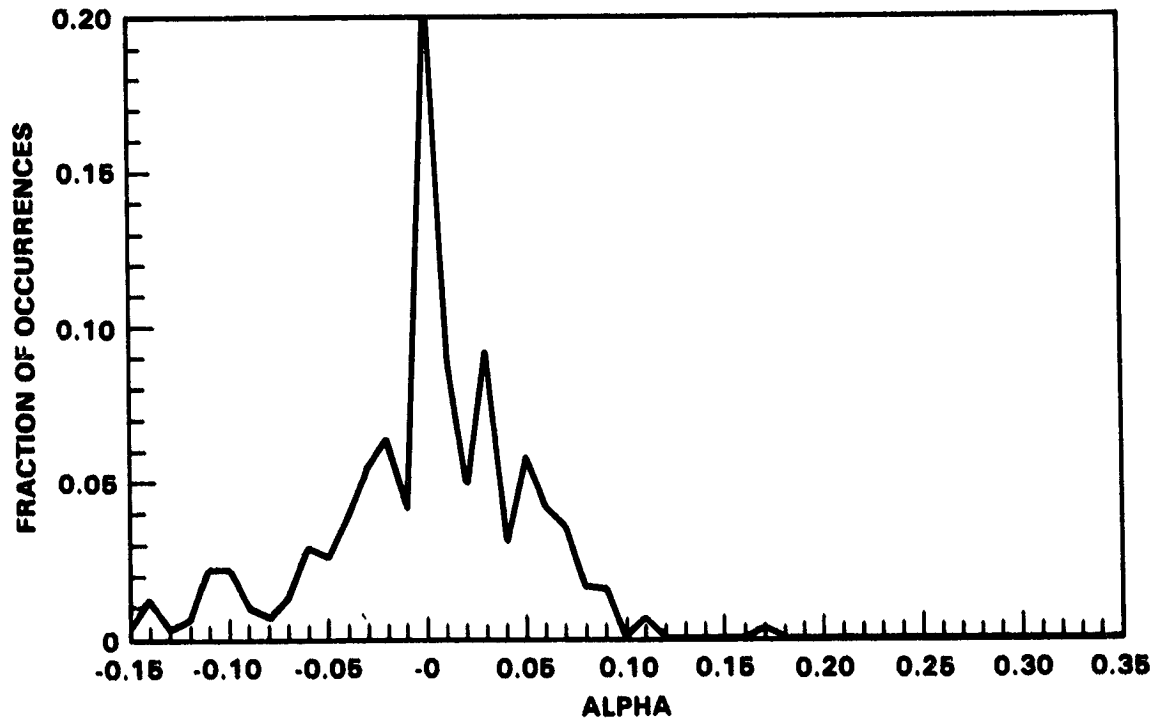
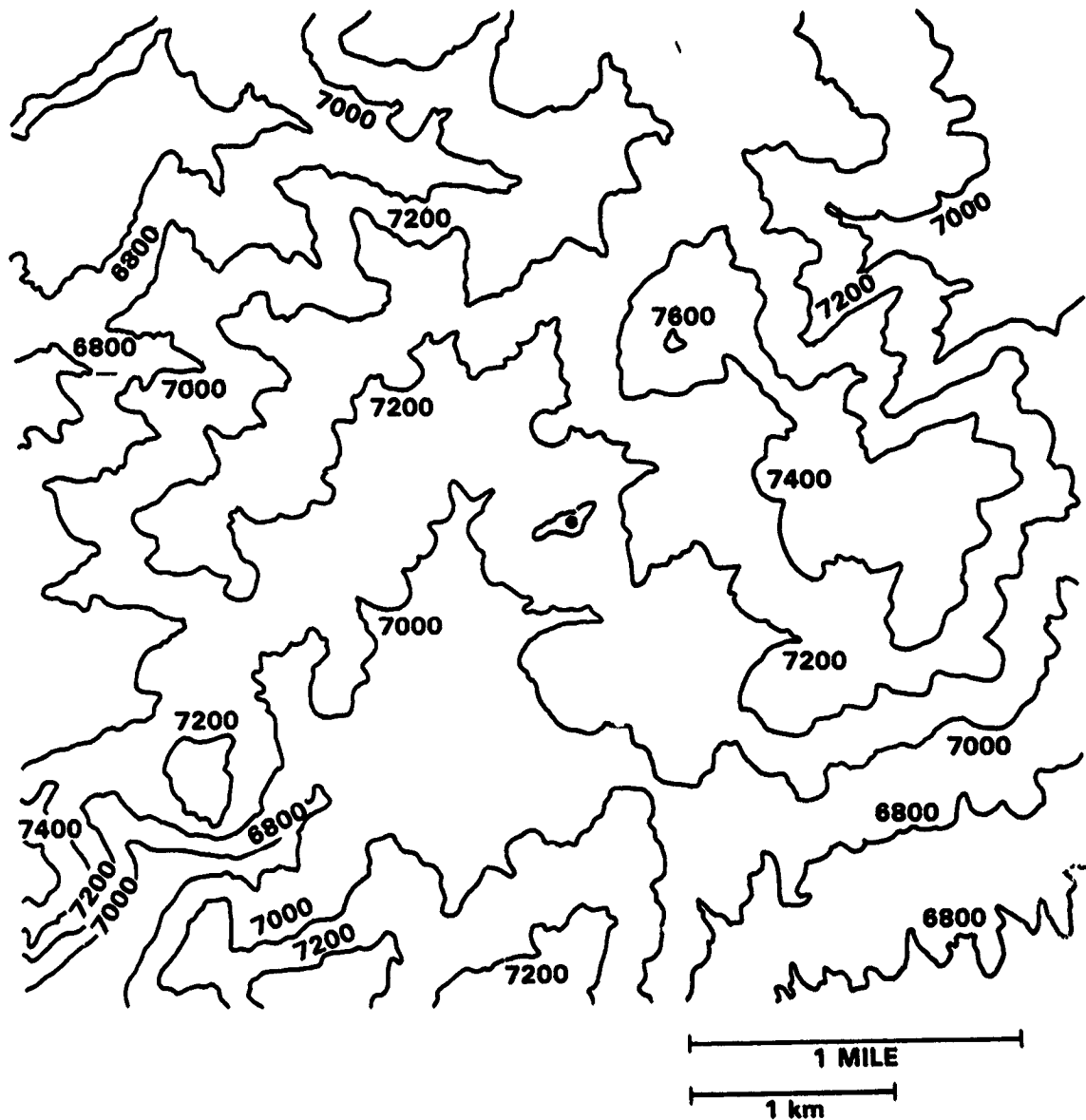


FIGURE 4. WIND SHEAR EXPONENT FREQUENCY DISTRIBUTION NEAR WELLS, NEVADA

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One can see that the power law distribution is quite different. The peak is now at a value near zero and there are a large number of cases where the wind speed hardly changes at all with height or actually decreases. What has gone wrong here? A glance at a topographical map provides one possible explanation.



**FIGURE 5. TOPOGRAPHICAL MAP OF AREA NEAR WELLS, NEVADA;
● INDICATES POSITION OF SHEAR MEASUREMENTS**

The terrain is relatively complicated, and there is no reason to suppose that the wind behavior at this site will be the same as that at a much flatter one.

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Another important factor for wind profiles is the thermal stability of the atmosphere. Figure 6 shows some profiles obtained by Tielemann [6] at Wallops Island on the Atlantic coast. They were taken for directions such that the wind first traveled over the ocean and then over a short stretch of beach before hitting the tower used for the measurements. As one might expect, for these moderately strong winds the speed increases with the logarithm of the height. However, the nature of the upwind terrain would also lead one to expect a roughness length of 10 cm or less. Instead, the two plots on the left give values between 1 and 4 m, leading to much larger shears than anticipated. For the curve on the left, the power law exponent up to 60 m is $\lambda \approx 0.5$.

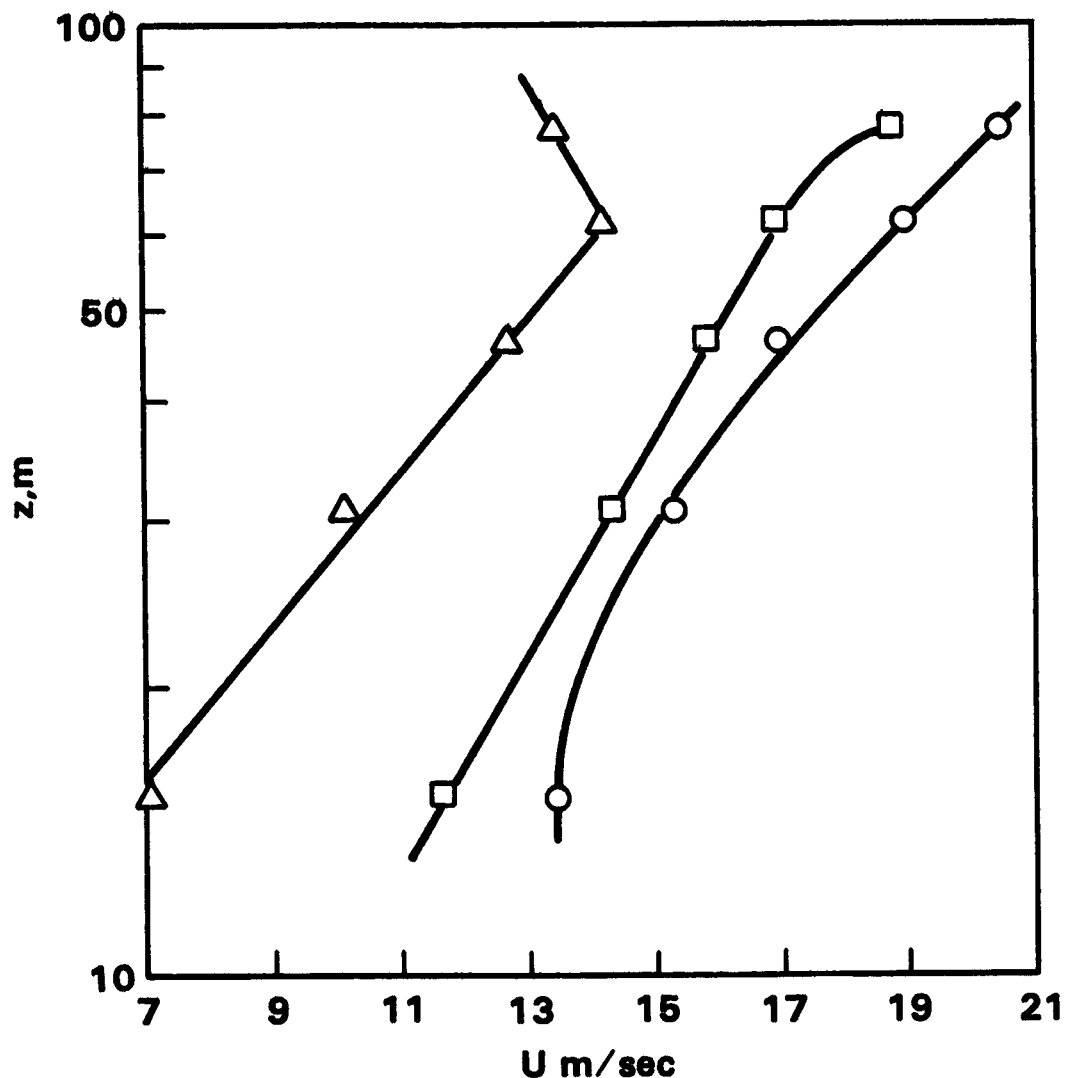


FIGURE 6. WIND PROFILES MEASURED AT WALLOPS ISLAND, VIRGINIA

What has happened is that the thermal effects on the atmosphere due to the proximity of the ocean have altered the structure of the wind. One no longer has a situation in which the turbulence is controlled solely

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by mechanical processes, and all those simple laws discussed earlier don't really apply. There is a comforting myth that if one has strong wind speeds the atmosphere can be treated as neutral; here are several examples that show this is indeed a myth. Tielemann suggests that this situation is quite common--strong winds, good energy potential but no simple wind profile.

A second example of the effects of stability is obtained by considering the phenomenon of nocturnal wind shears. These arise when strong surface cooling effectively decouples the winds at higher elevations from the frictional influence of the ground. A particularly severe case is the one shown in Figure 7, taken from data obtained from a tower in Oklahoma.

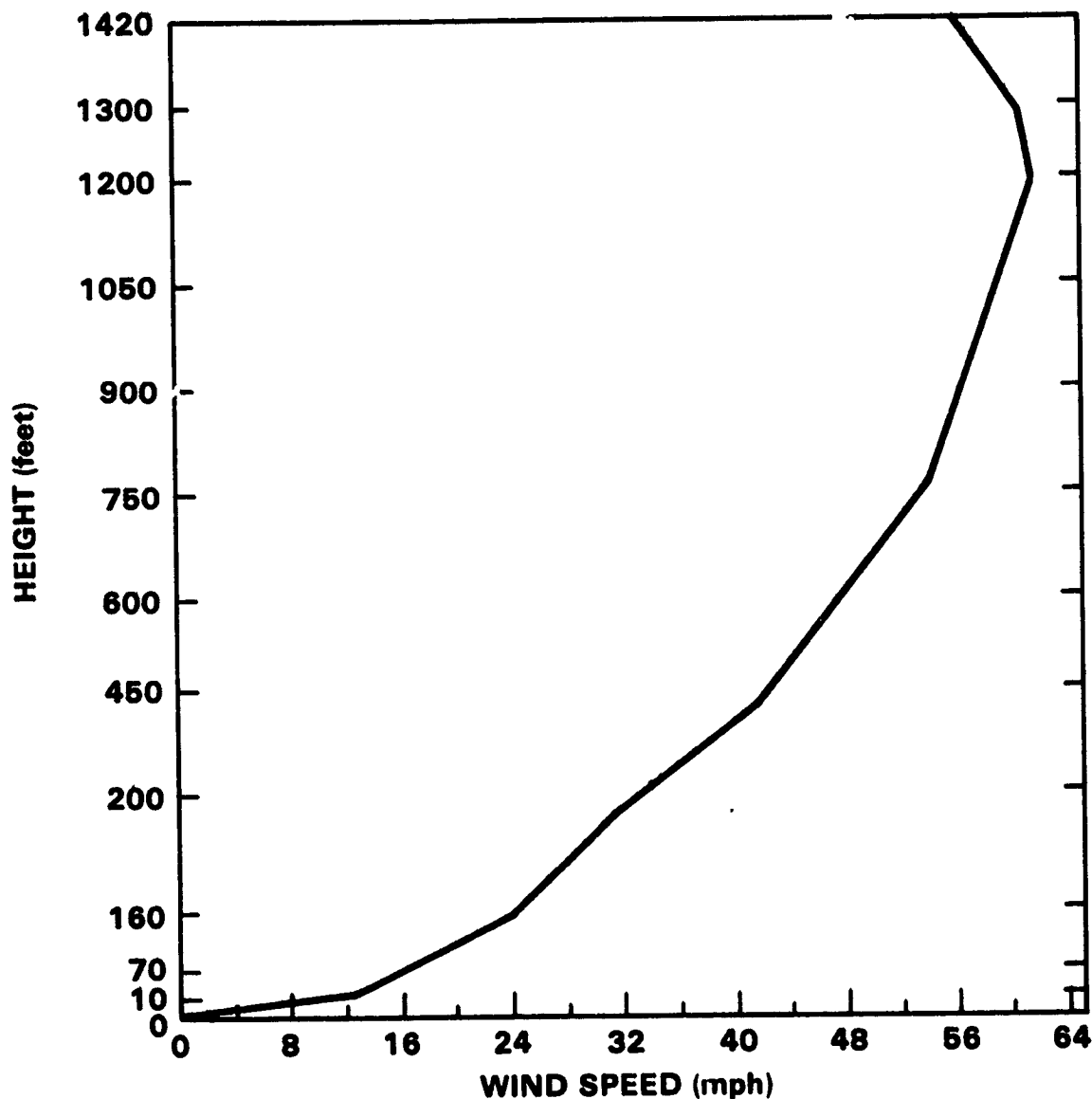


FIGURE 7. EXAMPLE OF NOCTURNAL SHEAR

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Once again the power law exponent approaches a value of 0.5; if a turbine is sensitive to large shears in the vertical, this could lead to some potentially serious problems.

So far the discussion has been limited to mean shears, i.e., shears of winds averaged for some period ranging between about 10 min and 1 hr. It is clear that the height extrapolations can be a tricky business. These difficulties can lead to poor estimates of energy capture or more severe shears than are desirable. There is another aspect of shears that is often overlooked but that could also produce stress on a blade higher than anticipated. That aspect is the fluctuating behavior of wind shear, and these can routinely produce some surprisingly high shear values even in areas where the mean shear appears relatively benign.

Figure 8 shows the distribution of shears measured over relatively smooth terrain in eastern Washington. The abscissa gives the difference in wind speed between two levels separated by 34.5 m (~ 113 ft), and with a mean height of 36.6 m. The speed at the lower level was 12 m/s (27 mph) and the test lasted 2 hr. A $1/7$ power law, a frequently used approximation for strong winds, corresponds to a velocity difference of 1.9 m/s. It is clear that much larger velocity differences are quite common.

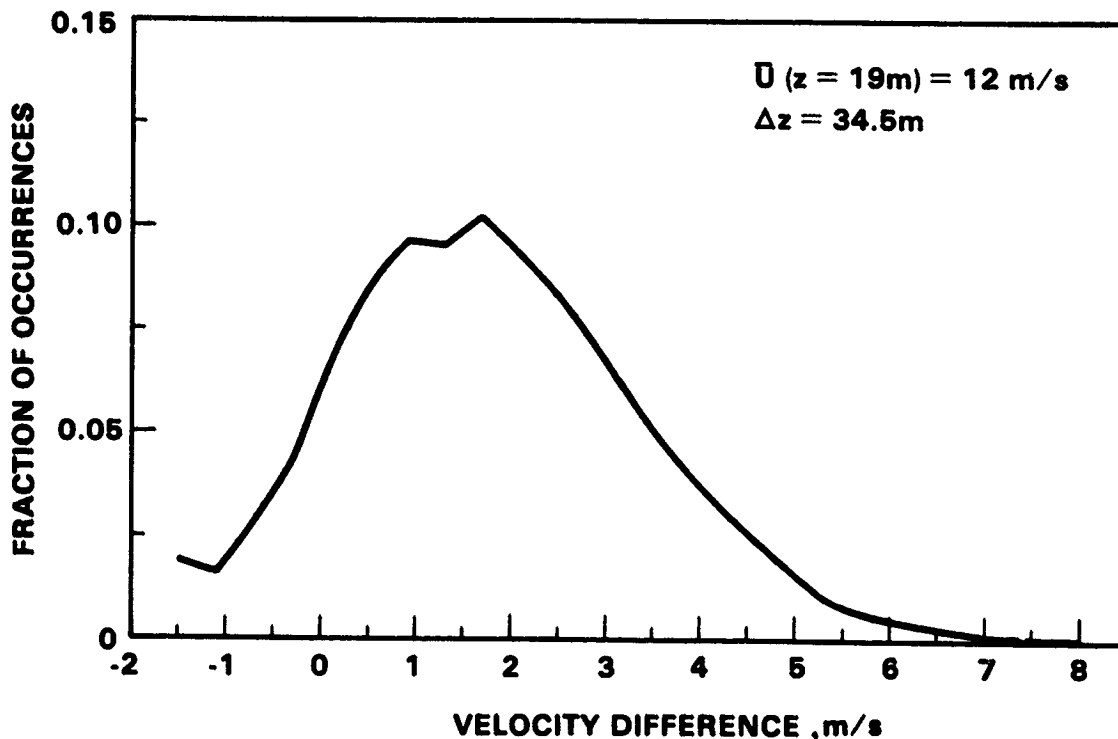


FIGURE 8. DISTRIBUTION OF WIND SHEARS MEASURED
NEAR RICHLAND, WASHINGTON

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Figure 9 shows the probability of the shear being less than or equal to a given amount, for a more general case. The shear here is expressed in normalized form; Δu is the fluctuating shear, $\Delta \bar{U}$ is the mean shear and $\sigma_{\Delta u}$ is the standard deviation of the fluctuating shear. This last quantity is roughly equal to the mean shear, so the ordinate is roughly a measure of the number of multiples of the mean shear by which the mean shear is exceeded. Values of shear three or more times the mean are readily obtained. This is a factor to be considered carefully when estimating the stresses a turbine blade might experience.

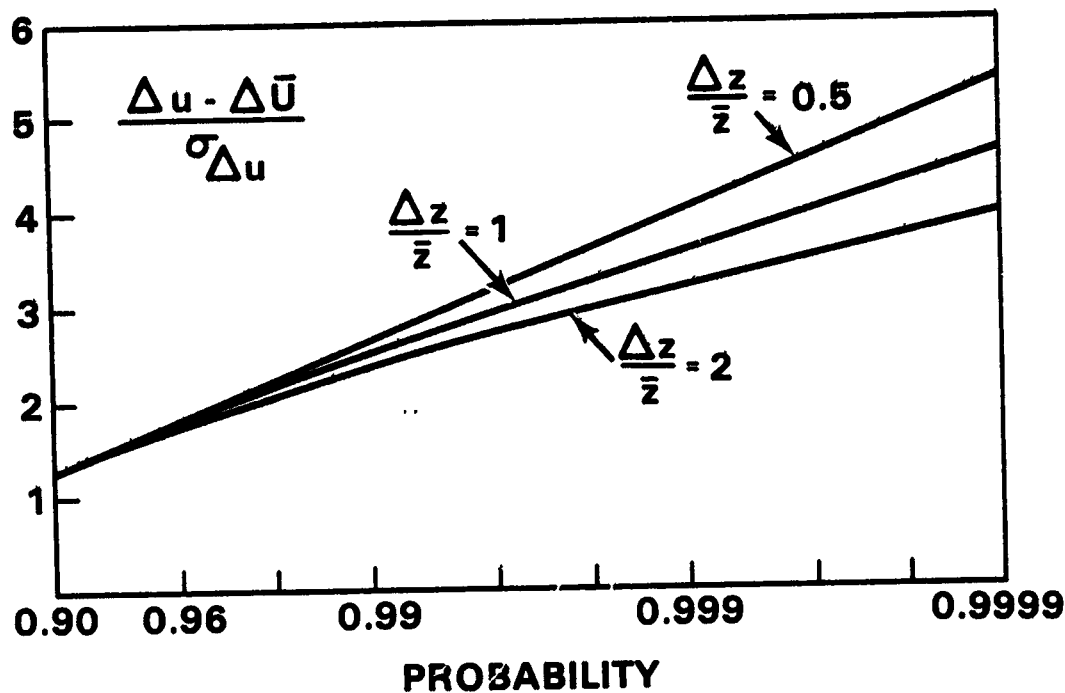


FIGURE 9. PROBABILITY OF NORMALIZED WIND SHEAR BEING LESS THAN A GIVEN VALUE

Now consider another aspect of wind fluctuations, viz., turbulence spectra and turbulent intensity. The spectrum tells how the turbulent energy is divided into various frequency domains. A design spectrum might be of the form suggested by Kaimal et al. [1] and Frost et al. [2] and given in Equation (3). Its form looks like that shown in Figure 10.

However, this form only applies under very slightly stable atmospheric conditions, and it is quite possible to get brisk winds under other conditions as well.

Figure 11 shows a plot made by Powell using a theory of Kaimal [7], which shows how the spectrum is modified under very slightly unstable conditions. The z_1 is the height of the lowest inversion in the atmosphere. There is quite a bit more energy in the low frequency end of the spectrum.

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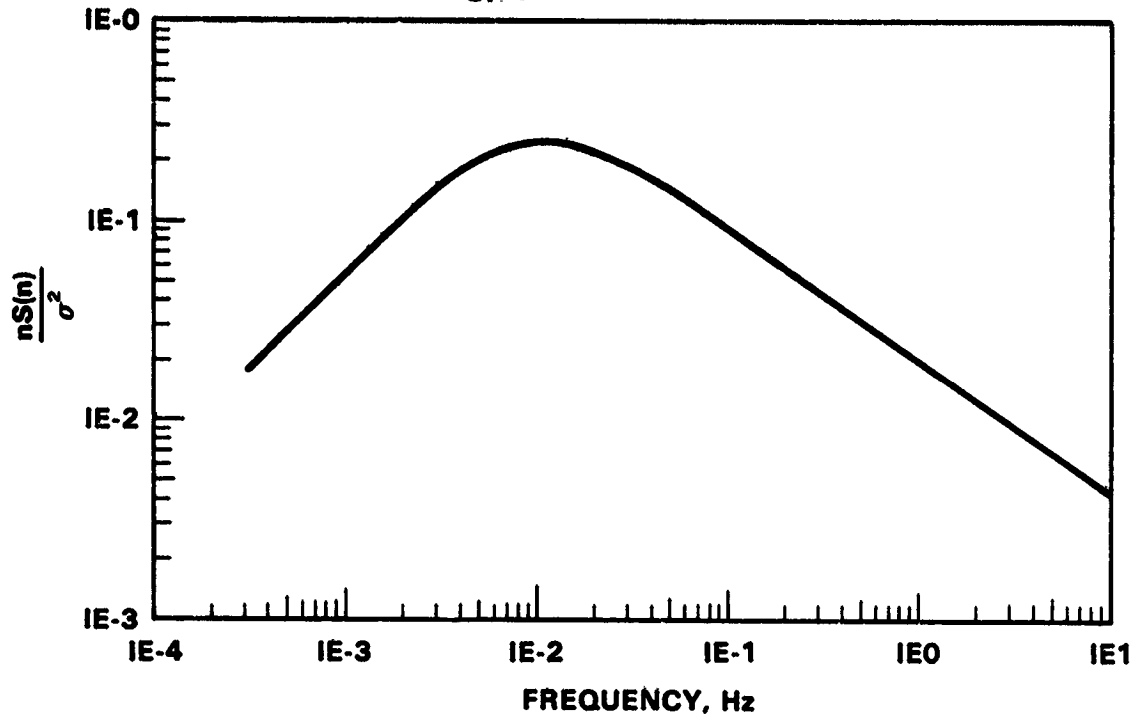


FIGURE 10. NORMALIZED SPECTRUM OF LONGITUDINAL TURBULENCE FOR NEUTRAL LIMIT OF STABLE CONDITIONS, $\bar{U} = 10$ M/S, $z = 50$ M

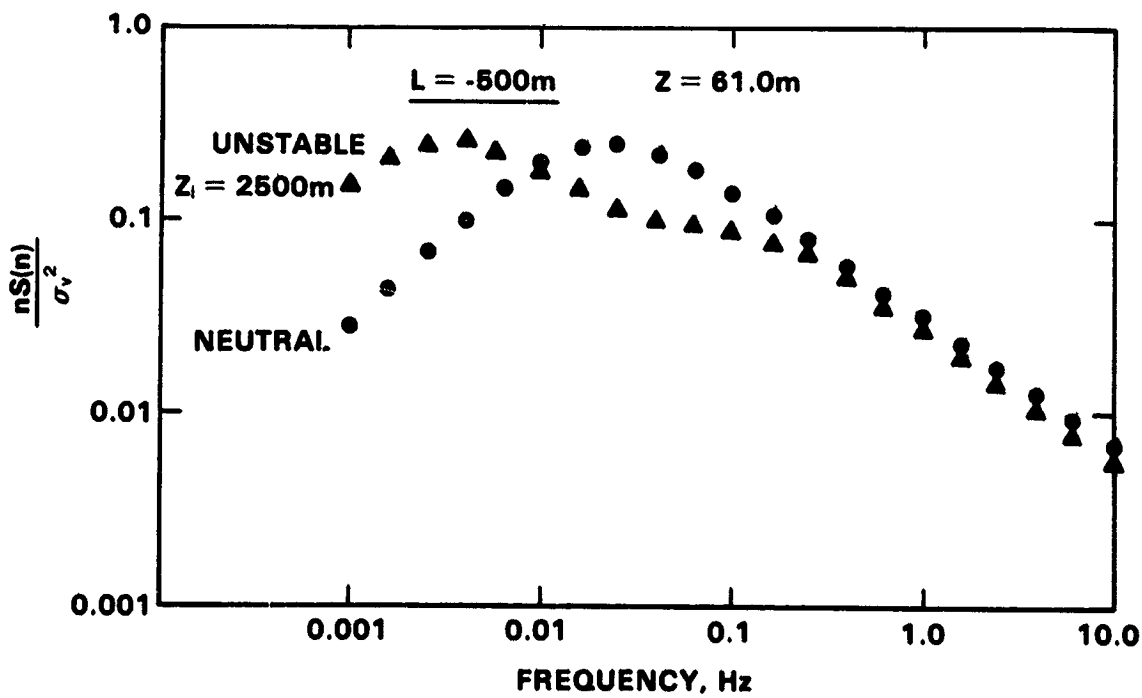


FIGURE 11. COMPARISON OF NEUTRAL SPECTRUM WITH UNSTABLE SPECTRUM, $\bar{U} = 13.3$ M/S

All of this discussion again assumes that the terrain surrounding the measuring point is quite simple. In fact, the theory for the unstable spectrum shown here was developed, in part, using data taken from a site that had about a 20 m elevation difference in a distance of 16 km. It should not come as a surprise, then, if rougher terrain affects the form of the spectrum. Dutton and his co-workers [8] reported on some spectra measured in a hilly region of Pennsylvania. Some results are shown in Figure 12.

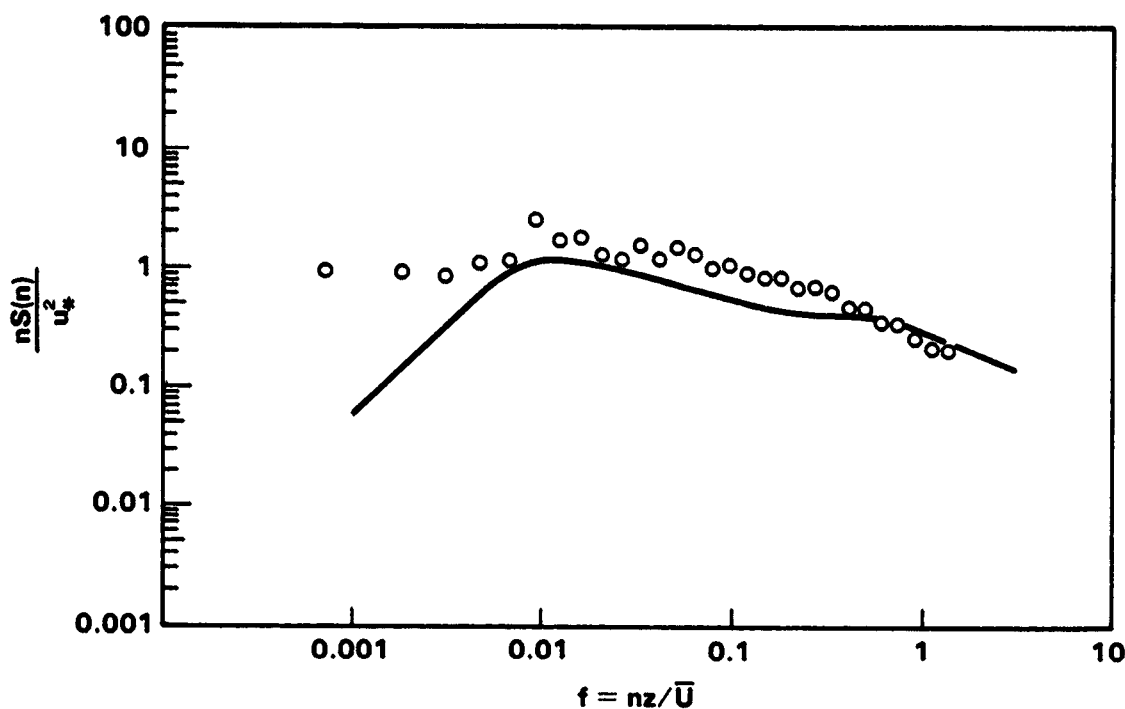


FIGURE 12. COMPARISON OF UNSTABLE SPECTRUM OVER FLAT TERRAIN (LINE) WITH UNSTABLE SPECTRUM IN HILLY TERRAIN (POINTS)

Here the solid line is an unstable spectrum applicable to the flat terrain case; the symbols are experimental results and show an even larger increase in the low frequency portion of the spectrum. This portion may well be relevant to yawing or control strategies and perhaps even to structural fatigue.

One often summarizes the behavior of the spectra--at the risk of losing some information--by merely specifying the turbulent intensity. This is equivalent to integrating under the whole spectrum to get the turbulent energy, taking the square root of that and then dividing by the mean speed. What are typical values of this quantity? It all depends on when and where one does the measurement. Powell has reviewed some data, taken over flat terrain, on the variation of turbulent intensity with stability.

In Figure 13, the ordinate is the turbulent intensity and the abscissa is the Richardson number, a measure of the stability. All these data

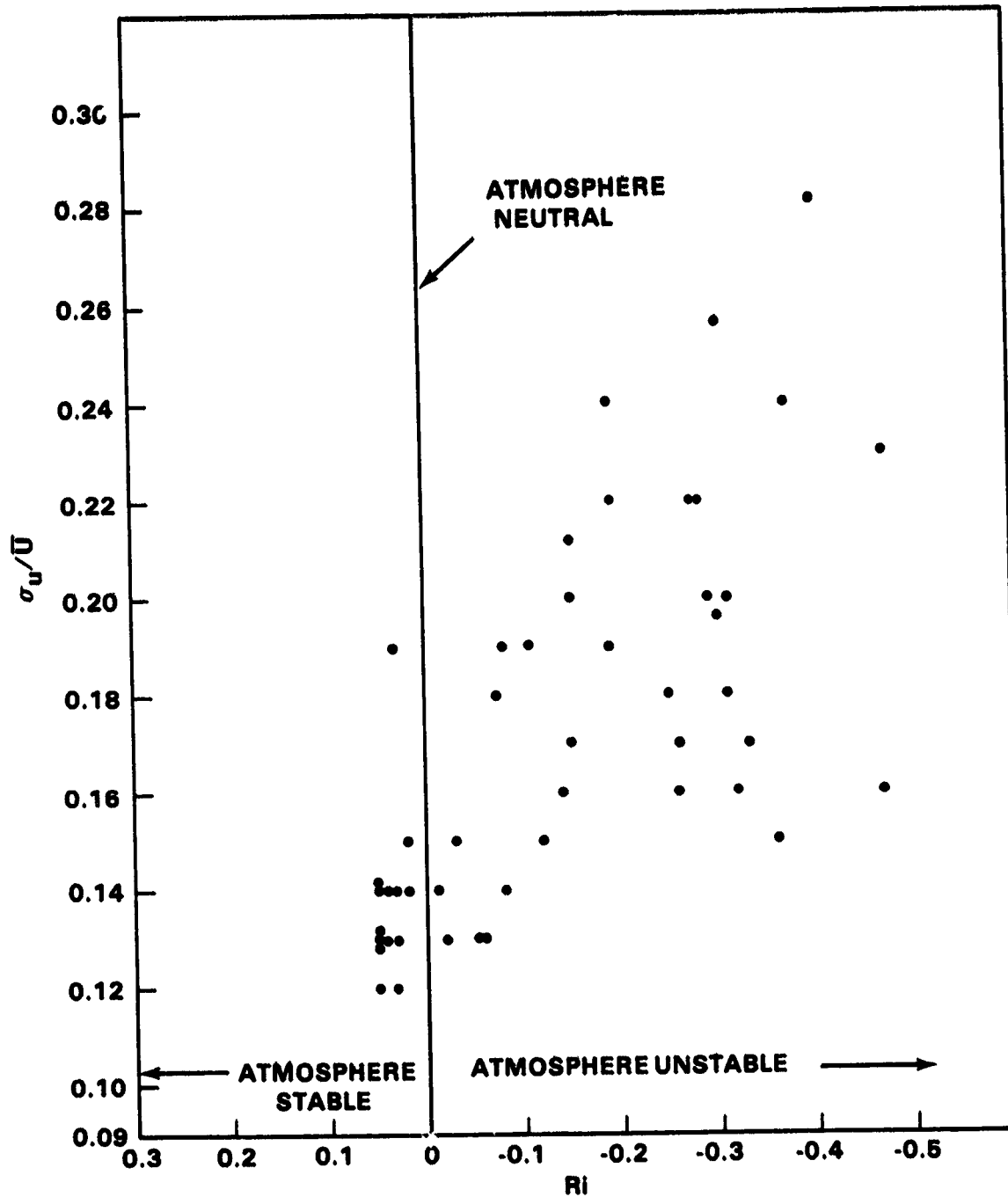


FIGURE 13. VARIATION OF TURBULENCE INTENSITY WITH STABILITY DURING MODERATELY STRONG WIND CONDITIONS

were taken during relatively windy conditions, well within the operating range of most turbines. The range of values is enormous. Much of it is attributable to increased low frequency contributions in the turbulent spectrum. Some scatter, however, is not well described by current theories.

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The influence of terrain may also be seen by examining some of the figures given in Table 1.

TABLE 1. TURBULENT INTENSITY σ_u/\bar{U}

<u>Site</u>	<u>Type</u>	<u>z</u>	<u>\bar{U}</u>	<u>σ_u/\bar{U}</u>
Hanford, WA	Flat	37 m	12-18 m/s	0.125
Boone, NC	Hilltop	69 m	11-18 m/s	0.143
White Sands, NM	Escarpment Edge	16 m	10-13 m/s	0.464

The data here represent only a few sets of measurements, but there is a striking difference between the first two sites and the last. Winds blowing up over the edge of the escarpment result in severe turbulence 16 m (about 50 ft) above the ground. It is certainly not the turbulence level one would get from an examination of data taken at the Bonneville Salt Flats.

In summary, what can be concluded from all this? Are handbook descriptions of the wind useless? Not at all. However, one must remember that their values should not be regarded in the same way as the specification of the tensile strength of some material or the electrical resistance of a given diameter wire. In many cases they may just be a description of some atmospheric properties found in simple terrain under ideal conditions. They are quite useful as a starting point in design, but if the performance or integrity of a machine depend critically on any of these atmospheric descriptors, extreme caution is advised.

The title of this paper contains the words "inherent uncertainties". In a sense this is a bit unfair. We are now in a position where many of the effects of atmospheric stability and terrain on various meteorological variables are understood. It is also possible to assess other situations where such effects might be important, even if one can't always make a quantitative prediction of their magnitude. Thus, at least some of the uncertainty really arises from attempts to pigeonhole the behavior of the atmosphere without explicitly allowing for effects we know are important. If one does this, he must expect wide variations about the mean quantities.

There is still a degree of scatter that is not fully understood, however, or that arises from the random character of the atmosphere. Whatever the reason for the so-called "uncertainties", the design process must clearly allow for a degree of flexibility, for too rigid an adherence to allegedly standard atmospheric characteristics could well prove troublesome in the long run.

ACKNOWLEDGMENT

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