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RATIONALE FOR DETERMINING DESIGN WIND VELOCITIES

BY

A. G. DAVENPORT

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RATIONALE FOR DETERMINING DESIGN WIND VELOCITIES

By A. G. Davenport[1]

SYNOPSIS

This paper first justifies the use of the "extreme wind velocity averaged over a mile or minute" as a "basic design wind velocity" in preference to absolute peak velocities which cannot be considered independently of the size of the structure, and of the dynamic response of anemometer, structure, and structural materials.

An attempt is, then, made to show from published records that reasonably systematic relationships exist between the ground roughness (as characterized by such general qualitative descriptions as "city," "treed countryside," and "open prairie") and both the magnitude of the extreme wind velocities near the ground and its rate of increase with height. This allows approximate estimates of the ratio of surface velocity to gradient velocity to be made. By these means, independent sets of anemometer records taken at locations differing in surface roughness can be compared.

By further introducing the extreme value theory a method is suggested whereby these sets of records may be numerically related taking into account the relative ground roughness, the number of years of record, the quality and consistency of the records, and the height of the anemometer. This process assists in minimizing the systematic errors which are often introduced into individual anemometer records.

Some published extreme-value data for the British Isles are analyzed according to the described procedure and an example is given illustrating how design wind velocities can be determined in a manner which takes into account

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the important influence of surface roughness, the variability of useful life of different structures, and the risks involved if the wind velocity is exceeded.

INTRODUCTION

One of the principal loads acting on above-ground engineering structures is that due to the wind. Its accurate determination, therefore, is of fundamental importance in deciding what degree of safety and economy can be achieved in such a structure.

Formerly, it was common practice to design structures to resist the highest wind ever recorded by the instruments then in use. Although this did provide a sort of yardstick from which design wind loads could be estimated, it was unreliable and subject to the difficulty that most meteorological records will eventually be broken. A longer period of record increased the chances of recording a very high wind velocity. Another problem was that instruments which responded rapidly to fluctuations in wind speed tended to indicate higher velocities than those which were more sluggish. In other known instances, the highest wind had unfortunately blown away the instrument and the crucial information was lost.

All these difficulties tended to throw the problem of determining design wind velocities into the lap of the statistician who, from the records of several years, could estimate the probability of a given wind velocity recurring. Such are the vagaries of climate that the structural engineer can never hope for information much more certain than this.

Further problems emerge from other considerations. Because the velocity of the wind is continually fluctuating, recorded peak velocities will depend largely on the sensitivity of the anemometer. The pressures exerted on a structure will also fluctuate, leading to dynamic amplification of the actual stresses in the structure. This dynamic amplification, as well as being dependent on the intensity and power of the fluctuations, will also depend on the size and shape of the structure (as they will determine the rate of build-up of gust pressures) and on the response of the structure and its constituent materials to dynamically applied loads. The dynamic amplification will vary, therefore, with the size and flexibility of the structure.

For these reasons, wind loads are perhaps best considered in terms of a steady, applied force, independent of the structure's shape, size, and dynamic characteristics, together with a coefficient denoting the amplification which can arise through the interaction of the superimposed pressure fluctuations and the structure's dynamic response. The resolving of this coefficient, however, which is similar in many respects to the "earthquake problem," is not discussed herein.

This paper is confined to the determination of what will be termed the basic design wind velocity, which corresponds to the extreme sustained wind velocity giving rise to the steady component of the pressure. It is, therefore, an average velocity and the determination of a suitable averaging interval forms part of this discussion.

An attempt is made, also, to determine how records from a wide variety of anemometers of differing exposures and periods of record may be related to one another, thereby minimizing the systematic errors which may arise in the records due to anemometer siting and to the improvement of their overall reliability. This requires that cognizance be taken of the important influence of surface roughness both on the magnitude of the surface velocities and on the increase of velocity with height. Combining these results with the extreme-value theory leads to an exploratory method through which basic design wind velocities of given probability of occurrence may be predicted for locations of differing surface roughness.

STRUCTURE OF NATURAL WIND

The wind is caused by the atmospheric pressure differentials which rise over the surface of the earth. The acceleration produced by these pressure differentials is accompanied by other components of acceleration known as the geostrophic acceleration, due to the curvature and rotation of the earth, and the centripetal acceleration. The resultant of these accelerations produces a motion in the free air, unaffected by friction near the surface, which is parallel to the lines of equal barometric pressure (known as isobars). The velocity of the free air is known as the gradient velocity.

Under steady state conditions the gradient velocity can be determined directly if the latitude, the radius of curvature of the isobars, and the pressure gradient (or spacing of the isobars) are known (1).[2] For zones of cyclonic winds (associated with a low pressure system and with storms and high winds) the gradient velocity V_G is given by

$$V_G = r\, w\, \sin\lambda \left[\sqrt{\frac{\frac{dp}{dN}}{\rho\, r\, w^2\, \sin^2\lambda} + 1} \;-\; 1 \right] \quad \ldots\ldots\ldots \quad (1)$$

in which r is the radius of curvature of isobars, w denotes the rotational speed of the earth; λ is the latitude, dp/dN represents the pressure gradient, and ρ is the density of the air. Eq. 1 lends itself ideally to simple nomographic solution, as shown by W. J. Humphreys (1), and the gradient velocity may be estimated directly from isobar charts. Accurate estimates of gradient velocity, however, are difficult to obtain unless the grid of meteorological stations measuring surface pressures is close.

The velocity of the gradient wind is, however, attained only at heights around 1,000 ft to 2,000 ft above the ground. Closer to the ground, the wind is retarded by the frictional forces and obstructions at the surface and the virtual stresses produced by the vertical exchange of momentum by turbulence; its direction, then, is no longer parallel to the isobars. Turbulence also causes rapid fluctuations in the velocity of a wide range of frequencies and amplitudes. The velocity of the wind at lower levels, therefore, is usefully expressed in terms of its mean speed and the deviations from this velocity.

The time or distance interval over which the mean is averaged depends on the purpose for which the wind velocity is to be used.

Choice of a Suitable Averaging Interval.—In determining basic wind velocities for the design of structures certain fundamental considerations determine what averaging interval is most appropriate. These may be stated as follows:

1. The interval should coincide, as far as possible, with some natural periodicity of the wind.

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[2] Numerals in parentheses, thus (1), refer to corresponding items in the Bibliography.

2. The interval should be "long" compared to both (a) the natural frequency of the structure, and (b) the response time of the instrument; in this way there will be no dynamic interaction between the structure and fluctuations in the mean wind; measured wind velocities will be independent of the instruments response.

3. The interval should be short enough to record the "peaks" of severe storms.

4. The interval should correspond to a body of air of sufficient size to envelop completely a structure and its vortex regions.

The "mile of wind" or the "minute of wind" both represent suitable, if not optimum, intervals for measuring high-wind velocities for purposes of structural design. Both these intervals satisfy the foregoing conditions for reasons now discussed:

1. By means of auto-correlation coefficients, Durst (2) found that in storm winds a major group of eddies, thermal in origin, had a wavelength of about 4,000 ft to 6,000 ft, corresponding closely to the mile interval or the minute interval in winds of 60 mph.

2. a. The natural period of most structures is of the order of 0.1 sec to 3 sec (3), with that for the Empire State Building of 8.14 sec (4). With the damping present in most structures, fluctuations corresponding to one mile in extreme winds would have infinitesimal dynamic action.

b. R. H. Sherlock and M. B. Stout (5), referring to the response time of commercial anemometers, wrote in 1937, "that because of the inertia of moving parts of the instruments the records could only be accepted as accurate if they were averaged over 10 seconds or more." Thus, even at 150 mph, the mile of wind (or the minute of wind) satisfies the second requirement.

3. The mile of wind also represents a body of air far larger than most structures, so that static pressures at least equivalent to this average speed can be anticipated.

4. The mile of wind will be of sufficiently short duration to record the peak of a sudden severe local thunderstorm or squall.

These arguments, justifying the use of the extreme mile or minute of wind as basic design velocities, are endorsed further in that the mile of wind has been recommended for use in the United States (where records are available for many years) as the basis for design wind velocities and the minute of wind in the British Isles.[3]

Increase of Velocity with Height: Influence of Surface Roughness and Stability.—One of the most important factors to be considered is the increase of this mean wind velocity with height; a corollary to this is the retarding effect of the surface friction on the wind velocity nearer the surface.

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[3] Since writing this, the existence of a gap in the energy spectrum of wind speed, centered at a frequency of about 1 cycle per hr, appears to have been established by Van der Hoven (Journal of Meteorology, Vol. 14, 1957, pp. 160-164). This, together with the results from a recent study at the University of Bristol, of over 100 spectra of strong winds now suggests that reliable predictions of the turbulence at higher frequencies (necessary in predicting maximum wind loads) can be made from the average wind speed taken over a longer period, such as one hour. In many countries climatological records of mean hourly wind velocities are more readily available. The discussion that follows applied equally to these mean hourly wind-speeds as well as to those averaged over a rather shorter period.

Various empirical, semi-empirical, and theoretical formulas have been derived to represent the variation of wind velocity with height. Three of the more familiar forms are the spiral, logarithmic, and exponential profiles. For structural purposes, the exponential or power law profile has been used most widely because of its simplicity. It can be stated as

$$V_z = k\, z^{1/\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where V_z is the velocity at height z above ground, and k and α are constants.

By suitable choice of exponent, Eq. 2 can be made to correspond closely over a considerable range to the other forms of profile which are less empirical. The power law is applicable only in the layer extending from the ground up to the height at which the gradient velocity is first attained (usually in the range of 1,000 ft to 2,000 ft). Above this height, the wind velocity may be regarded as constant.

D. Brunt (6) has noted that "If the variation of wind with height be represented by a lower law z^p it is found that p is increased by an increase in either roughness or stability" (z being the height above ground). Here Brunt refers specifically to a range of heights above approximately 10 m (33 ft), the height being of interest to structural engineers.

An attempt is now made to evaluate these influences of stability and surface roughness on first, the rate of increase of mean velocity with height; and second, the magnitude of the mean surface velocity. Both of these values are of prime importance in estimating basic design wind velocities for structures.

Stability.—The stability of a storm is measured by the lapse rate or 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 ~~natural~~ stability (7,8). Rudolf Geiger (9) has stated that this condition is generally attained at velocities greater than 6 m per sec (13 mph). Observations of hurricanes Edna (1954) and Ione (1955) off the New England coast, reported by Edwin Kessler (10), apparently confirm the general assertion that the stability of mature and large-scale storms, whether of the tropical or extra-tropical variety, is close to being neutral.

Exceptions may be found, however, in severe local storms such as thunderstorms and frontal squalls (and perhaps in larger storms such as hurricanes in their early incipient stages, before full maturity is reached) which are notably unstable, where air near the ground is warmer than that aloft. As a consequence of this instability, extreme thermal interchange takes place between the air near the surface and the faster moving upper air which is unretarded by friction near the surface. Under circumstances of extreme instability, the value of the exponent $1/\alpha$ may attain the limiting value of zero, corresponding to zero increase in velocity with height. At Agra, Barkat Ali (11) measured an exponent of 0.02 (1/50) in very unstable conditions and O.G. Sutton (7) suggests a value of 1/100.

From these remarks the following general inferences may be drawn with regard to the effects of stability on the profile:

a. Severe local storms, such as thunderstorms or frontal squalls, are extremely unstable and so the increase of mean velocity with height is very small; the frictional characteristics of the ground surface may have almost negligible effects on the velocity profile.

b. Large-scale mature storms of either tropical or extra-tropical description exhibit nearly neutral stability with no marked tendency for violent thermal interchange; the dominating influence on the velocity profile in these storms is not the stability but the surface roughness.

Surface Roughness.—The important question now arises as to how great an effect surface roughness has on the wind velocity profile in large-scale mature storms which are probably the most important. In comparison with the vast amount written in engineering papers on this general subject, scant attention has been given to this particular question. It appears to be of paramount importance in the accurate evaluation of wind velocities.

It should first be emphasized that what is referred to by the term "surface roughness" is neither the shielding due to individual obstacles nor the orographic effects influencing the airflow in mountain regions, but the cumulative statistical drag effect of many obstructions on the wind. The surface roughness, therefore, is characterized by the density, size, and height of the buildings, trees, vegetation, rocks, etc., on the ground, around, and over which the wind must flow; it will be a minimum over the ocean and a maximum in a large city.

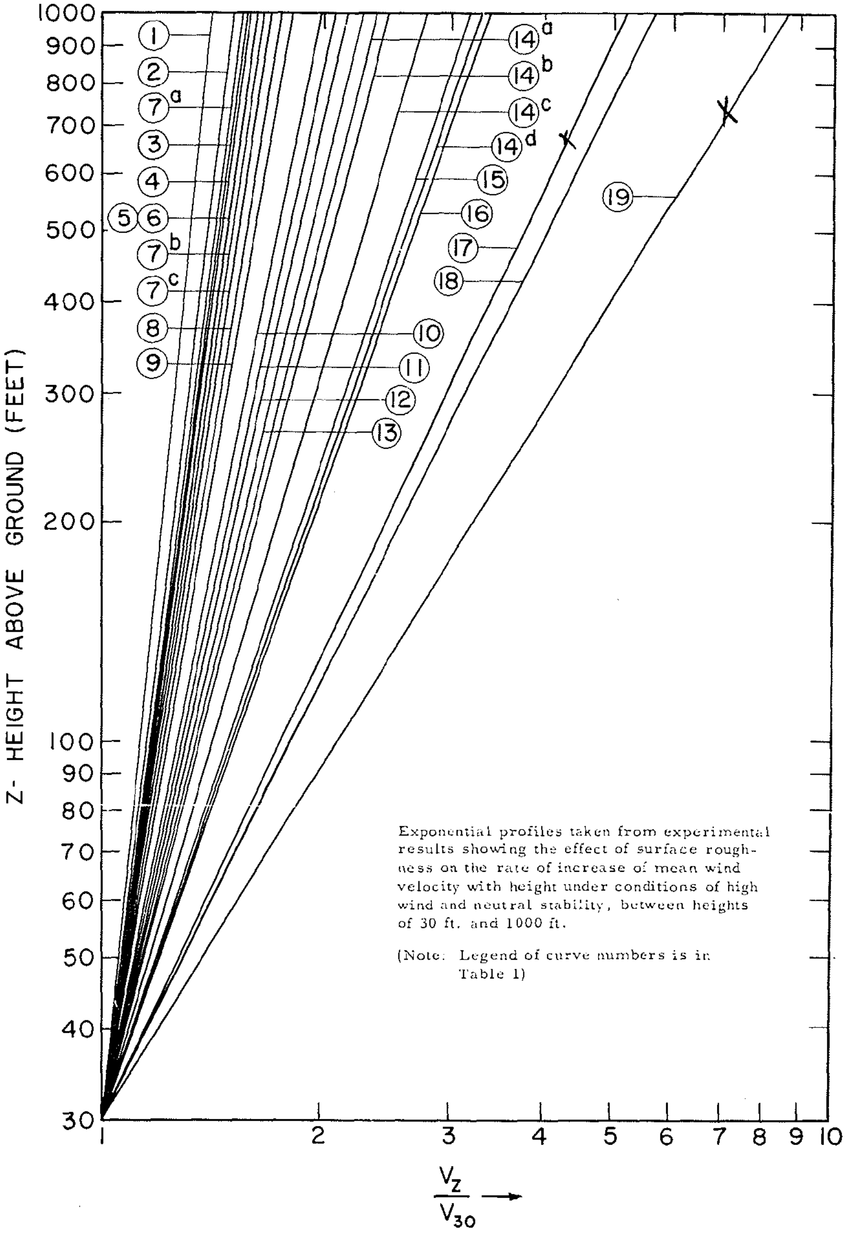
For years the measurement of wind-velocity profiles has been of interest in the fields of meteorology, aviation, agriculture, and wind power as well as in civil engineering. Information has now accumulated from which it is possible to evaluate the influence of the surface roughness on the wind velocity profile.

In Table 1, the exponents $1/\alpha$ corresponding to the accumulated experimental results of a number of observers are shown on a comparative basis and the corresponding power law profiles plotted in Fig. 1. The records from which these exponents and equivalent power-law curves are derived are given in the Appendix. Where the results were not explicitly stated as a power law, it was found that, in each case, a power law could be closely fitted to the records with only small deviations. It should be noted that the records refer specifically to mean velocity profiles prevailing above a height of 30 ft in strong winds, over flat ground surface at lapse rates which, if not explicitly stated, from the nature of the storms studied presumably could not have differed greatly from the adiabatic. The records, therefore, are homogeneous except that the nature of the ground roughness and the aggregate nature of obstructions vary widely, from the smooth surface of the sea to the rough obstructed surface of a large city.

The exponent of the power law increase is seen to vary between 1/10.5 and 1, depending only on the surface roughness characteristics. It is seen that Curves 1 to 9 have exponents lying between 1/10.5 and 1/5.9 and, in each case, the surrounding terrain was characteristically flat and open. The average for the observations taken on land lies close to 1/7 which is a familiar exponent found at the boundaries of pipes and wind tunnels in which mechanical turbulence predominates and the fluid is neutrally stable. The exponents of Curves 12 to 16 lie between 1/5 and 1/2.8 and average 1/3.5. For these curves the terrain corresponded to the rougher characteristics of treed and wooded farmland, towns, scrub trees, etc. Curves 17, 18 and 19 are derived from records obtained in large cities (Copenhagen, Paris and New York) which probably represent conditions of extreme surface roughness; the corresponding exponents are 1/2.1 and 1/1.6. For all the curves (except 10 and 11 which are probably not typical of level country) the value of the exponent is seen to increase in a

TABLE 1.—INFLUENCE OF SURFACE ROUGHNESS ON VALUES OF THE EXPONENT $1/\alpha$ IN THE POWER-LAW VARIATION OF MEAN WIND VELOCITY WITH HEIGHT UNDER CONDITIONS OF STRONG WIND OR ADIABATIC LAPSE RATE BETWEEN HEIGHTS OF 30 FT AND 1,000 FT

Curve No.	Source	Location	Upper Limit of Investigation, in feet	Description of Terrain in Site Locality	$\frac{1}{\alpha}$	Remarks
1	Goptarev	Caspian Sea (off Apsheron Penin.)	166	Coastal waters of inland sea	$\frac{1}{10.5}$	.095
2	Juul	Masnedsund, Denmark	182	Flat shore on "Ocean of Small Islands"	$\frac{1}{8.3}$	.121
3	Scrase	Salisbury Plain, England	43	Open grassland without hedgerows or trees	$\frac{1}{7.7}$	.130
4	Wing	Ballybunion, Ireland	492	Flat treeless grassland, Atlantic Ocean 1/2 mile distant	$\frac{1}{7.4}$	.135
5	Sherlock	Ann Arbor, Michigan, U.S.A.	250	Open slightly rolling farm land	$\frac{1}{7}$	.143
6	Taylor	Salisbury Plain, England	-	Open grassland without hedgerows or trees	$\frac{1}{7}$	.143
7a	Giblett	Cardington, Beds., England	150	Open level agricultural land with only isolated trees	$\frac{1}{7.8}$	.128
7b	Frost	Cardington, Beds., England	350	Same as above	$\frac{1}{5.9}$	.170
7c	Frost	Cardington, Beds., England	1,000	Same as above	$\frac{1}{6.7}$	.149
8	Deacon	Sale, Victoria, Australia	503	Gently rolling grazing land with few trees	$\frac{1}{6.25}$	.160
9	Heywood	Leafield, Oxfordshire, England	313	Open fields divided by low stone walls and hedges	$\frac{1}{5.9}$	.170
10	Kamei	Japan	-	Rough coast	$\frac{1}{5}$	.200 Observations not necessarily typical of level country
11	Wax	Orkney Islands	118	Flat topped grass hill, 1/3 mile inland from high cliff overlooking the sea	$\frac{1}{4.6}$	.218
12	Huss and Portman	Akron, Ohio, U.S.A.	352	Gently rolling country with many bushes and small trees	$\frac{1}{4.55}$	.220
13	Francken-berger and Rudloff	Quickborn, Germany	230	Relatively level meadow land but with numerous hedges and trees around the small fields	$\frac{1}{4.35}$	.230
14a	Smith	Upton, Long Island, N.Y., U.S.A.	410	Level country uniformly covered with scrub oak and pine to a height of 30 ft	$\frac{1}{4}$	.250
14b	Panofsky	Upton, Long Island, N.Y., U.S.A.	410		$\frac{1}{3.85}$	.260 Hurricanes Carol and Edna 1954:
14c	U.S. Weather Bureau	Upton, Long Island, N.Y., U.S.A.	410		$\frac{1}{3.3}$	(fastest 1 min. mean speed) .303
14d	U.S. Weather Bureau	Upton, Long Island, N.Y., U.S.A.	410		$\frac{1}{2.9}$	(fastest 6 min. mean speed) .345
15	Kamei	Japan	-	Three Japanese towns	$\frac{1}{3}$	.333
16	Dines	Farnborough, England	1,650	Wooded and treed farm land	$\frac{1}{2.8}$	.357
17	Jensen	Copenhagen, Denmark	242	Centre of a large city	$\frac{1}{2.2}$	.435
18	Taylor	Paris, (Eiffel Tower)	900	Centre of a large city	$\frac{1}{2}$	.500
19	Rathbun	New York (Empire State Building)	1,263	Centre of a large city	~~$\frac{1}{1.6}$~~ 1/2.6	.625 X



Exponential profiles taken from experimental results showing the effect of surface roughness on the rate of increase of mean wind velocity with height under conditions of high wind and neutral stability, between heights of 30 ft. and 1000 ft.

(Note: Legend of curve numbers is in Table 1)

FIG. 1.—EFFECT OF SURFACE ROUGHNESS ON RATE OF INCREASE OF MEAN VELOCITY WITH HEIGHT

manner which is remarkably consistent with the increase in the roughness of the terrain and the number of obstructions.

Effect of Velocity.—It should be noted that velocity can be expected to have a slight secondary effect on the profile in that the value of the surface friction increases slightly with wind velocity. As a result, the rate of increase of mean wind velocity with height increases slightly with velocity. This is familiar in wind-tunnel work.

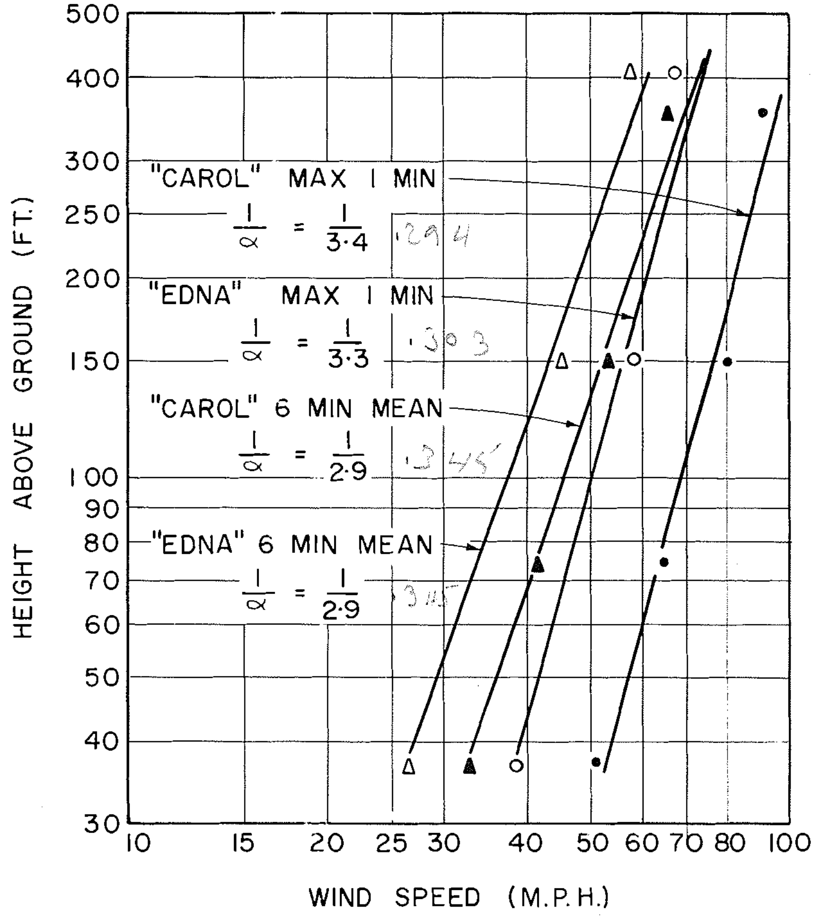


FIG. 2.—OBSERVATIONS OF HURRICANES "CAROL" AND "EDNA" (1954) AT BROOKHAVEN, LONG ISLAND. (TERRAIN: FLAT COUNTRY WITH SCRUB TREES)

Numerical evidence of the indirect influence of the velocity on the velocity-height relationship is furnished by G. F. Collins' investigations of nine storms (30), mainly at Brookhaven Laboratory, Long Island. He found (Fig. 2), by examining the 5-min mean velocities at different elevations up to 410 ft, that the exponent of the power-law profile increased by approximately 0.02 for every 10-mph increase in surface wind velocity; at 50 mph the value being 0.27 (that is, 1/3.7) and the extrapolated value at 80 mph being 0.33 (1/3.0). These profiles, according to Collins, fitted the experimental records extremely well with the value of the standard deviation equalling 1.26 mph. These results, however, indicate that the effect of wind velocity (over the range of maxima encountered) is not nearly as great as that due to the differences in surface roughness.

Bearing in mind the influence of the wind velocity on the rate of increase of wind velocity with height, it is now possible to suggest the following approximate values for power law exponents corresponding to more or less qualitative descriptions of the surface roughness or aggregate nature of the surface obstructions:

Description of the Terrain	Power-Law Exponent	
For open country, flat coastal belts, small islands situated in large bodies of water, prairie grassland, tundra, etc.	1/7	0.143
For wooded countryside, parkland, towns, outskirts of large cities rough coastal belts	1/3.5	0.286
For centers of large cities	1/2.5	0.40

These values 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 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 seems improbable), no increase in velocity with height would seem appropriate.

Records.—If reliable long-term anemometer records were available for all areas exhibiting differing characteristics of surface roughness and incidence to severe storms, the discussion could perhaps be left at this point; a basic wind velocity could be determined for each geographical location based on a statistical analysis of wind records over a period of 40 yr or 50 yr, and then applied to a wind-velocity profile appropriate to the surface roughness of the vicinity. Unfortunately, there are serious obstacles to this approach (certainly, in a sparsely populated country such as Canada) since meteorological records are not always satisfactory enough for the following reasons:

Only a small number of stations in Canada will have records extending back a sufficient number of years. At some locations the anemometer will have been moved several times during the period of record, affecting the exposure and the homogeneity of the records. Severe storms may have blown the anemometer away or rendered it inoperative, thus losing crucial information. The anemometer may also give readings which are not representative of level country due to the siting of the anemometer on or near a building. Hugh L. Dryden and George C. Hill, for example, suggest that the well-exposed anemometer on top of the Empire State Building, situated more than 200 ft above the roof, reads 23% higher than the approaching flow, due to the presence of the building (31). If, at airports, anemometers were raised high enough to be free from the influence of the buildings they would present a hazard to aircraft. In winter, the period of worst storms, Dines anemometers sometimes clog with blowing snow. Ice accretions sometimes form on cup anemometers. Anemometer readings taken in mountains, in valleys, and on coastal cliffs are subject to orographic effects sometimes resulting in noticeably higher velocities.

All of these considerations add emphasis to Sherlock's (32) recommendation, shared by many others, that design velocities should be based "on a statistical analysis of wind records over a period of 40 to 50 years." Also the results obtained from the records of one station should be related to those from other neighboring stations by a suitable statistical method. Only in this way can spurious and systematic errors arising in the records of an individual station be minimized.

The next step, therefore, is to explore a suitable method whereby the accumulated records of all meteorological wind records might be correlated. Since it is not desirable to restrict the admissible records to those obtained from anemometers situated in "open level country" (this, in certain regions of Canada, for example, would decimate the available records), it is first necessary to investigate more fully the effects of surface roughness on the velocities measured near the surface over level ground.

It has already been noted that there is some height at which the influence of the ground friction transmitted upwards through eddy viscosity, has a negligible effect on the velocity of the wind as it responds to the pressure gradient. If the velocity at this height is denoted by V_G (the gradient velocity), and the height at which this velocity is first attained by z_G, then by reference to the power-law increase of velocity with height

$$V_z = V_G \left(\frac{1}{z_G}\right)^{1/\alpha} z^{1/\alpha} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

In order to determine the ratio of the velocity at height z above the ground to the gradient velocity, it is first necessary to determine values of z_G corresponding to the various surface roughness categories already discussed. An attempt is now made to do this on the basis of the pertinent experimental records that are available.

Examination of Sherlock's (16) investigations at Ann Arbor, Mich., indicates that for these conditions of flat open country, the value of z_G (the height at which the gradient velocity is first attained) is of the order of 900 ft. This value agrees reasonably well with that obtained by Taylor, at Salisbury Plain, (discussed by W. W. Pagon (17)) for similar terrain in which average values of z_G for strong winds were 1,250 ft in summer and 885 ft in winter. An approximate value of 900 ft, therefore, is chosen for the value of z_G in flat open country.

In large cities, Pagon (17), citing Taylor's studies at the Eiffel Tower in Paris, suggests a value of z_G for strong winds in a large city of 2,020 ft in summer and 1,420 ft in winter. An approximate average value of 1,700 ft is adopted for the present. The value of 1,300 ft is chosen for the intermediate conditions of rough wooded country. These values of z_G of 900 ft, 1,300 ft, and 1,700 ft (together with the appropriate exponents), corresponding to the three types of roughness conditions, give the three curves of Fig. 3.

It is not suggested at this stage that these curves are highly accurate. Indeed, the qualitative aspects of the problem do not permit great accuracy. It should be noted that in these curves the values of $1/\alpha$ are founded on a relatively greater amount of information than are the values of z_G; the errors involved in the latter, however, (which may differ by 200 ft) are of less consequence.

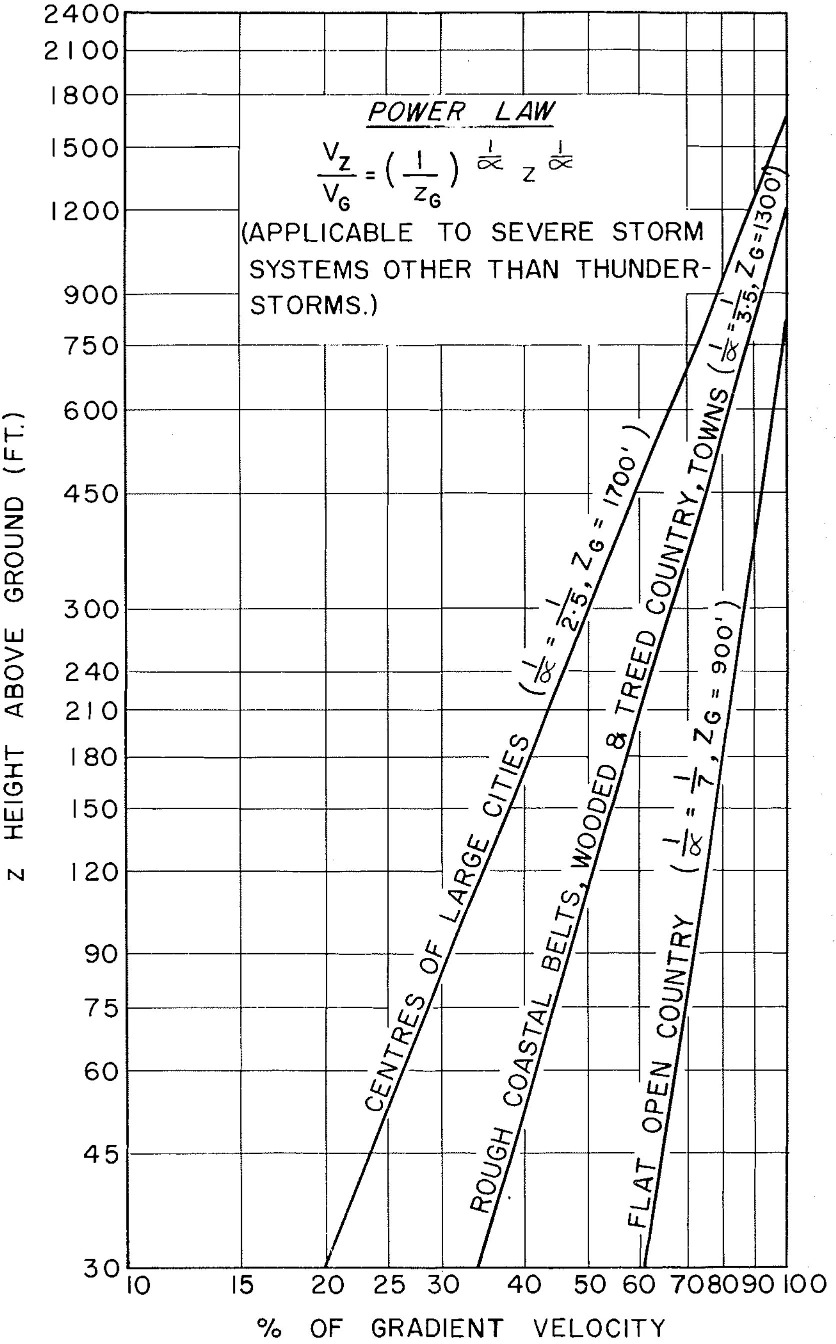


FIG. 3.—INCREASE OF VELOCITY WITH HEIGHT OVER LEVEL GROUND FOR THREE DIFFERENT TYPES OF SURFACE ROUGHNESS ACCORDING TO THE POWER LAW

Some confirmation of the rough accuracy of these curves is afforded by the comparison of the surface velocities over terrain of different surface roughnesses. In their study of the climate of Central Canada, W. G. Kendrew and D. Currie (33) observe that "the mean (annual wind speed in the prairies is between 12 and 16 mph. The speed is appreciably less in parklands with means of 9-12 mph and, again, less in forests 5-9 mph; the increased friction among the trees is the main cause." These reductions in wind velocity, compared to the archetypal flat open country of the prairies, are entirely compatible with those suggested by Fig. 3.

A comparison of mean wind speed in nine Canadian cities (34) and at airports on their outskirts indicates that the speed in the city is 65% of that near the outskirts (the value suggested by Fig. 3 is 59%). Elevation, shielding, and siting of the anemometers and periods of observation vary in every case, but the trend is obvious. A study of hurricane winds at Lake Okeechobee, Florida, by the U.S. Corps of Engineers (35), indicated that the wind off the land (everglades, covered with scrub cypress, etc.) averaged 60% of the wind over water when the latter was 50 mph, and 74% when the latter was 80 mph.

H. Ferrington (36), discussing the wind velocities found in Great Britain (in general terms, a terrain characterized by treed, rolling country and straggling urban areas), has made the following interesting note:

> "On one occasion when the whole of the British Isles was covered with parallel isobars running nearly west to east, all stations on the western side gave the wind as force 8 (42 mph) while those on the eastern side gave force 5 (21 mph) so that the velocity was reduced by one-half in consequence of the "friction" of the land. If the velocity at the exposed western stations be taken at two-thirds the velocity of the wind free from friction, we get the following interesting result which is probably correct enough for practical use; one-third of the velocity is lost by the sea friction on the western side, and one-third more by the land friction of the country between west and east."

In a series of measurements made at Valentia, N. Ireland, L. H. G. Dines (37) found that for this locality (flat open lowlands verging on the sea) the ratio of the surface wind to the gradient wind for 27 occasions on which the surface wind exceeded 15 m per sec, (34 mph) was 0.58. S. P. Wing (15) at a similar locality found an identical value for all directions taken together.

N. Carruthers (38), quoting an unpublished note by C. E. P. Brooks, gives the following values for the ratio of the wind velocity at 10 m (33 ft) above ground to the gradient wind W/G:

Exposure	W/G, in %
Open sea	60
Low islands	55
Windward coasts and neighboring lowland	50
Leeward coasts, neighboring lowland and sea	40
Open land, unsheltered	40
Sheltered land and townsites	30

All these values are again remarkably close to the values suggested by Fig. 3.

Design Velocities.—It is now possible to return to the problem of determining design velocities appropriate to different geographical regions. The prediction of probabilities and return periods of extreme wind velocities has been suggested many times. In 1932, S. P. Wing (39) used the normal distribution curve to obtain the distribution curves for extreme wind velocities in several large American cities. More recently, Arne L. Johnson (40) has remarked that this type of distribution "gives a significant deviation from observed values." Since the date of Wing's correspondence, the extreme-value distribution (due largely to E. J. Gumbel (41)) has been developed. Johnson, who analyzed the anemometer records for both extreme indicated gusts and hourly mileages at thirteen stations in Sweden and six in the British Isles, states that "the results obtained do not contradict the assumption that the distribution of extreme values of type No. 1 is in close agreement with the distribution of the actual wind velocities," (p. 119 (40)). Arnold Court (42) analyzed the records of twenty five weather stations in the United States, having 37 yr of satisfactory records, according to the same theory and states "all of the wind data seems to follow the theory."

This distribution function takes the form (41)

$$\phi(x) = e^{-e^{-y}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

The reduced variate

$$y = a(x - u) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where a is the scale factor and u the mode of the extreme value data.

Suppose that all anemometer records are analyzed to obtain the parameters a and u (in terms of which the return period of extreme surface velocities can be completely determined according to the extreme value theory). Then, an estimate of the distribution of extreme gradient velocities at this location is given by the parameters 1/k, a, and k_u where k is a "roughness coefficient" defined by

$$k = \left(\frac{z_G}{z_A}\right)^{1/\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

z_A being the height of the anemometer and z_G and $1/\alpha$ being given approximately by Fig. 3.

The object now is to try to correlate these estimates of the gradient velocities in order to reduce the systematic errors which may have occurred in the anemometer records, to improve the estimate of extreme-wind velocities occurring at stations with shorter periods of records, and to minimize the subjective elements involved in the determination of design-wind velocities.

Suppose that anemometer n situated at latitude ϕ_n and longitude λ_n possesses records extending back a period of N_n yr which, by extreme-value analysis, yields values for the scale factor and mode of a_n and u_n. Suppose that the best estimate of the "roughness factor" is k_n, then the corresponding values of scale factor and modal value referring to the gradient velocity at this point are $1/k_n$; $a_n = a'_n$ and $k_n u_n = u'_n$.

It is now assumed that these parameters follow some m^th^ degree contour surface (where m is less than the total number of records being analyzed) of the forms

$$a' = \sum_{j=0}^{m} \sum_{i=0}^{j} A_{ij} \lambda^i \phi^{j-i} \quad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

and

$$u' = \sum_{j=0}^{m} \sum_{i=0}^{j} B_{ij} \lambda^i \phi^{j-i} \dots\dots\dots\dots\dots \quad (8)$$

The values of the coefficients A_{ij} and B_{ij} are now obtained by fitting the observed values to these surfaces by the method of least squares. This problem is one well suited to electronic computation. In fitting the values, it would be appropriate to weight them first, by the factor $\sqrt{N_n}$ which puts more reliance on the records of longer period and, second, by a factor Q determined unavoidably, by a subjective evaluation of the quality of the records, with regard to the siting of the anemometer, the number of times it has been moved, and the possible amplification effects of mountains, valleys, etc. For example, a first-class weather station, where the anemometer is situated on level ground away from shielding and has not been moved, might be given a weighting of 9 or 10 (out of a possible 10), whereas an anemometer situated close to the roof of a building, in a shielded area or in a valley, might be weighted by a factor of only 1 or 2. The least-squares process minimizes the errors in a' and u' due to the many causes cited, on the assumption that the weighted errors are normally distributed.

This process leads directly to the contours of a' and u' for the territory considered. If it is now desired to erect a structure at a certain location to last a period of T yr ($T > 10$) with a risk of q that the basic design wind velocity V will be exceeded within this time, the return period R of this wind velocity V is given by

$$R = \frac{-T}{\log_e (1 - q)} \approx \frac{T}{q} \quad \text{if q is small} \dots\dots\dots\dots \quad (9)$$

This represents a probability of 1/R. By extreme value theory, the value of the required gradient velocity

$$V_G = \frac{1}{a'} \left\{ - \log_e \left[- \log_e \left(1 - \frac{1}{R}\right)\right]\right\} + u' \dots\dots\dots\dots (10)$$

where a' and u' are determined from the contours.

The values of the velocity nearer the surface corresponding to this gradient velocity are determined from Fig. 3 according to the appropriate roughness conditions.

If the structure is to be erected on a hill or in a valley, a suitable amplification factor should be used. Examples of these are given by Pagon (17) and P. C. Putnam (43). The only way to determine this will often be by actual observation of wind velocities at the site for a short period and then comparing their value with those at a nearby anemometer on level terrain.

In this way, it becomes possible to relate the "basic design wind velocity" for each structure to the roughness characteristics of the ground surrounding it, the anticipated span of the structures useful life, and the risks consequent on the design wind velocity being exceeded. Any system which does not take into account the wide variation in those factors which are to be encountered obviously does not permit either a full measure of safety or economy to be effected.

Extreme Wind Speeds Over the British Isles.—To study their practicality, the method and procedures described were applied to some extreme value data obtained by H. C. Shellard (Table 3). Of the forty eight stations whose anemograph records have been analyzed by Shellard, only those described in "The Gazetteer of British Meteorological Stations," (H.M.S.O., London, 1931), are referred to here since the essential site descriptions of the other stations are not available in published form and, in any case, consist largely of those stations with only short periods of record.

Values of U and 1/a were calculated from Shellard's values for the 'once in ten years' and 'once in a hundred years' extreme wind speeds and these are recorded in Table 3. These values were also checked against Shellard's original computation sheets, with his kind permission.

TABLE 2.—TYPES OF TERRAIN GROUPED ACCORDING TO THEIR AERODYNAMIC ROUGHNESS

Category	Description	$\frac{1}{\alpha}$	z_G
1	Very smooth surfaces: e.g. large expanses of open water; low unsheltered islands; tidal flats; lowlands verging on the sea	$\frac{1}{8.5}$	800
2	Level surfaces with only low, surface obstructions: e.g. prairie grassland; desert; arctic tundra	$\frac{1}{7.5}$	900
3	Level, or slightly rolling surfaces, with slightly larger surface obstructions: e.g. farmland with very scattered trees and buildings, without hedgerows or other barriers; wasteland with low brush or surface vegetation; moorland	$\frac{1}{6.5}$	1,000
4	Gently rolling, or level country with low obstructions and barriers: e.g. open fields with walls and hedges scattered trees and buildings	$\frac{1}{5.5}$	1,100
5	Rolling or level surface broken by more numerous obstructions of various sizes: e.g. farmland, with small fields and dense hedges or barriers; scattered windbreaks of trees, scattered two-story buildings	$\frac{1}{4.5}$	1,200
6	Rolling or level surface, uniformly covered with numerous large obstructions: e.g. forest, scrub trees, parkland	$\frac{1}{3.5}$	1,350
7	Very broken surface with large obstructions: e.g. towns; suburbs; outskirts of large cities; farmland with numerous woods and copses and large windbreaks of tall trees	$\frac{1}{3}$	1,500
8	Surface broken by extremely large obstructions: e.g. center of large city	$\frac{1}{2.5}$ - $\frac{1}{1.5}$	1,800

The roughness category of each station was assessed by comparing the photographs and descriptions of the anemometer stations given in the "Gazetteer" (op. cit.) with the descriptions given in Table 2. (These roughness categories for each station are given in Table 3). Knowing the roughness category and the height of the anemometer (z_A) the roughness factor (k_A) was found from Fig. 4, and recorded in Table 3. The anemometer height given in Table 3

TABLE 3.—ANALYSIS OF EXTREME MEAN HOURLY WIND SPEEDS OVER THE BRITISH ISLES[a]

Stations[b]	Lat. -N °	'	Long. ° '	Category	z_A (ft)	k_A	$\frac{1}{a}$	U (mph)	Established gradient with $k_A \times \frac{1}{a}$	Established gradient with $k_A \times U$ (mph)	Q	N	Wt. $\alpha Q\sqrt{N}$
Larwick	60	09	1 08W	2	39	1.65	5.30	56.4	8.75	93.1	7	24	3
Stornoway	58	11	6 21W	2	40	1.60	6.00	54.2	9.60	86.4	9	18	4
Tiree	56	32	6 55W	2	42	1.60	6.52	50.1	10.40	80.2	12	28	6
Aberdeen	57	10	2 06W	6	41	2.75	4.69	32.9	12.90	91.0	9	15	3
Eskdalemuir	55	19	3 12W	4	35	1.88	3.97	45.5	7.50	85.6	9	32	5
Aldergrove	54	39	6 13W	4	42	2.05	3.79	38.5	7.77	78.9	10	25	5
Pt. of Ayre	54	25	4 22W	1	40	1.50	5.21	47.7	7.82	71.6	11	19	5
Holyhead	53	19	4 37W	2	38	1.60	5.28	49.4	8.45	79.0	8	19	4
Southport	53	38	3 00W	2	33	1.65	5.02	48.3	8.28	79.7	12	42	8
Sealand	53	13	3 00W	4	42	1.80	4.41	40.8	7.94	73.4	10	19	4
Catterick	54	22	1 37W	4	33	1.90	6.80	35.4	12.92	67.3	10	10	3
Spurnhead	53	35	0 07E	1	34	1.55	3.58	48.5	5.24	75.2	13	29	7
Cranwell	53	02	0 30W	3	33	1.68	4.78	38.5	8.05	64.7	12	23	6
Birmingham	52	29	1 56W	7	118	2.40	4.06	34.2	9.75	82.0	10	31	6
Cardington	52	07	0 25W	3	135	1.40	6.06	42.9	8.48	60.1	12	23	6
Gorleston	52	35	1 43E	3	34	1.60	3.77	42.1	6.03	67.4	9	36	5
Felixstowe	51	37	1 20E	4	40	1.70	4.10	41.9	6.97	71.2	9	17	3
Shoeburyness	51	32	0 49E	4	89	1.57	4.49	44.9	7.05	70.5	10	29	5
Manston	51	21	1 21E	5	46	2.00	3.70	39.9	7.40	79.8	13	12	5
Kew Obs'vty	51	28	0 19W	8	75	2.75	2.42	29.7	6.65	81.7	7	24	3
Croydon	51	21	0 07W	7	105	2.15	4.26	37.4	9.16	80.5	9	23	4
Lympne	51	05	1 01E	4	48	1.75	3.72	42.7	6.51	74.7	10	27	5
Boscombe Down	51	10	1 45W	4	33	1.90	3.74	39.4	7.10	74.9	10	22	5
Calshot	50	49	1 18W	2	42	1.60	4.55	42.3	7.28	67.7	10	24	5
St. Ann's Hd.	51	41	5 11W	1	70	1.40	9.51	57.8	13.31	80.9	8	14	3
Scilly	49	56	6 18W	1	57	1.45	5.92	55.2	8.58	80.0	12	28	7
Lizard	49	57	5 12W	2	60	1.50	5.13	53.0	7.70	79.5	8	17	4
Pendennis	50	09	5 03W	3	42	1.65	4.30	58.2	7.10	96.0	7	20	3
Plymouth	50	22	4 08W	2	65	1.55	5.22	48.4	8.09	75.0	7	30	4

[a] Shellard, H. C., "Extreme Wind Speeds over Great Britain and Northern Ireland." Meteorological Magazine, vol. 87, Sept. 1958, pp. 257-265. [b] Stations are grouped according to general geographic locality.

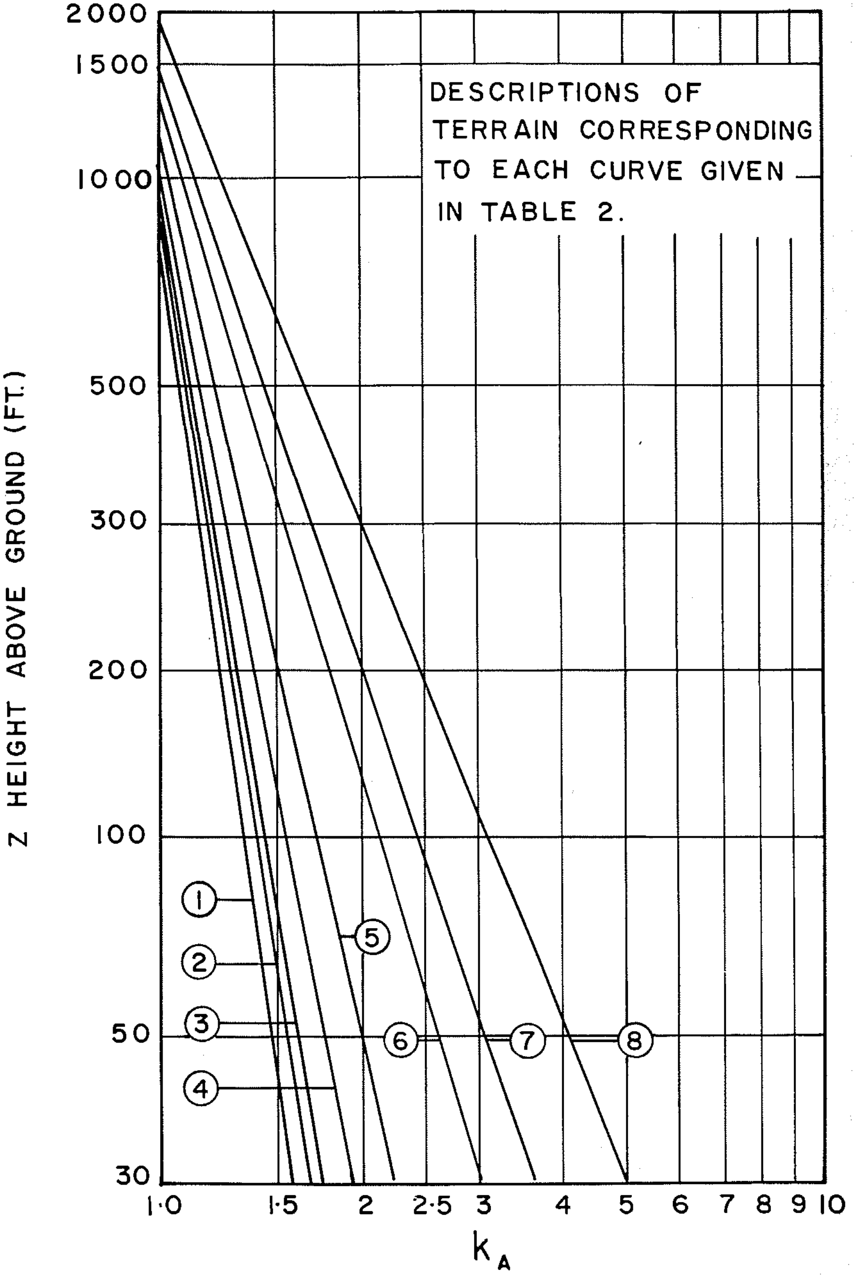


FIG. 4.—ROUGHNESS FACTORS (k_A) FOR DETERMINING THE RATIO OF GRADIENT TO SURFACE WIND SPEEDS OVER DIFFERENT TYPES OF TERRAIN

is either the so-called 'effective height' of the anemometer or the actual height given in the "Gazetteer;" in some cases, owing to poor exposure, neither height is entirely satisfactory.

From the same descriptions given in the Gazetteer, a Q-factor was determined for the anemometer site, based upon an assessment of the absence (or presence) of (a) possible orographic influences, (b) buildings and other local shielding and amplifying influences, and (c) the uniformity of the roughness for different wind fetches (particularly in a generally westerly direction, the direction of prevailing winds). Unfortunately, it was not possible to assess another important influence on the records, namely, the number of times the anometer had been moved during the period of record.

These values of Q (assessed out of a possible total of fifteen) were multiplied by the square root of the number of years of record ($\sqrt{N}$), and a 'weight' proportional to this product (in round numbers) is recorded in Table 3. On this basis, stations with higher weights were judged to be more reliable than those with relatively lower weights. It was found that estimates of U and 1/a deviating substantially from the average can always be associated with unsatisfactory anemometer exposures (such as cliff or hill-top sites), partially shielded sites, or stations with only short period records; consequently, weights are low. The large proportion of coastal and urban sites indicates that, in many cases, the exposure leaves much to be desired.

In order not to bias the results, assessments of the roughness category and Q-factor were made, as far as possible, without reference to the already determined values of 1/a and U. In a more detailed analysis, reference to mean annual wind speeds and direction rosettes would, perhaps, assist in assessing roughness categories and in revealing any anomalous directional properties of the surface winds.

The estimated values of 1/a and U for the gradient wind, obtained from the roughness factor and the surface values of these parameters are recorded in Table 3 and are summarized graphically in Fig. 5.

Also shown in Fig. 5 are contours of U and 1/a; these are drawn by eye and are based on the assumption that the average properties of the gradient wind field are not subject to wide variation over an area the size of the British Isles.

The map shown in Fig. 5 might form the basis for determining design wind velocities.

Illustrative Example.—If, for example, it is desired to erect a structure at some locality on the (U = 80 mph; 1/a = 8.0 mph) contour to have an anticipated lifetime T = 10 yr with a risk q = 10% that the design wind velocity is exceeded during this period, then the required return period for this design wind speed is $R = \frac{T}{q} = \frac{10}{0.1} = 100$ yr. The 'design gradient wind velocity' (V_G) is then given by

$$V_G = U + \frac{1}{a}\left\{-\log_e\left[-\log_e\left(1-\frac{1}{R}\right)\right]\right\} \qquad (11)$$

$$= 80 + 8.0 \times 4.6$$
$$= 117 \text{ mph}$$

This, in fact, gives the extreme mean hourly velocity for the gradient wind. Recent unpublished information indicates that the mean minute wind velocity

LEGEND: 90: 9·0 ⑥ LOCATION OF STATION SHOWN BY CIRCLE.
U : 1/a WEIGHT UNITS – MILES PER HOUR.

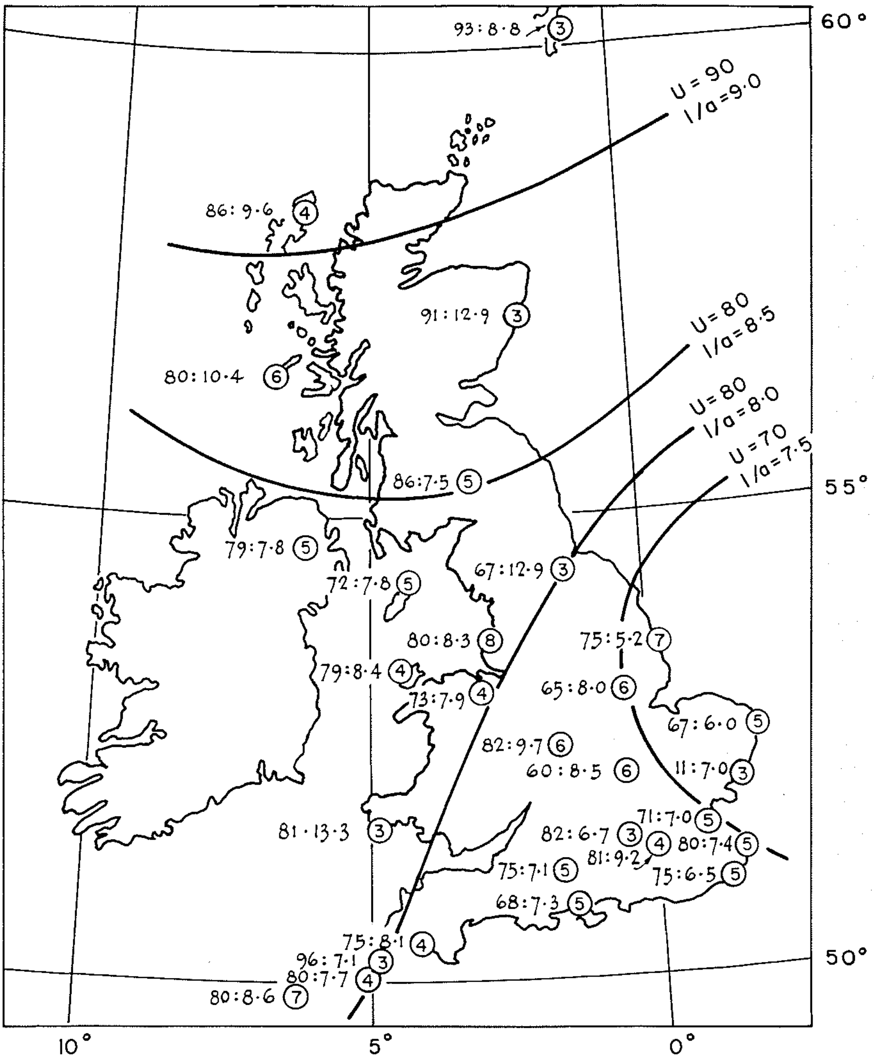


FIG. 5.—PARAMETERS OF EXTREME MEAN HOURLY GRADIENT WIND SPEED OVER THE BRITISH ISLES

(advocated in this report) is on the average 25% greater than this and so the extreme 'mean minute' speed is 117 x 1.25 = 146 mph.

If, now, the structure is to be erected in a town, for which (from Table 3) z_G is 1,500 ft and $1/\alpha = 1/3$, the design wind velocity at height z (ft) is given by

$$V_z = 146 \left[\frac{z}{1,500}\right]^{1/3} \qquad \text{.............. (12)}$$

and $V_{100} = 59$ mph.

For open country without obstructions the expression would be

$$V_z = 146 \left(\frac{z}{900}\right)^{\frac{1}{7}} \qquad \text{.............. (13)}$$

and $V_{100} = 106$ mph.

Finally, if the structure is to be erected in the center of a large city, the design wind velocity would be given by

$$V_z = 146 \left(\frac{z}{1,800}\right)^{1/2.5} \qquad \text{.............. (14)}$$

and $V_{100} = 46$ mph.

The further difficult and largely unresolved problems of assessing the marked influence of the wind velocity profile on the pressure distribution, and of determining what dynamic amplification may arise due to the unsteady flow of gusts, lie outside the province of this paper which has attempted merely to discuss the derivation of a basic design mean velocity to which, it is felt, these other factors can then be related.

ACKNOWLEDGMENTS

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APPENDIX II.—RECORDS OF WIND VELOCITY PROFILES

*1. GOPTAREV'S OBSERVATIONS

Location: Caspian Sea off Apsheron Peninsula
Terrain: Coastal waters of inland sea
Reference: 12

These observations taken at the site of offshore oil wells include many measurements of very strong winds. The average values for twenty seven occasions when the mean wind velocity (for 10 min) at 5.7 m (19 ft) above the sea exceeded 15 m per sec (approximately 34 mph) were as follows:

Height		Velocity	
meters	feet	m per sec	mph
5.7	19	16.80	37.8
15	50	19.30	43.3
27.3	91	20.07	45.2
50.6	168	20.57	46.5

2. JUUL'S OBSERVATIONS

Location: Masnedsund, Denmark
Terrain: Flat level coast of "ocean of small islands" (off sea wind)
Reference: 13

Height		Velocity	
meters	feet	m per sec	mph
5	16.5	14.2	32
15	49.5	16.5	37
35	115.5	17.2	39
55	182.0	18.8	42

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* Numbers refer to those given in Fig. 1 and Table 1.

3. SCRASE'S OBSERVATIONS

Location: Salisbury Plain
Terrain: Open grass-covered plain
Reference: 14

Reported profile in adiabatic conditions given by power law with exponent of 0.13 (1/7.7). Wind measurements were made between heights of 3 m and 13 m (approximately 10 ft and 43 ft).

4. WING'S OBSERVATIONS

Location: Ballybunion, Ireland
Terrain: Low level plain. Atlantic Ocean $\frac{1}{2}$-mile beyond low level sand dunes.
Reference: 15

Height		Velocity	
meters	feet	m per sec	mph
4.5	15	10.7	24
92	300	14.3	32
149	492	15.6	35

(These records refer to curve '1' of Fig. 8 of Wing's paper "which is a curve which most of the high winds there very nearly approach," (p. 9, (15)).

5. SHERLOCK'S OBSERVATIONS

Location: Ann Arbor, Mich.
Terrain: Open farmland
Reference: 16

Fastest 1 min mean velocities

Height		Velocity	
meters	feet	m per sec	mph
15	50	19.9	44.5*
23	75	20.1	45 *
30	100	20.3	45.5*
38	125	21.0	47
46	150	21.2	47.5
53	175	21.7	48.5
61	200	21.7	48.5
76	250	24.1	54

6,18 TAYLOR'S OBSERVATIONS

These records were taken from Pagon's paper (17) in which Taylor's records are summarized in terms of the following Ekman spiral parameters.

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* These values may be slightly higher than would otherwise be obtained because measurements were made near the brow of a slight rise.

	Cities	Open Country
θ	45^0	20^0
z_G (ft) summer	2020	1250
winter	1420	885

where θ = angle between directions of surface and gradient winds
z_G = height at which gradient velocity is first attained.

Taylor's experiments were conducted at Salisbury Plain and at the Eiffel Tower.

The Ekman spirals specified by the above parameters correspond closely with power laws with exponents of $\frac{1}{2}$ and 1/7 (for "cities" and "open country" respectively).

7a. GIBLETT'S OBSERVATIONS

Location: Cardington, England
Terrain: Large flat open airfield
Reference: 2

The ratio of wind velocities recorded by an anemometer at 150 ft to those at 50 ft under neutrally stable conditions and wind velocities in excess of 20 mph, was found to be 1.14 which corresponds to a power law increase with an exponent of 1/7.8.

N. B. Frost (18) has drawn attention to possible differences in exposure of the two anemometers used in this investigation which may account for the slight discrepancy between Giblett's results and Frost's.

7b, c. FROST'S OBSERVATIONS

Location: Cardington, England
Terrain: Flat open airfield

These were obtained from Sutton (19) (see also 18) who states:

> "Layers 5 - 400 ft and 4 - 1,000 ft have been investigated by R. Frost using instruments suspended from a captive balloon over the airfield at Cardington, Southern England. His results indicate that in these layers the profile can be represented by power laws in all conditions of temperature gradient. From a further examination of extended profiles from 4 - 1,000 ft, Frost concludes that the value of $\frac{1}{\alpha}$ (the power law exponent) in conditions of adiabatic lapse rate is .149 (1/6.7) which is very close to the value 1/7 (.142) occurring in the generally accepted power-law profile for the turbulent boundary layer of a flat plate in a wind tunnel."

In the experiments between the heights 4 ft and 400 ft (18), the average wind velocities from fifty seven separate observations for which the lapse rate was approximately adiabatic were as follows:

Height		Velocity	
meters	feet	m per sec	mph
1	4	3.57	7.98
9	30	5.02	11.26
24	80	6.04	13.51
46	150	6.60	14.79
107	350	7.70	17.23

(Corresponding exponent = $0.17 = \frac{1}{5.9}$)

8. DEACON'S OBSERVATIONS

Location: Sale, Victoria, Australia
Terrain: Gently rolling grazing land with very few trees
Reference: 20

Thirty-one successful observations were made of wind velocities greater than 20 mph at 40 ft and averaging 27.6 mph and the ratio of the velocities at different heights found to average at the following values:

Height		
meters	feet	$U_z/\overline{U}_{40}$
12	40	1
64	210	1.272
153	503	1.540

9. HEYWOOD'S OBSERVATIONS

Location: Leafield, Oxfordshire
Terrain: Open fields divided by low stone walls and hedges
Reference: 21 (and 20)

Deacon (20) states "In Heywood's Table 7 there are 38 observations with approximately adiabatic lapse rate and wind speed at 95 m (312 ft) greater than 8.5 m/sec (279 ft/sec) and these give a mean ratio $\overline{U}_{95}/\overline{U}_{12.7} = 1.40$."

10, 15. KAMEI'S OBSERVATIONS

These were obtained from the study of wind velocity profiles in three Japanese towns and, also, along the coast and represent summarized results (22).

The power law exponents suggested by these studies were

1/3 in towns and
1/5 at the coast.

11. WAX'S OBSERVATIONS

Location: Costa Hill, Orkney Islands
Terrain: Rough coast, flat-topped hill, 1/3 mile inland from high cliff overlooking sea
Reference: 23

Height		Velocity	
meters	feet	m per sec	mph (100-sec mean)
17.7	58	19.5	43.7
26.8	88	20.9	46.8*
36.0	118	22.6	50.7

12. HUSS AND PORTMAN'S OBSERVATIONS

Location:	Akron, Ohio, U. S. A.
Terrain:	Gently rolling country with many bushes and small trees
Reference:	24 (and 20)

Deacon (20) states that "These authors evaluated $1/\alpha$ by least squares from 5 min mean velocities at 6 heights between 12 m and 107 m (39 ft and 350 ft). The 40 values for wind speeds greater than 9 m per sec (29.5 fps) at 50 m (164 ft) give a mean α = .219 with a standard deviation of the individual values of 0.042."

13. FRANCKENBERGER AND RUDLOFF'S OBSERVATIONS

Location:	Quickborn (near Hamburg), Germany
Terrain:	Level meadowland with numerous hedges and trees around the small fields
Reference:	25 (and 20)

Deacon (20) states that the mean of twenty one observations of mean wind speeds at 70 m (230 ft) greater than 15 m per sec (49.2 fps) gives the following

Height		
meters	feet	$\overline{U}_z/\overline{U}_{10}$
10	33	1
30	99	1.285
70	230	1.508

14a. SMITH'S OBSERVATIONS

Location:	Brookhaven, Upton, Long Island, U. S. A.
Terrain:	Level country uniformly covered with scrub oak and pine
Reference:	26

Reported average exponent for thirteen winter storms was 0.25.

14b. PANOFSKY'S OBSERVATIONS

Location:	Brookhaven, Upton, Long Island, U. S. A.
Terrain:	Level country uniformly covered with scrub oak and pine
Reference:	28 (and 20)

Deacon (20) gives the following velocity ratios for conditions of wind at 91 m (298 ft) greater than 9 m per sec (29.5 fps).

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* Average of two simultaneous readings of 46.1 and 47.5 mph.

Height		
meters	feet	$\overline{U}_z/\overline{U}_{10m}$
11	36	1.02
45	147	1.47
91	298	1.81
125	410	1.91

14c, d. U. S. WEATHER BUREAU OBSERVATIONS

Location: Brookhaven, Upton, Long Island, U. S. A.
Terrain: Level country uniformly covered with scrub oak and pine
Reference: 27

Records taken during hurricanes Edna and Carol (1954) are shown in Fig. 2.

16. DINES' OBSERVATIONS

Location: Royal Aircraft Establishment, Farnborough, England
Terrain: Treed and wooded farmland and fields
Reference: 29

Height		Velocity*	
meters	feet	m per sec	mph
50	165	7.2	16.2
100	330	8.9	20.0
150	495	10.4	23.4
200	660	11.4	25.6
250	825	12.2	27.4
300	990	12.9	29.0
400	1320	14.5	32.6
500	1650	15.6	35.1

17. JENSEN'S OBSERVATIONS

Location: Copenhagen, Denmark
Terrain: Center of a large city
Reference: 44

In Jensen's Fig. 1, the following observations are recorded.

Height z		$\frac{\text{Velocity at height z m}}{\text{Velocity at 100 m}}$
meters	feet	
34	111	.68
50	164	.75
74	242	.91

$\alpha \sim 0.38$

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* Measured by balloons and theodolites: average of 25 experiments in which velocities > 10 m per sec.

19. RATHBUN'S OBSERVATIONS

Location: Center of New York City
Terrain: Heavily built up city
Reference: 4

Velocities for the storm of March 22, 1936 (the most severe recorded) were as follows:

	Height		Velocity	
	meters	feet	m per sec	mph
N. Y. City Met. Obs.	18.9	62	12.5	28
U. S. Weather Bureau	138	454	25.9	58
Empire State Building	385	1263	40.2	90

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