Estimating Wind Loads on Glasshouses

R. A. Aldrich, D. A. Wells
MEMBER
ASAE

ABSTRACT

THE structural design of glasshouses must provide for safety from wind damage while permitting maximum light transmission to the crop. A literature review of codes of practice, recommendations and data concerning wind loads on buildings showed several different procedures for describing the wind speed near the ground and predicting design pressures on low profile buildings.

INTRODUCTION

The investment in a glasshouse structure can exceed $69,000 per acre. Additional capital is required for environmental control and production equipment needed for the planned cropping program. This investment requires reasonable assurance that the enterprises operating within the structures will produce an acceptable financial return. Light is a limiting factor in crop growth. Thus, opaque framing members should be of minimum size, consistent with providing adequate strength to resist anticipated loads over the expected life of the structure.

The wind forces to which glasshouses are exposed are at present poorly defined. In most countries glasshouses are designed with reference to a compromise code of recommended minimum standards which combine code of practice wind loading with experience in glasshouse construction. This design procedure has limitations in that most minimum standards are based on wind speeds at a 10 m height, and construction experience is difficult to quantify. Glasshouses are low profile buildings with the winds moving over them being affected by adjacent topography and ground cover. A rational design procedure needs realistic estimates of wind loads in order to produce structurally sound and economically useful glasshouses.

PRESENT CODES OF PRACTICE AND RECOMMENDATIONS

The many codes of practice and design recommendations present widely differing ways of determining wind loads on structures. The Minimum Standards for Glasshouse Construction—Loading STL 106 (ref. 13) gives a basic wind speed from which the design speed is obtained through the proper selection of factors related to topography, building life, and a combination of ground roughness and building size. Pressure coefficients are then applied to the design wind speed to estimate the force acting on any given building surface.

In the USA the National Greenhouse Manufacturer's Association (ref. 8) recommends pressure coefficients for walls and roof and leaves the selection of a design wind speed to the discretion of the designer. An isopleth map of the USA is given to assist the designer in selecting a basic wind speed.

There are other codes and recommendations that apply to low profile buildings in general. For example, the American Society of Agricultural Engineers (ref. 1) gives pressure coefficients that are used with data from isopleth maps of wind speeds at 25 and 50 yr recurrence intervals. No adjustments for topography and ground cover are suggested.

The objectives of this study were to: (a) examine present methods used to estimate wind forces on glasshouses; (b) compare pressure coefficients for wind loads based on measurements from commercial glasshouses with those based on wind tunnel data; and (c) develop recommendations for estimating wind loads on glasshouses.

DESIGN WIND SPEEDS

There are two separate but related problems in setting design wind forces on glasshouses. The first is to establish a value for the design wind speed, and the second is to assign values to pressure coefficients for specific locations on the glasshouse.

Topography and such things as hedges, trees, buildings, etc. will affect the wind patterns near the ground. Since glasshouses are rarely higher than 6 m at their highest point, they will be subject to the ground effects over their entire surface. Thus, knowledge of the wind distribution near the ground is important in evaluating potential forces on glasshouses.

Basic wind speeds for glasshouse design have been designated by authorities in several countries. Some sources give a method for relating the basic wind speed at anemometer height (generally 10 m) to the effective height of the glasshouse. Other sources assume a constant wind speed below 10 m. Effective heights of buildings as given by the several sources are shown in Table 1.

Long term wind data are generally not available for a given glasshouse site so design wind speeds must be estimated from data obtained at other locations, or a reasonable value assumed based on experience. Scruton and Newberry (1963) presented three methods for estimating the design wind speed. One method used the gradient wind speed with coefficients selected according to site location and gust length. The other two methods were based on surface winds measured at the 10 m

Article was submitted for publication in March 1978; reviewed and approved for publication by the Structures and Environment Division of ASAE in December 1978. Presented as ASAE Paper No. 76-4003.

Approved for publication as Paper No. 5463 in the Journal Series of the Pennsylvania Agricultural Experiment Station.

The authors are: R. A. ALDRICH, Professor, Agricultural Engineering Dept., The Pennsylvania State University, University Park; and D. A. WELLS, Senior Scientific Officer, NIAE, Silsoe, Bedford, England.

TABLE 1. EFFECTIVE BUILDING HEIGHT FOR DETERMINING DESIGN WIND SPEED. h_1 IS EAVE HEIGHT, h_2 IS RIDGE HEIGHT, h_3 IS BUILDING HEIGHT TO THE GEOMETRIC CENTER OF GABLE FACE AREA

Source	Reference No.*	Effective Height			
		Sidewall	Roof	Gable	Building
CP3	(3)	h_1	h_2	h_2	-
STL 106	(13)	$\frac{h_1}{2}$	$\frac{h_1 + h_2}{2}$	h_3	-
NGMA	(8)	5 ft	15 ft	10 ft	-
ASAE†	(1)	-	-	-	
Scruton and Newberry	(10)	-	-	-	$\frac{2 h_2}{3}$
Holland	(12)	-	-	-	$\frac{h_1 + h_2}{2}$
Belgium) France) Germany)	(12)	-	-	-	h_2

*See references for identification of sources

†Building only h_1, or, if $(h_2 - h_1) \geq h_1$; then $\frac{h_1 + h_2}{2}$

height modified by appropriate factors. The three methods are presented below in equation form:

I. Gradient Wind Speed Method

$$U_z = F_g V_g (z/z_g)^{1/\alpha} \quad \text{[1]}$$

where

U_z = the design wind speed in mph at height, z

F_g = 1.25, the gust factor for extreme gusts of about 3 s duration

$$V_g = U + \frac{U}{10} \log_e r \quad \text{[2]}$$

V_g = the mean hourly gradiant wind speed

U = extreme hourly gradient wind speed

r = return period, years

$1/\alpha$ = 1/14, a power law exponent based on topography

z_g = 900 ft, gradient height

II. Surface Wind Method (Highest Mean Hourly) with Separate Gust and Topography Factors

$$U_z = F_{10} K V_{10} \left(\frac{z}{10}\right)^{1/\alpha} \quad \text{[3]}$$

where

F_{10} = 1.5, a gust factor for extreme gust at 10 m height of 3 s length based on topography

K = 1.1, a topography factor

V_{10} = highest mean hourly wind speed

$1/\alpha$ = 1/14, a power law exponent

III. Surface Wind Method. The Highest 3 s gust with 30 yr recurrence interval

$$U_z = U_{10} \left(\frac{z}{10}\right)^{1/11} \quad \text{[4]}$$

the exponent 1/11, includes topography and gust effects.

The minimum basic wind speed (10 m above ground) given in STL 106 (ref. 13) is 45 m/s (100 mph) for most of the United Kingdom (UK). This is a simplification of an isopleth map of maximum 3 s gust speeds of 50 yr return period as determined from information provided by the Meteorological Office of the UK. The design wind speed is obtained by using properly selected topography, ground roughness and building size and life factors. The topography and life factors were arbitrarily set at 1.0 and 0.93 respectively. The 0.93 represents an expected life of 20 yr.

$$U_z = 0.93 \times 1.0 \times U_{10}(S_2) \quad \text{[5]}$$

S_2 = the ground roughness, building size and height factor

An isopleth map in the Code of Basic Data for Design of Buildings (CP3) (ref. 3) gives basic wind speeds for the UK. The wind speeds shown are based on a 50 yr recurrence interval for maximum gusts averaged over 3 s. The design wind speed is obtained by using properly selected values for factors related to topography, ground roughness, etc. In equation form:

$$U_z = S_1 \times S_2 \times S_3 \times U_{10} \quad \text{[6]}$$

where

S_1 = a topography factor with value 0.9, 1.0 or 1.1

S_2 = a ground roughness, building size and height factor

S_3 = a building life factor

Minimum values for S_2 are given for heights of 3 m or less. A value of 0.93 for S_3 represents a design building life of 20 yr and a probability of 63 percent that the design wind speed will be exceeded once in the lifetime of the structure.

In Holland (Spek, 1972) a power law exponent of 1/4 is used to adjust basic wind speeds for heights below 10 m. A wind factor of 0.9 and a building size factor of 0.85 are then applied to the wind pressure determined for a particular height. In equation form:

$$U_z = U_{10} \left(\frac{z}{10}\right)^{1/4} \quad \text{[7]}$$

$$q_z = 0.9 \times 0.85 \times k\,(U_z)^2 \quad \text{[8]}$$

The American Society of Agricultural Engineers (ref. 1) recommends a basic wind speed at 30 ft (9.1 m) and a height reduction factor based on the 1/7 power law. Basic wind speed is from an isopleth map of wind speeds in the US for a particular recurrence interval for the fastest mile averaged over 1 h. A recurrence interval of 25 yr is recommended for glasshouses. In equation form:

$$U_z = U_{30} \left(\frac{z}{30}\right)^{1/7} \quad \text{[9]}$$

The National Greenhouse Manufacturer's Association (ref. 8) recommends using the 1/7 power law to reduce wind speeds for heights below 30 ft (9.1 m). A gust factor of 1.3 is then applied to the wind pressure to obtain the design pressure, thus:

$$U_z = V_{30} \left(\frac{z}{30}\right)^{1/7} \quad \text{[10]}$$

$$q_z = 1.3\,k\,(U_z)^2 \quad \text{[11]}$$

Values for V_{30} are from an isopleth map of fastest 1 h mile of wind for a 50 yr recurrence interval.

The Metal Building Manufacturer's Association (ref. 7) recommends a constant value of basic wind speed for all heights from ground surface to 50 ft (15.2 m). The basic wind speed is to be selected from an isopleth map of fastest mile for the recurrence interval considered applicable to the building being designed. A similar recommendation is made by the American Society of

Civil Engineers (ref. 2).

Hoxey and Wells (1964) used a simple power law expression to relate wind speed at any height below 10 m to the wind speed at 10 m. Their expression is:

$$U_z = U_{10} \left(\frac{z}{10}\right)^{\alpha} \quad [12]$$

where

U_{10} = the mean wind speed time averaged over 1 s.

The exponent, α, was found to vary from approximately 0.15 to 0.17 depending on the time of year, and to be independent of averaging time between 1 and 15 s. Lower values were determined from winter data and larger values from summer data; they determined a value of 0.108 for α for relating 3 s gusts to heights below 10 m.

Some sources give "basic wind pressures" rather than wind speeds as a starting point for load calculations. In France (Spek, 1972) three zones are specified for both normal and extreme wind pressure at 10 m. Extreme wind pressures are 1.75 normal pressure values. Normal wind pressures are: 51.0 kg f/m², 71.4 kg f/m² and 91.8 kg f/m² for zones I, II, and III, respectively. These correspond to wind speeds of 29, 34, and 38 m/s. There is a reduction factor of 0.75 based on expected building life. There is also a linear relation used to reduce pressures for heights below 10 m. Thus:

$$q_z = (0.75 + 0.025z)\, q_{10} \quad [13]$$

In Belgium (Spek, 1972) a normal pressure of 45 kg f/m² is given for all heights between ground and 10 m. Extreme pressure is taken to be twice normal pressure. The German Code (Spek, 1972) adjusts wind pressure with height. A pressure of 25 kg f/m² applies to heights up to 4 m, 40 kg f/m² for heights from 4 to 6 m, and 50 kg f/m² for heights above 6 m.

Wind speed and pressure reduction factors, that are based on horizontal dimension, are given in some references. In CP3 (ref. 3) the factor S_2 is based on a building size whose least horizontal dimension is greater or less than 50 m. The French and Belgian Codes (Spek, 1972) give a pressure reduction factor of 0.7 if the least dimension is equal to or greater than 100 m. The French Code gives a variable factor for reducing pressures for glasshouses with least dimensions less than 100 m. The relationship is:

$$K_L = (L)^{-0.0775} \quad [14]$$

where

K_L = the pressure reduction factor and L is the least horizontal dimension equal to or less than 100 m.

Table 2 gives values for design wind speeds and pressures calculated according to the above Codes and recommendations. Similar conditions of ground, topography, etc. were assumed as a basis for selecting values from the references. The basic wind speed was either 45 m/s or a value published by the source. The use of 45 m/s wind speed with the last four sources is not correct procedure in that it implies that their height reduction methods can describe the profile of a 3 s gust. However, the values of the design pressures would be changed little if a more precise relationship was used.

The use of gradient wind speed according to ref. 10 and the NGMA (ref. 8) recommendation produces the most conservative values for design wind speed. The choice of method for estimating the design wind speed or pressure becomes a matter of personal judgment by the designer (unless restricted by Code requirements).

TABLE 2. DESIGN WIND SPEEDS AND PRESSURES DETERMINED BY SEVERAL METHODS

Source and Method	Height Factor	Topography ground gust, life	Basic wind speed	Design wind speed*	Design wind pressure
			m/s	m/s	N/m²
CP3(3) 3 s gust 50 year recurrence Isopleth map. 10 m	tabular value 0.78	0.93	45	33.5	690
STL 106(13) maximum 3 s gust 50 year recurrence. 10 m	tabular value 0.81	0.93	45	34	710
Scruton and Newberry(10) gradient wind at 900 ft $V_g = U + \frac{U}{10} \log_e r$ Isopleth map.	$(\frac{z}{900})^{1/14}$	1.25	33	41	1030
Scruton and Newberry (13) surface wind at 33 ft. Mean hourly speed 50 year recurrence. Isopleth map.	$(\frac{z}{33})^{1/14}$	1.65	23	35	750
Scruton and Newberry(10) surface wind at 33 ft highest 3 s gust. Isopleth map. 30 year recurrence interval	$(\frac{z}{33})^{1/11}$	None	40	36	795
Hoxey and Wells(14) used with CP3 wind speed and life factor.	$(\frac{z}{10})^{1/9.1}$	0.93	45	37	840
Holland(12) surface wind at 10 m.	$(\frac{z}{10})^{1/4}$	0.765§	45 35.5†	33 26	510 320
NGMA(8) fastest mile/h at 30 ft, 50 year recurrence. Isopleth map	$(\frac{z}{30})^{1/7}$	1.35	45 34†	39 29	1210 670
ASAE (1) fastest mile/h at 30 ft. 25 year recurrence. Isopleth map	$(\frac{z}{30})^{1/7}$	None	45 34†	39 29	935 515
France(12) basic pressure at 10 m for three zones.	(0.75 + 0.025z)	0.75	45 890‡	45 -	770 550

*Design wind speed and pressure calculated for 3 m height.
†Second number is minimum recommended wind speed from that source.
‡Normal pressure (N/m²) for zone III. Highest pressure for France.
§Applies to pressure calculated from design wind speed.

DESIGN PRESSURE COEFFICIENTS

Equations giving the wind pressure acting normal to a building surface are generally of the form:

$$p = C_p k U_z^2 \quad [15]$$

where

- p = pressure, N/m² in SI Units, lbf/ft² in Imperial Units, kg f/m² in Metric Units
- C_p = pressure coefficient
- k = $\rho/2$
- k = 0.613 in SI Units (N/m², m/s)
- k = 0.00256 in Imperial Units (lb f/ft², mph)
- k = 0.0625 in Metric Units (kg f/m², m/s)
- U = design wind speed at height z, m/s or mph

The pressure coefficient C_p may include both external and internal pressures, but generally separate values are given. In the latter case:

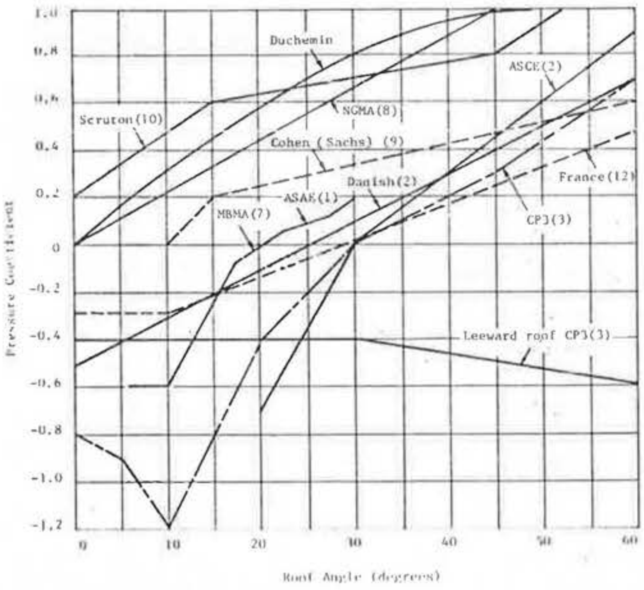
$$p = (C_{pe} - C_{pi})\, k U_z^2 \quad [16]$$

where

- C_{pe} = external coefficient, and
- C_{pi} = internal coefficient

a negative value for p indicates the resultant pressure acts outward.

Values for pressure coefficients for most building shapes have been established from wind tunnel studies. Since it is very difficult to accurately model the wind near the ground, coefficients determined from model studies may not represent full scale conditions, especially for low profile buildings.



LEEWARD ROOF COEFFICIENTS (ALL ANGLES)				
-0.2	-0.3	-0.4	-0.5	-0.6
Denmark(2)	France(2) STL106(13)	Germany(12) ASAE(1) NGMA(8)	Holland(12) ASAE(1) MBMA(7) Belgium(12)	Swiss(4) Hoxey and Wells(6) ASCE(2)

NOTE: Numbers in parentheses refer to appended references.

FIG. 1 External pressure coefficients for single span gable roofs.

Each code of practice or recommendation lists pressure coefficients considered to be safe and reasonable in regard to designing for wind loads. Some codes provide rather crude coefficients that are intended to represent maximum loads regardless of wind direction. Other codes give local pressure coefficients for designated areas of the building to account for winds moving at a specific angle of attack. For most low profile buildings, the maximum wind loads occur with wind moving either parallel or perpendicular to a wall.

All codes and recommendations give values of pressure coefficients for single span gable roofs that are functions of roof slope and wind direction. Values of windward roof pressure coefficients from several sources have been plotted in Fig. 1. The values plotted from ASAE (ref. 1), MBMA (ref. 7), and France (Spek, 1972) are for a height to span ratio of 0.25. Those from CP3 (ref. 3) are for a height to span ratio equal to or less than 0.5. Single value coefficients for the leeward roof are also included. Although there is general agreement that a suction force exists on all leeward roofs, no such agreement is apparent concerning coefficients for windward roofs. At the normal roof slope for a glasshouse, approximately 27 deg, the windward roof coefficients range from −0.20 from the ASCE recommendations to +0.60 from the NGMA recommendations. The NGMA recommendations are based on the Ketchum (ref. 8) equation, $C_p = \theta/45$ where θ deg is the slope of the roof. A plot of values from the Duchemin equation is also shown as a matter of historical interest in that it was one of the earliest published methods for estimating wind loads on sloping surfaces.

In five of the eight curves in Fig. 1, the values change algebraic sign between roof slopes of 20 and 30 deg. It is evident that additional information is needed in order to reconcile the differences between values given by the several sources. Recent work by Wells and Hoxey (refs. 5, 6, 14) should help resolve the question for roofs of single span glasshouses. Their data from a single span glasshouse with a roof slope of 26 deg show an external pressure coefficient of +0.1 for the windward roof and an internal pressure coefficient of −0.66* for wind moving perpendicular to the ridge direction; the sum of these yields an overall windward roof coefficient of +0.76. This compares with −0.2 from STL 106 for the same roof. The Swiss Code (ref. 4) is quoted in many references as a very detailed source for pressure coefficients. The value of the external coefficient of +0.2 from the Swiss Code (Table 3) for a 30 deg slope is very close to the value of +0.10 developed by Wells and Hoxey. The net coefficients become +0.4 from the Swiss Code and +0.76 from Wells and Hoxey. The differences between published values emphasize the problem of using data from model studies in wind tunnels to develop coefficients for full scale buildings.

Pressure coefficients from several sources are given in Table 3. The values listed apply to single span glasshouses with equal permeability in all surfaces. Windward wall coefficients range from +0.1 (Holland) (Spek, 1972) to +1.5 (Scruton and Newberry, 1963). Values of coefficients for leeward walls vary from −0.2 (CP3) (ref. 3) to −1.5 (Scruton and Newberry, 1963). Similar situations exist for the roof.

The range of values for suction on the leeward slope of the roof illustrates further the problems in interpretation and application of such data to structural design.

Some sources give local pressure coefficients for specific building areas and wind directions. Internal pressure coefficients are given by some sources while others state that tabular values combine external and internal pressures. Where there is no indication of internal pressure coefficients, it must be assumed that the tabular values include the internal pressure effect.

Published coefficients and factors result from statistical analyses of available data and judgment in the evaluation of the analyses, all for the purpose of providing a reasonable basis for designing safe, economical structures. The coefficients from Scruton and Newberry (1963) are much higher than values from any other source. They represent a conservative approach to wind loading design and in view of values from Hoxey and Wells (1974), would lead to an uneconomical frame with unused load carrying capacity.

In the design process it should not be necessary to use the high local coefficients in the selection of primary framing members but only in designing such elements as secondary framing members, wind bracings and fasteners for cladding. A properly designed glasshouse frame should provide for load sharing between framing members so that high local loads are carried by adjacent elements.

A large number of glasshouses are built as multi-span gable buildings. A summary of pressure coefficients from several sources is given in Table 4. There are large differences in values given for all roof slopes

*There is some question as to the general application of this value because of excess permeability in the leeward roof of the test glasshouse.

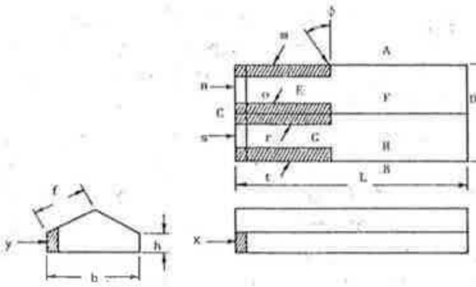
except the last leeward roof. Local pressure coefficients from CP3 (ref. 3) indicate high suction pressure along the outside edges and along the ridges. Values based on one set of measurements from Wells and Hoxey (1973) have been included. The measurements were on a seven-span Venlo structure, with the wind moving parallel to the ridges. They are in general agreement with the values from CP3.

There are no published coefficients for multi-span rounded roof buildings such as those being constructed using either film plastics, non-reinforced rigid plastics or glass fibre reinforced plastics. Three sources give values of coefficients for single span rounded roof buildings (Table 5). The similarity of values from the three sources suggests they may have been developed from the same data. The coefficients from Sherlock (1946) are very close to the values for an $h/L = 0.5$ given by ASCE (ref. 2) and Sachs (1973). The ASCE (ref. 2) states that data for rounded root buildings are very limited.

The values plotted in Fig. 2 show the effect of wind speed factors and wind pressure coefficients on final design pressures used in the selection of roof framing members. The pressures given are for a single span gable greenhouse calculated for a basic wind speed of 45 m/s with factors and coefficients applied appropriate to the code of recommendation.

It should be emphasized that the coefficients from the work of Hoxey and Wells are derived from measurements on a full size glasshouse. However, the increased permeability on the leeward roof of their test glasshouse may have resulted in a lower than average internal pressure. Pressures calculated from the Dutch Code and NGMA recommendations are of the same magnitude, and in two cases are of opposite sign. If wind loading controls the member selection, a final design based on ASAE recommendations would be very different from one based on NGMA criteria. The use of NGMA values for coefficients results in the most conservative estimates for wind loads.

TABLE 3. PRESSURE COEFFICIENTS FOR SINGLE SPAN GABLE ROOF GREENHOUSES



Wind Angle ϕ	Walls				Roofs			
	A	B	C	D	E	F	G	H
Hoxey and Wells(11) h:b:L = 1:2.7:9.1, Roof Slope = 26 deg								
0	+0.65	-0.4	-0.6	-0.6	+0.10	+0.10	-0.6	-0.6
90	-0.10	-0.10	+0.9	-	-0.30	-0.30	-0.3	-0.3
For ϕ = 0°, C_{pe} = +1.0 for area, x_A = 0.05 Lh, C_{pe} = 0.9 area, x_B = 0.05 Lh; C_{pe} = +0.3 for area, n = 0.05 Lf, C_{pe} = -0.9 for area, s = 0.05 Lf. For ϕ = 90° C_{pe} = -0.7 for areas, x_A & x_B = 0.1 Lh, C_{pe} = -1.2 for areas n & s = 0.1 Lh. For ϕ = 0° C_{pi} = 0.66. For ϕ = 90°, C_{pi} = -0.01								
STL 106(13) values include external and internal pressure effects. Roof slope 25-27deg								
0	+0.7	-0.4	-0.4	-0.4	-0.2	-0.2	-0.4	-0.4
90	-0.4	-0.4	+0.7	-0.4	-0.4	-0.4	-0.4	-0.4
Drag coefficient = +0.05 applied to area = bL								
CP3(3) Roof slope = 27 deg								
0	+0.7	-0.2	-0.5	-0.5	-0.1	-0.1	-0.4	-0.4
90	-0.5	-0.5	+0.7	-0.2	-0.7	-0.6	-0.7	-0.6
For ϕ = 0°, C_{pe} = -0.8 for areas, y_C & y_D = 0.25 bh. For all ϕ's, C_{pe} = -1.1 for area, r = 0.15 fL, C_{pe} = -0.8 for area, m = 0.15 fL. For all ϕ's, C_{pi} = -0.3								

Wind Angle ϕ	Walls				Roofs			
	A	B	C	D	E	F	G	H
Scruton & Newberry(10) values include external and internal pressure effects. Roof Slope 27°								
0	+1.5	-1.5	——	——	+0.6	+0.6	-1.7	-1.7
90	——	——	+1.5	-1.5	——	——	——	——
For all ϕ's, C_{pe} = 1.20 for areas m, o, r, t = 0.2 fL and areas, n, s = 0.1 fL								
Swiss(4) h:b:L = 1:8:16 Roof slope = 30 deg								
0	+0.8	-0.5	-0.5	-0.5	+0.2	+0.2	-0.6	-0.6
90	-0.3	-0.3	+0.9	-0.3	-0.5	-0.1	-0.5	-0.1
For ϕ = 10-90°, C_{pe} = -1.0 for area, n = 0.1 Lf, C_{pe} = -1.0 for areas, Y_c & Y_d = 0.25 bh. For all ϕ's, C_{pi} = ± 0.2								
Holland(12) h:b = 1:4.5								
0	+0.1	-0.5	-0.5	-0.5	+0.5	+0.5	-0.5	-0.5
90	-0.5	-0.5	+1.0	-0.5	-0.5	-0.5	-0.5	-0.5
For all ϕ's, C_{pi} = ± 0.3								
NGMA(8)								
0	+1.0	-0.4	-0.4	-0.4	+0.59	+0.59	-0.36	-0.36
90	-0.4	-0.4	+1.0	-0.4	-0.36	-0.36	-0.36	-0.36
ASAE(1) MBMA(7) Roof Slope = 27 deg								
0	+0.7	-0.4	-0.4	-0.4	+0.12	+0.12	-0.5	-0.5
90	-0.4	-0.4	+1.0	-0.4	-0.5	-0.5	-0.5	-0.5
For purlins, roof panels and fasteners, C_p = 1.25 x normal coefficient. For girts, wall panels and fasteners, C_p = ± 1.0 x normal coefficient								

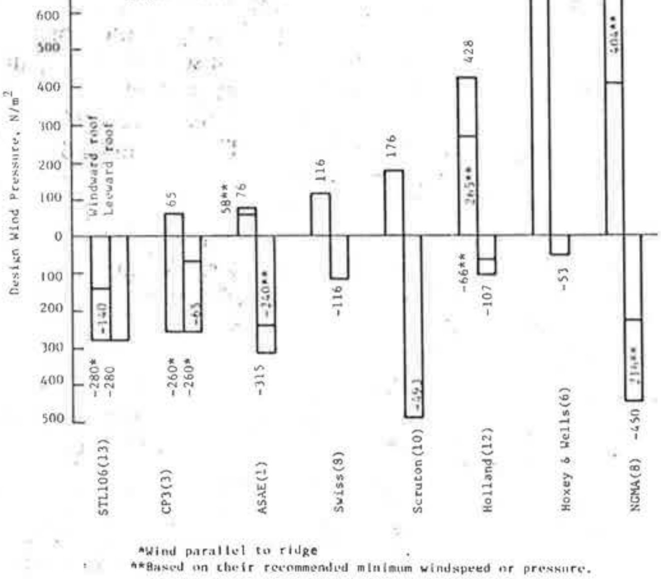
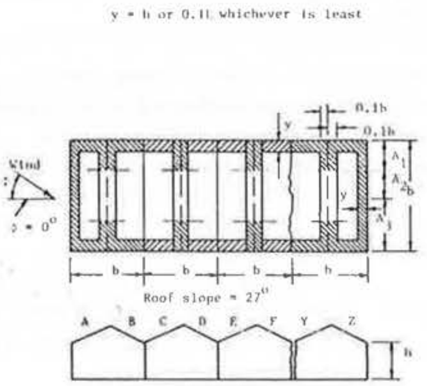


FIG. 2 Design wind pressures on the roof of a single span gable greenhouse. Appropriate factors and coefficients applied. Wind across ridge unless otherwise noted.

TABLE 4. PRESSURE COEFFICIENTS FOR MULTI-SPAN GABLE ROOF GREENHOUSES



Source	Wind Angle φ	First Span A	First Span B		Second Span C	Second Span D	Other Inside Spans E	Other Inside Spans F	End Span Y	End Span Z	Local Coefficient	
CP3(3)	0°	-0.3	-0.6		-0.4	-0.3	-0.2	-0.3	-0.2	-0.5	-2.0	-1.5
	For φ = 90° C_{pe} = -0.8 for distance A_1 = h, C_{pe} = -0.6 for distance A_2 = h, C_{pe} = -0.2 for distance A_3, C_{pi} = -0.3 for all wind angles. Wall coefficients from Table 3											
Holland(12)	0°	+0.5	-0.125		+0.125	+0.125	+0.125	-0.125	+0.125	-0.5	None	
	90°	-0.5	-0.5		-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	None	
	Windward wall C_{pe} = +0.8, other walls C_{pe} = -0.5, C_{pi} = ± 0.3											
Germany(12)	0°	+0.15	-0.2		+0.08	-0.2	+0.03	-0.2	+0.03	-0.4	None	
	Windward wall C_{pe} = +0.8, other walls C_{pe} = -.04											
MBMA(7)	0°	+0.12	-0.5		-0.5	-0.33	-0.25	-0.33	-0.25	-0.33	None	
	Windward wall C_{pe} = +0.7, other walls C_{pe} = -0.4											
Wells* & Hoxey (14)		For φ = 90° C_{pe} = -1.1 for distance A_1 = h, C_{pe} = -.02 for A_2 and A_3										
		Windward walls C_{pe} = +0.5, Leeward wall C_{pe} = -0.35, C_{pi} = -0.2. Side walls C_{pe} = 0.2										

*From one set of measurements

CONCLUSIONS

Of the methods studied, Scruton and Newberry (1963) predict the highest design wind speed at glasshouse height using the gradient wind at 900 ft. Other sources use hourly means with gust factors, fastest mile with gust factors, and gust speed averaged over 3 s. Each method represents a particular interpretation of available data.

The wind load on glasshouses is estimated by using coefficients that relate wind velocity to pressure normal to a surface. There are large differences between coefficients from the several sources. All sources except Hoxey and Wells (1974) published coefficients based on model studies in wind tunnels. The coefficients from Hoxey and Wells are based on measurements of wind pressures on a full size glasshouse. They give higher coefficients than most sources and of opposite sign for some surfaces.

In the absence of a legal code prescribing design loads, the engineer has several alternatives available for estimating wind effects, all of which have been developed from empirical data. The engineer must assume loads in the structural analysis that will lead to a safe, economical design. Excess strength at high cost is poor design, just as is failure from inadequate strength. The combination of probabilistic and deterministic procedures makes evaluation of one element in the design process very difficult. A successful design results from the proper use of engineering judgment in assessing the relative importance of all factors in the design process.

RECOMMENDATIONS

The review of several codes of practice and recommendations emphasizes the role of engineering judgment

TABLE 5. PRESSURE COEFFICIENTS FOR SINGLE SPAN ROUNDED ROOFS

h/l	Windward Quarter ASCE(2)	Windward Quarter ASAE(1)	Windward Quarter SACHS(9)	Central One-Half ASCE(2)	Central One-Half ASAE(1)	Central One-Half SACHS(9)	Leeward Quarter ASCE(2)	Leeward Quarter ASAE(1)	Leeward Quarter SACHS(9)
Roof from ground level*									
0.1	+0.15	+0.12	+0.14	-0.8	-0.7	-0.8	-0.5	-0.58	-0.5
0.2	+0.25	+0.25	+0.28	-0.9	-0.7	-0.9	-0.5	-0.58	-0.5
0.3	+0.43	+0.37	+0.43	-1.0	-0.7	-1.0	-0.5	-0.58	-0.5
0.4	+0.55	+0.49	+0.57	-1.1	-0.7	-1.1	-0.5	-0.58	-0.5
0.5	+0.70	+0.60	+0.71	-1.2	-0.7	-1.2	-0.5	-0.58	-0.5
0.6	+0.85	-	+0.85	-1.3	-	-1.3	-0.5	-	-0.5
ROOF ON VERTICAL WALLS									
0.0	-0.7	-	-	-0.7	-	-0.7	-	-	-
0.1	-0.9	0	-0.9	-0.8	-0.8	-0.8	-0.5	-0.58	-0.5
0.2	-0.9	0	-0.9 0.0†	-0.9	-0.9	-0.9	-0.5	-0.58	-0.5
0.3	-0.3 0.15†	+0.19	-0.3 0.15†	-1.0	-1.0	-1.0	-0.5	-0.58	-0.5
0.4	+0.42	+0.39	+0.43	-1.1	-1.1	-1.1	-0.5	-0.58	-0.5
0.5	+0.70	+0.68	+0.7	-1.2	-1.2	-1.2	-0.5	-0.58	-0.5
0.6	-	-	-	-1.3	-	-1.3	-0.5	-	-0.5

h/l = ratio of rise of roof to span
*Sherlock(11) published values for Cpe for a semi-circular single span roof of +0.67 for θ = 0-30 deg, +0.12 for 30-48 deg, -1.22 for 48-120 deg and -0.63 for 120-180 deg.
These values were based on model studies in a wind tunnel.

†No reasons were given for the alternative values.

and experience in the interpretation of empirical data. Any recommendations setting forth guides and data for wind pressure calculations should present them in a manner that will enhance good engineering design practice. The data should be sufficient to allow the prediction of critical loads on framing members, cladding and fasteners. Areas of potentially high positive or negative pressures should be indicated so the engineer can account for them in the design.

The following recommendations are proposed to apply to all greenhouses, unless specifically noted otherwise:

1 The basic wind at 10 m should be given in the form of isopleth maps with wind speeds developed from 3 s gust averages with a recurrence interval of 25 yr. A 3 s gust will produce wind with dimensions exceeding 20 m, square, a large enough area for acceptable greenhouse design analysis. A recurrence interval of 25 yr will cover the useful life of most commercial greenhouses.

2 The power law should be used to relate wind speed at any height to that at 10 m. In equation form:

$$U_z = V_{10} \left(\frac{z}{10}\right)^{1/10}$$

No further adjustments for height should be used. The design wind speed should be determined for the mid-heights of the area being considered, and the resulting pressure applied uniformly over the area.

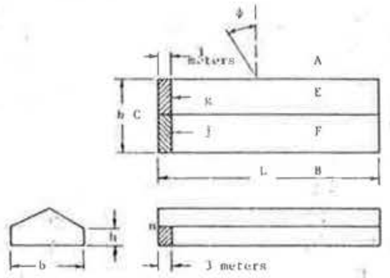
3 Factors relating to ground cover, exposure, or similar influences should not be used. The site conditioins in the future cannot be described with certainty and a protected site can become open, or the reverse can happen.

4 The coefficients given in Table 6 are presented as reasonable for design of main framing members, and local coefficients used for design of secondary framing members, cladding, and fasteners. The pressure acting normal to a surface is expressed by:

$$P_z = C_p K (U_z)^2$$

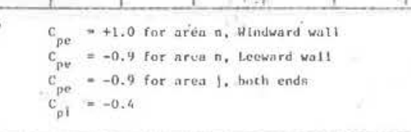
TABLE 6. RECOMMENDED WIND PRESSURE COEFFICIENTS FOR GREENHOUSES

A. Single span gable roof, roof slope 27 deg



Wind Direction (φ°)	Walls			Roofs		
	A	B	C	D	E	F
0	+0.65	-0.40	-0.60	-0.60	+0.15	-0.60
90	-0.10	-0.10	+0.90	-0.40	-0.30	-0.30
0°	C_{pe} = +1.0 for area n, Windward wall C_{pe} = -0.9 for area n, Leeward wall C_{pe} = -0.9 for area j, both ends C_{pi} = -0.4					
90°	C_{pe} = -0.7 for area n, Windward end, both walls C_{pe} = -1.2 for areas g and j, Windward end C_{pi} = 0					

B. Single span rounded roof



f/b	Roof on vertical walls			Roof from ground		
	Windward Quarter	Central Half	Leeward Quarter	Windward Quarter	Central Half	Leeward Quarter
0	-0.7	-0.7	-0.7	-	-	-
0.1	-0.9	-0.8	-0.6	+0.1	-0.8	-0.6
0.2	-0.6	-0.9	-0.6	+0.25	-0.9	-0.6
0.3	-0.3	-1.0	-0.6	+0.4	-1.0	-0.6
0.4	+0.4	-1.1	-0.6	+0.65	-1.1	-0.6
0.5	+0.7	-1.3	-0.6	+0.85	-1.2	-0.6

All values for transverse wind
Windward walls, C_p = +0.7 for all values of f/b
Leeward walls, C_p = -0.4 for all values of f/b
For wind parallel to roof, C_p = -0.7 for all roofs

C. Multi-span gable and rounded roof

	First Roof		Second Roof		Other Inside Roof		Last Roof	
	Wind.	Lee.	Wind.	Lee.	Wind.	Lee.	Wind.	Lee.
Gable Roofs	+0.12	-0.5	-0.5	-0.33	-0.25	-0.33	-0.25	-0.33
Rounded Roof	-0.9	-0.6	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3

Local C_{pe} = -1.5 for all gable roofs 1 m on either side of ridge and along outer edges. Windward walls, C_p = +0.7, other walls C_p = -0.4

References

1 ASAE. 1974. Recommendation R288.3. Designing buildings to resist snow and wind loads. AGRICULTURAL ENGINEERS YEARBOOK. pp. 343-347.

2 ASCE. 1961. Wind forces on structures. Final Report. Paper 3269. Trans. of Am. Soc. Civil Engineers. Vol. 126, Part II.

3 BSI. 1972. Code of basic data for design of buildings. Chapter V Loading. Part 2 Wind Loads. British Standard Institution.

4 Davenport, A. G. 1960. Wind loads on structures. Tech. Paper 88. Division of Building Research. National Research Council. Ottawa, Canada.

5 Hoxey, R. P. and D. A. Wells. 1974. Full-scale measurements of wind loads on glasshouses. Proceedings of Symposium on Full-Scale Fluid Dynamic Measurements. Leicester, England. July.

6 Hoxey, R. P. and D. A. Wells. 1974. Full-scale wind pressure and load measurements single span 6.4 x 21.3 glasshouse. DN/G/515/2301. Natn. Inst. Agric. Engr. Silsoe, England. (unpubl.)

7 MBMA. 1963. Recommended design practices manual. Metal Building Manuf. Assoc.

8 NGMA. 1972. Protection standards for greenhouses. National Greenhouse Manufacturer's Association.

9 Sachs, Peter. 1973. Wind forces in engineering. Pergamon Press. Oxford.

10 Scruton, C. and C. W. Newberry. 1963. An estimation of wind loads for building and structural design. Proceeding ICE 1963 25:97-126.

11 Sherlock, R. H. 1946. Wind velocities for the design of low buildings. College of engineering. University of Michigan. May.

12 Spek, J. C. 1972. Design calculations for glasshouses. Publ. 76. Instituut Voor Tuinbouwtechniek, Wageningen, Holland. September.

13 United Kingdom. 1970. Minimum standard for glasshouse construction-loading. STL 106. Ministry of Agriculture, Fisheries and Food. United Kingdom.

14 Wells, D. A. and R. P. Hoxey. 1973. Wind loading of glasshouses. Proceedings Subject Day on Greenhouse Engineering. Natn. Inst. of Agric. Engr. England. November.