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DESIGN OF ROOFTOPS AGAINST GRAVEL BLOW-OFF

R.J. KIND, R.L. WARDLAW
NATIONAL AERONAUTICAL ESTABLISHMENT

OTTAWA

SEPTEMBER 1976

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DESIGN OF ROOFTOPS AGAINST GRAVEL BLOW-OFF

CONCEPTION DE TOITS PREVENANT LE DISPERSEMENT PAR LE VENT DES COUVERTURES DE GRAVIER

by/par

R.J. KIND, R.L. WARDLAW

SEPTEMBER 1976/SEPTEMBRE 1976

ABSTRACT

A method is presented for estimating the wind speeds required to cause scour or blow-off of rooftop gravel for various building configurations. It is based mainly on results from wind tunnel tests which were conducted specifically to obtain the required data. Using information available in the literature, a method has been formulated for estimating the maximum probable wind speed that can be expected at any particular building site and rooftop level. The basis of the methods and their limitations are discussed in an appendix. The information is presented in a convenient design-oriented format.

RESUME

On présente une méthode permétant d'estimer la vitesse du vent entrainant la dispersion ou le balayage de la couverture de gravier sur les toits d'édifices de formes variées. Cette méthode est fondée principalement sur des résultats de souffleries, les essais ayant été entrepris en vue d'obtenir les données nécéssaires.

A partir de l'information disponible dans la littérature scientifique, on a formulé une méthode permetant d'estimer la vitesse maximale probable du vent pour n'importe quel emplacement des bâtiments ou n'importe quelle hauteur de toit en particulier. Les fondements et limitations des méthodes proposées sont discutés en appendice. L'information est presentée sous un format pratique destiné aux architectes et ingénieurs.

CONTENTS

SYMBOLS

Symbol	Definition
a, b	paving block array dimensions; see Graph 1
d	nominal gravel size as determined by sieve analysis (50% by weight is larger than this size and 50% by weight is smaller)
E	exposure factor; the ratio of mean wind speed at rooftop level at the building site to that at the standard reference height/terrain condition
EG	exposure-gust factor ($EG \equiv E \times G$)
F_p	parapet height/paving block array factor

SYMBOLS (Cont'd)

Symbol	Definition
F_s	gravel-size factor
F_α	wind-direction sensitivity factor
G	gust factor; ratio of one-second gust speed to hourly mean wind speed
g	gravitational acceleration
H	parapet height; see Graph 1
h	building height; see Graph 1
k	average height of roughness elements (trees, other buildings, etc.) upwind of building site
ℓ	building length; see Graph 1
m	mass of stones
n	an exponent in Equation (6), Appendix A
R	return period in years
$\bar{u}$	mode of annual maximum wind speed; see Graph 4
u	wind speed for return period R; see Graph 4
V	speed of gusts of wind at rooftop level
$V_{c1}, V_{c2}, V_{c3}, V_{c4}$	critical wind speeds; see Appendix A
v	speed of stones leaving rooftop
w	width of building; see Graph 1
z	height above ground level
α	wind angle; see Graph 1
ρ	air density
τ_{max}	maximum wind shear stress on any gravel-covered area of the rooftop

Subscripts

ref	denotes reference conditions tabulated in Table A-1
1, 2, 3	refers to critical speeds V_{c1}, V_{c2} and V_{c3}

1.0 INTRODUCTION

This report, prepared at the request of Dow Chemical of Canada Limited, provides the designer with a simple procedure and the necessary information for estimating the wind speeds at which gravel of a given size will be blown off rooftops of buildings of simple shape. Data are presented only for flat-roofed rectangular buildings; wind tunnel tests were conducted specifically to obtain these data. The report also presents a simple procedure, based on information available in the literature, for determining design wind speeds at rooftop level.

The wind speed required to blow gravel off a given rooftop depends on three primary factors, namely stone size, aerodynamic force exerted by the wind on the stones and the distance or height that the stones must travel to leave the rooftop. Unfortunately the aerodynamic force exerted by the wind on the stones is not simply related to the nominal wind speed. A simple relationship does not exist because this force depends on the detailed structure of the airflow over the stones and this in turn depends on the nature of the terrain upwind of the building, on the orientation of the building with respect to the wind direction, on the geometry of the building (e.g. building height, building shape, parapet height, geometry of paving block arrays on the rooftop, protrusions on the rooftop, etc.) and on the effects of nearby buildings.

As the stone size d increases larger aerodynamic forces, and hence higher wind speeds, are required to move the stones. It is found that the wind speed required to blow gravel off rooftops is proportional to $\sqrt{d}$ provided that the distance and height that the stones must travel are relatively small, as is often the case.

As is well known, the speed of the wind increases with increasing height above the surface of the earth. The height of the building is therefore important. Furthermore, the rate at which the wind speed increases with height depends on the nature of the terrain, hence the importance of terrain roughness. For given conditions at high altitude (above about 1500 ft.) the wind speed near the earth's surface is lower over rough terrain than over smooth terrain. Meteorological stations are usually situated in open level terrain and record wind speeds at a standard anemometer height of about 30 ft. (10 meters). It is therefore convenient to consider this height/terrain combination as the reference case. The effects of terrain roughness and of rooftop elevation are dealt with by means of an 'exposure factor', E. This exposure factor is the ratio of the mean wind speed at rooftop level at the building site to the mean wind speed for the reference height/terrain combination. Meteorological stations usually report only mean wind speeds, that is time-averaged speeds for an averaging period ranging from about five minutes (common in the U.S.A.) to one hour (in Canada and Europe). In the U.S.A. the data are often presented in terms of the speed of the "fastest mile of wind", in which case the averaging time is inversely proportional to this speed (e.g. a 'fastest mile' speed of 60 mph implies an averaging time of 1/60 hours or one minute). Since the roofing gravel is sensitive to gusts whose speed can be substantially larger than the mean wind speed, a gust factor G is introduced. The gust factor is defined herein as the ratio of the maximum wind speed occurring in a one second gust to the hourly mean wind speed. Both the exposure factor E and the gust factor G are evaluated from information available in the literature. In the procedure used to determine the design wind speeds a combined exposure-gust factor EG (the product of E and G) is used to account for height/terrain and gust effects.

The orientation of the building with respect to the wind direction can have a profound effect on the structure of the airflow over the rooftop and hence on the aerodynamic force acting on the stones for a given wind speed. For example, if the wind is approximately normal to the upstream face of the building ($\alpha \simeq 90^\circ$) the airflow separates at the upstream edge of the rooftop and the gravel is in a 'sheltered' region. If, on the other hand, the wind blows in a diagonal direction ($\alpha \simeq 45^\circ$) strong vortices form along the upstream edges of the rooftop and these vortices in effect amplify the speed of the wind; the stones under the vortices are then subject to relatively large aerodynamic forces. For this reason the danger of gravel blow-off tends to be greatest for wind angles of about 45°.

The flow pattern over the building and in particular over the rooftop, will naturally be influenced by the shape of the building. This report deals explicitly only with the simplest of building shapes, namely rectangular parallelipipeds. Even so the height:length:width (h:ℓ:w) proportions of the building are of some importance; one would expect the flow over the rooftops of low-rise buildings ($h << \ell, w$) to be somewhat different from that over medium-rise ($h \simeq \ell, w$) and high-rise ($h >> \ell, w$) buildings. This report gives data for low-rise shapes and for high-rise shapes with $\ell/w = 1$ and 2.

As might be expected, parapet height is of major significance. Parapets effectively shield the stones from the wind so that the aerodynamic force on the stones is reduced for a given nominal wind speed when the parapet height is increased. When the wind angle α is roughly 45° parapets cause the cores of the vortices mentioned earlier to form at greater heights above the gravel, thus reducing the effects of these vortices.

When the wind angle α is roughly 45°, paving block arrays placed near the upstream corner of the rooftop cause an increase in the nominal wind speed at which stones begin to move. The paving blocks do not significantly modify the structure of the airflow. Rather, they simply replace the roofing gravel in the regions where the aerodynamic forces on stones would otherwise be most intense (i.e. under the vortices). The size, shape and location of the regions where the aerodynamic forces are potentially most intense depends on the structure of the airflow over the rooftop and hence on the geometry of the building; parapet height is particularly important. The effects of building shape, parapet height and paving block array geometry are therefore interdependent and cannot be decoupled; a parapet height/paving block array factor F_p is used to account for the combined effects of the parameters.

The analysis/design procedure presented in Section 2.0 includes steps to deal with each of the effects outlined in this Introduction.

The gravel is assumed to have a specific gravity of 2.7 (appropriate for limestone or granite) and the air is assumed to have standard sea-level properties throughout this report.

2.0 STEP-BY-STEP ANALYSIS/DESIGN PROCEDURE

This section presents a detailed procedure for determining the design wind speed, that is the maximum wind speed which a rooftop must be designed to safely withstand, and for determining the wind speed which a given rooftop design can safely withstand. By iteration, that is by trying a succession of different rooftop designs, a safe design can be arrived at. The basis of the procedure and its limitations are discussed in detail in Appendix A. The procedure is presented by means of a flow chart.

2.1 Terminology and Nomenclature

Some of the terminology appearing in the flow chart of the procedure has not been defined in the Introduction and will therefore be defined here.

Return Period: the 'return period' or 'period of recurrence' expresses the probability that, in a given year, the wind speed will exceed a given value. For example if the return period of 70 mph winds is 30 years in a given locality the probability that the wind speed will exceed 70 mph in any one year is 1/30 or 0.033. The designer must decide what return period represents an acceptable level of risk in any particular case.

Exposure Type: for present purposes, terrain roughness is classified into three categories:

- Exposure A (open or standard exposure) — open level terrain with only scattered buildings, trees or other obstructions, open water or shorelines thereof.
- Exposure B suburban or urban areas, wooded terrain, or centres of large towns.
- Exposure C centres of large cities with heavy concentrations of tall buildings. At least 50 percent of the buildings exceed four storeys.

Roughness Height (k): this is the average height of the roughness elements, such as trees and buildings just upwind of the building site. Its values lie approximately within the following ranges:

$k \simeq 3$ ft. for exposure A

20 ft. $< k <$ 30 ft. for exposure B

50 ft. $< k <$ 100 ft. for exposure C

When dealing with relatively low buildings in type B or C terrain the designer must estimate an appropriate value for k for the building site. It is conservative to choose low values.

Critical Gust Speeds (V_c): these are speeds of gusts of wind at rooftop level which are defined as follows:

V_{c1} the gust speed at which one or more stones are first moved an appreciable distance (say several inches) by the wind.

V_{c2} the gust speed above which scouring of stones would continue more or less indefinitely if the wind speed were maintained.

V_{c3} the gust speed above which an appreciable number of stones (say more than about five) leave the roof by going over the upstream parapet (AB in Graph 1).

The objective of a major part of the procedure is to determine the values of these critical speeds for any given rooftop.

Reference Cases (denoted by subscript ref): as explained in Appendix A, certain cases have been chosen as references or benchmarks, and critical gust speeds for other cases are determined by multiplying the reference critical speeds ($V_{c_{ref}}$) by appropriate factors to account for differing gravel size and differing dimensions of parapets and paving block arrays.

All nomenclature is defined in the List of Symbols at the front of this report. The nomenclature used to define building and rooftop geometry is also defined diagrammatically in Graph 1.

2.2 Flow Chart and Graphs

The analysis/design procedure is presented by means of a flow chart which appears on the following pages. All the diagrammatic data which are used in the procedure are collected in Graphs 1 to 10 which follow the flow chart.

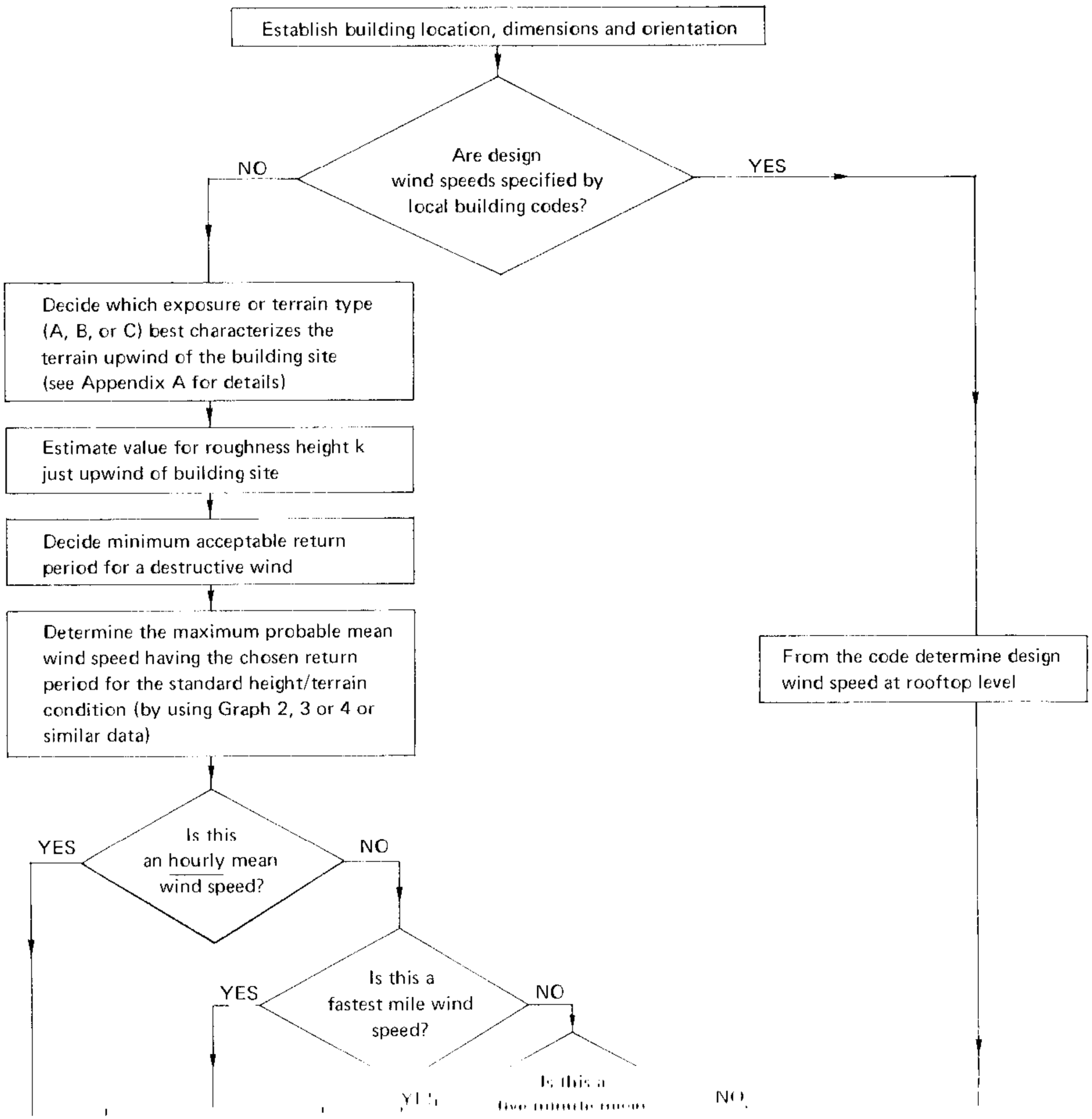
NOTES:

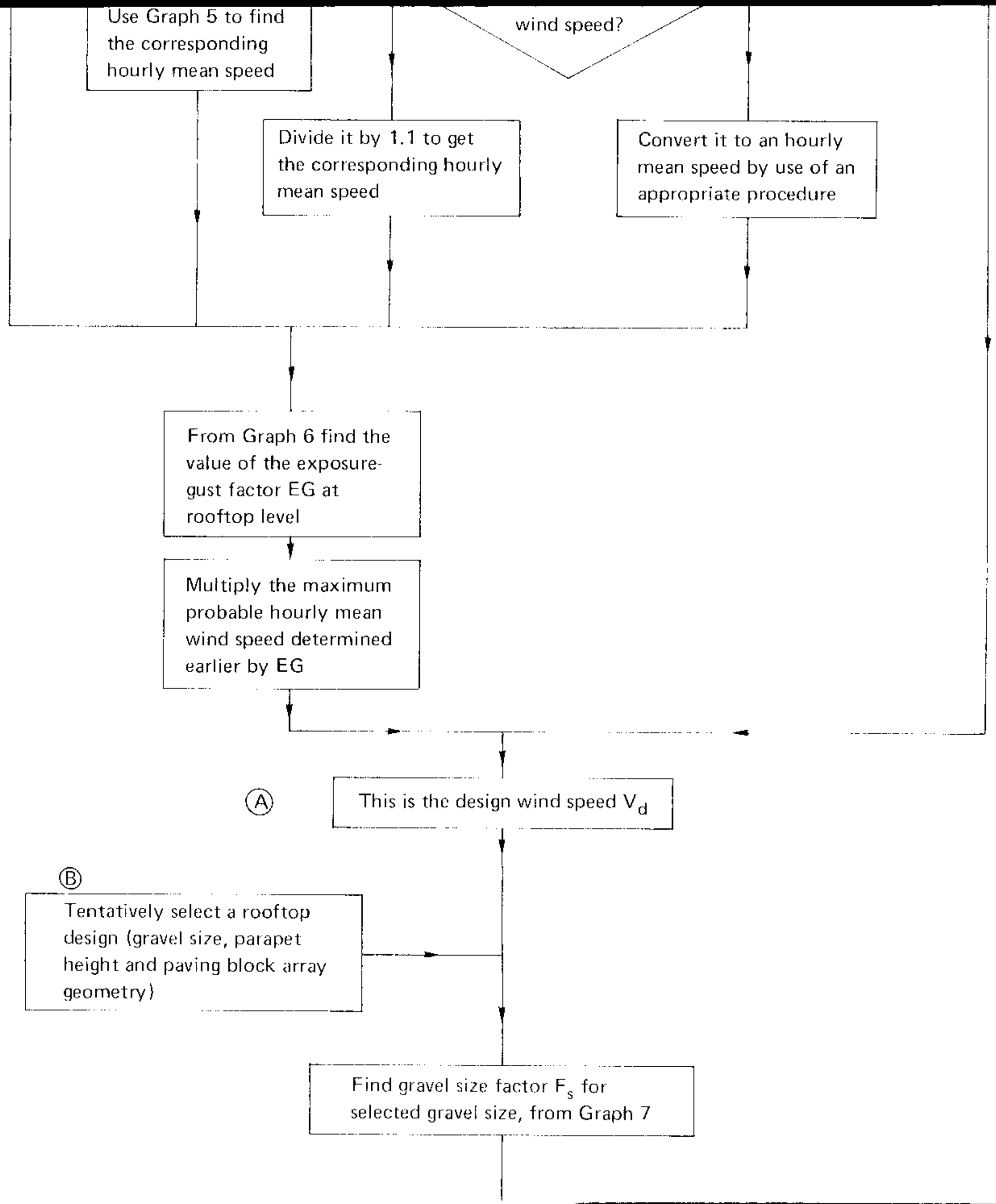
(1) It is assumed that the wind is at 45° to the upwind corner.

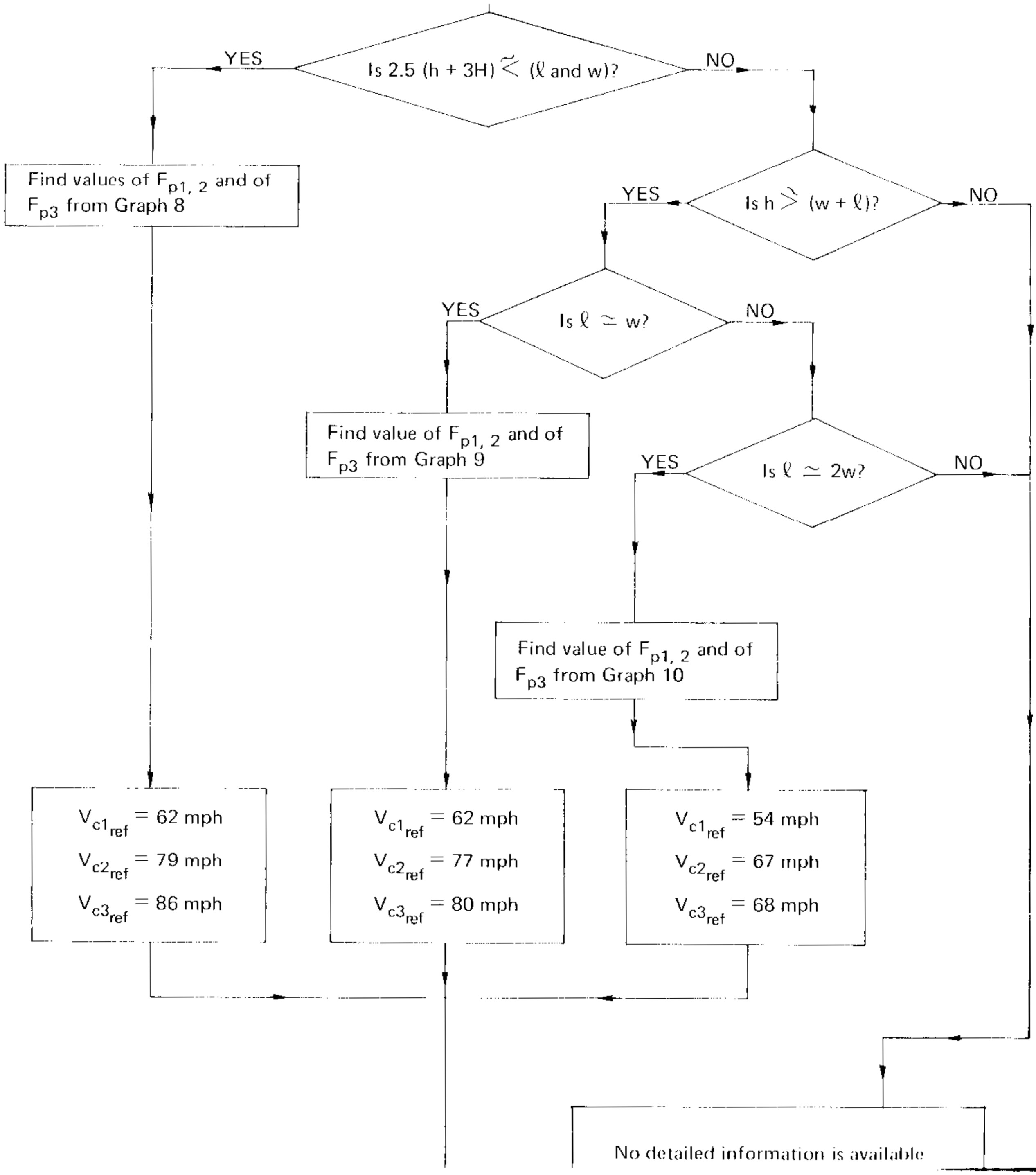
(2) If the terrain in all directions around the building site is characterized by the same exposure type and if the direction of the strongest probable wind is unknown, the design of all four corners must be the same.

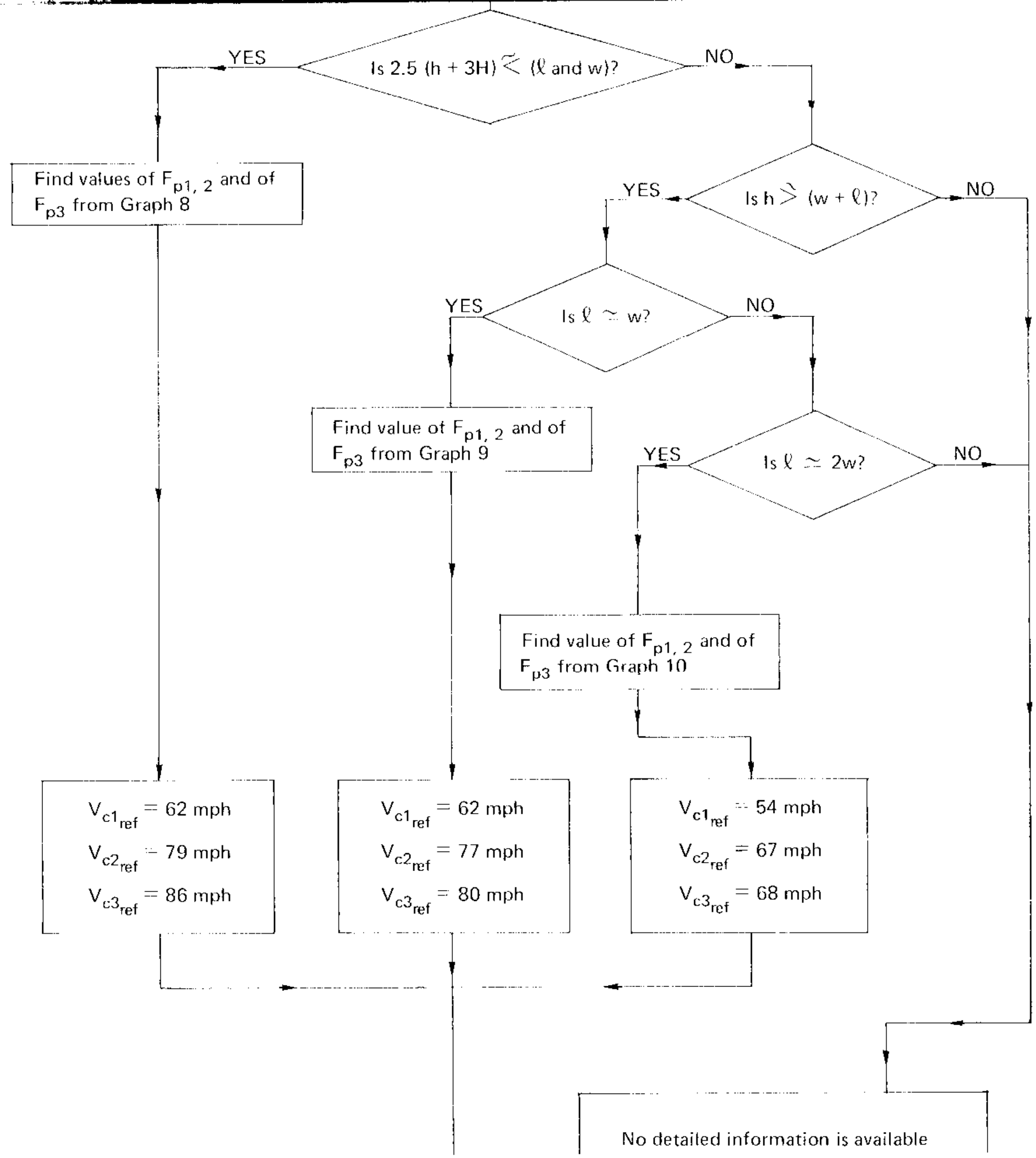
(3) If the strongest probable winds blow only from one known direction and/or if the exposure type varies around the building site it may be possible and desirable to use smaller paving block arrays in less critical corners. If such is the case, the procedure should be carried out separately for each of the four corners of the building.

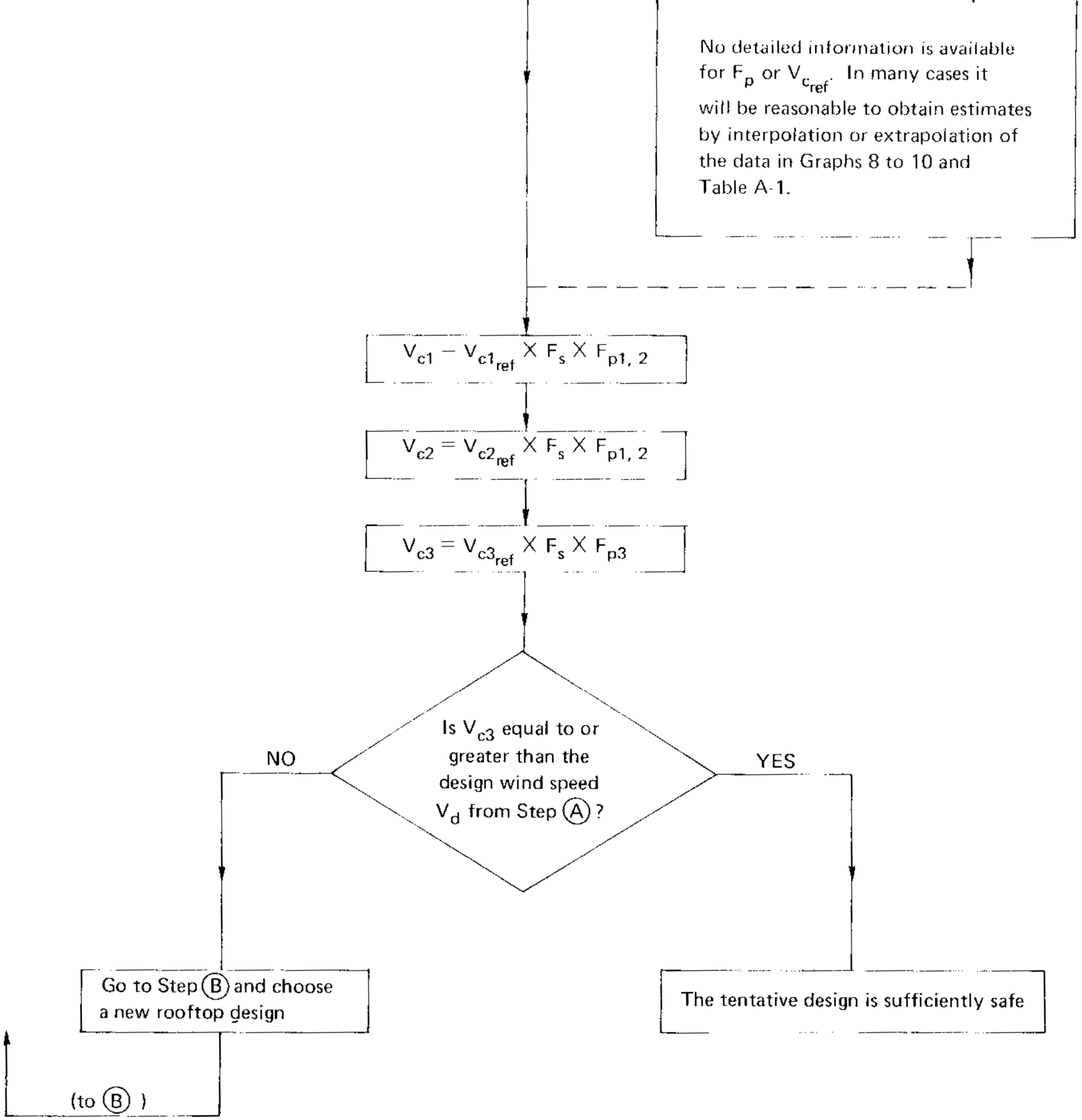
Two examples illustrating use of the procedure are given in Section 2.3, immediately following Graph 10.


Establish building location, dimensions and orientation
Are design wind speeds specified by local building codes?
NO
YES
Decide which exposure or terrain type (A, B, or C) best characterizes the terrain upwind of the building site (see Appendix A for details)
Estimate value for roughness height k just upwind of building site
Decide minimum acceptable return period for a destructive wind
Determine the maximum probable mean wind speed having the chosen return period for the standard height/terrain condition (by using Graph 2, 3 or 4 or similar data)
From the code determine design wind speed at rooftop level
Is this an hourly mean wind speed?
YES
NO
Is this a fastest mile wind speed?
YES
NO


wind speed?
Use Graph 5 to find the corresponding hourly mean speed
Divide it by 1.1 to get the corresponding hourly mean speed
Convert it to an hourly mean speed by use of an appropriate procedure
From Graph 6 find the value of the exposure-gust factor EG at rooftop level
Multiply the maximum probable hourly mean wind speed determined earlier by EG
A
This is the design wind speed V_d
B
Tentatively select a rooftop design (gravel size, parapet height and paving block array geometry)
Find gravel size factor F_s for selected gravel size, from Graph 7

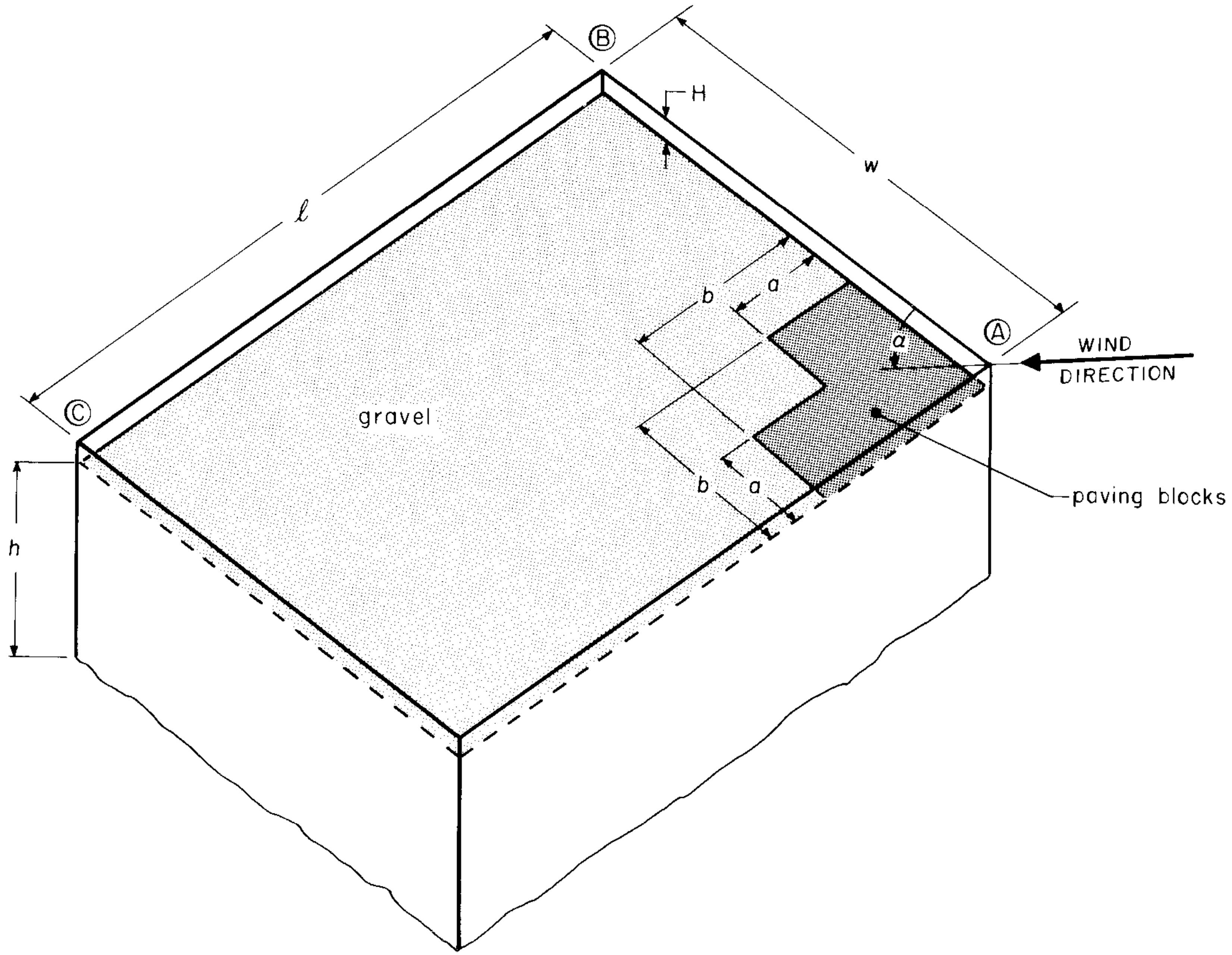

Is 2.5 (h + 3H) ≷ (ℓ and w)?
YES
NO
Find values of $F_{p1,2}$ and of F_{p3} from Graph 8
Is h ≳ (w + ℓ)?
YES
NO
Is ℓ ≃ w?
YES
NO
Find value of $F_{p1,2}$ and of F_{p3} from Graph 9
Is ℓ ≃ 2w?
YES
NO
Find value of $F_{p1,2}$ and of F_{p3} from Graph 10
$V_{c1_{ref}}$ = 62 mph
$V_{c2_{ref}}$ = 79 mph
$V_{c3_{ref}}$ = 86 mph
$V_{c1_{ref}}$ = 62 mph
$V_{c2_{ref}}$ = 77 mph
$V_{c3_{ref}}$ = 80 mph
$V_{c1_{ref}}$ = 54 mph
$V_{c2_{ref}}$ = 67 mph
$V_{c3_{ref}}$ = 68 mph
No detailed information is available


Is 2.5 (h + 3H) ≷ (ℓ and w)?
YES
NO
Find values of $F_{p1,2}$ and of F_{p3} from Graph 8
Is h ≳ (w + ℓ)?
YES
NO
Is ℓ ≃ w?
YES
NO
Find value of $F_{p1,2}$ and of F_{p3} from Graph 9
Is ℓ ≃ 2w?
YES
NO
Find value of $F_{p1,2}$ and of F_{p3} from Graph 10
$V_{c1_{ref}}$ = 62 mph
$V_{c2_{ref}}$ = 79 mph
$V_{c3_{ref}}$ = 86 mph
$V_{c1_{ref}}$ = 62 mph
$V_{c2_{ref}}$ = 77 mph
$V_{c3_{ref}}$ = 80 mph
$V_{c1_{ref}}$ = 54 mph
$V_{c2_{ref}}$ = 67 mph
$V_{c3_{ref}}$ = 68 mph
No detailed information is available

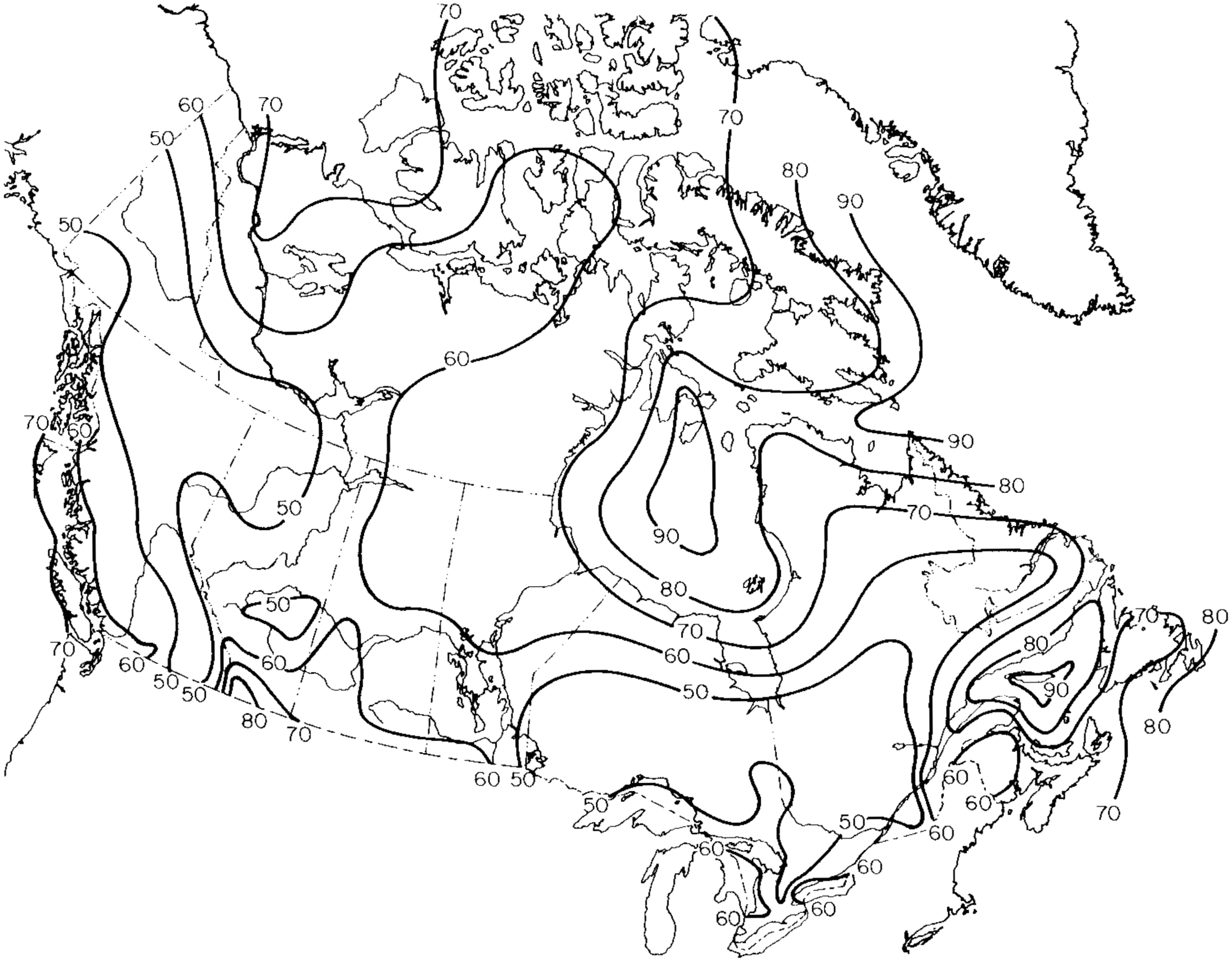


FLOW CHART OF THE PROCEDURE

[redacted]

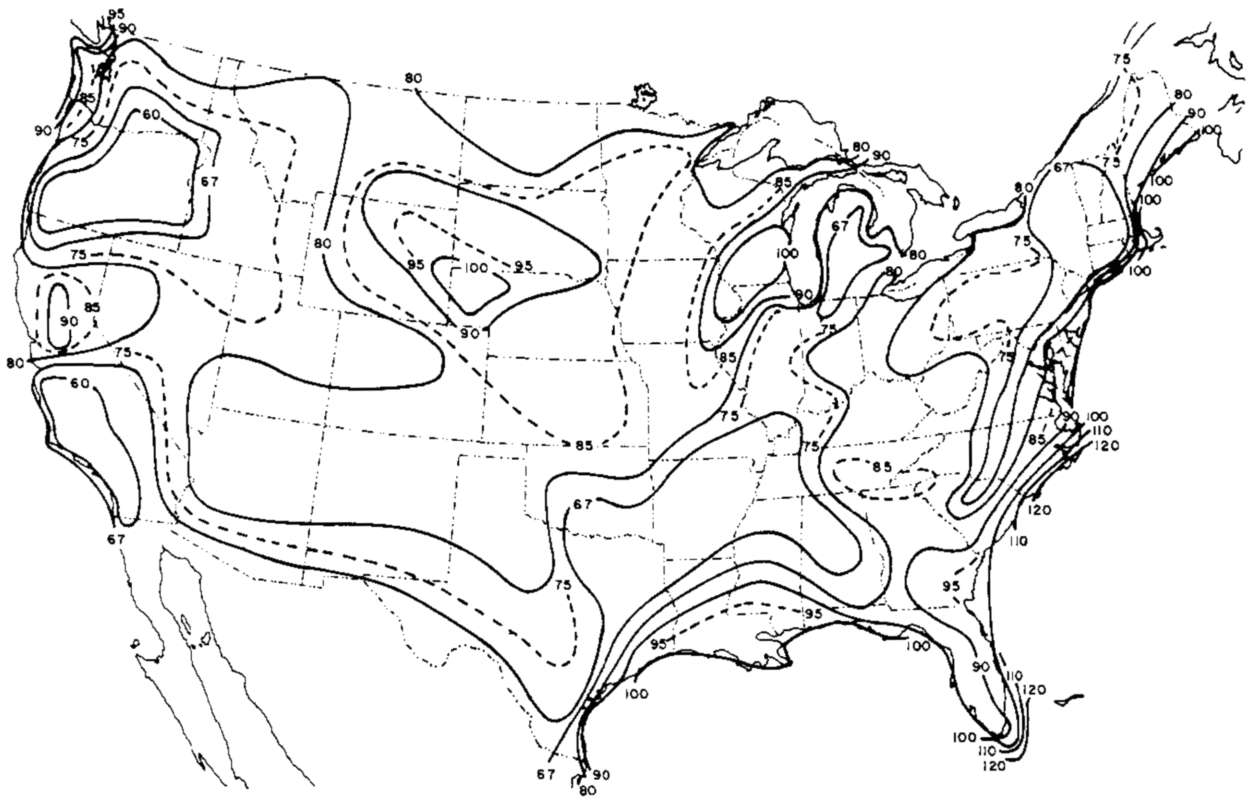


GRAPH 1: SKETCH OF BUILDING AND ROOFTOP TO DEFINE NOMENCLATURE

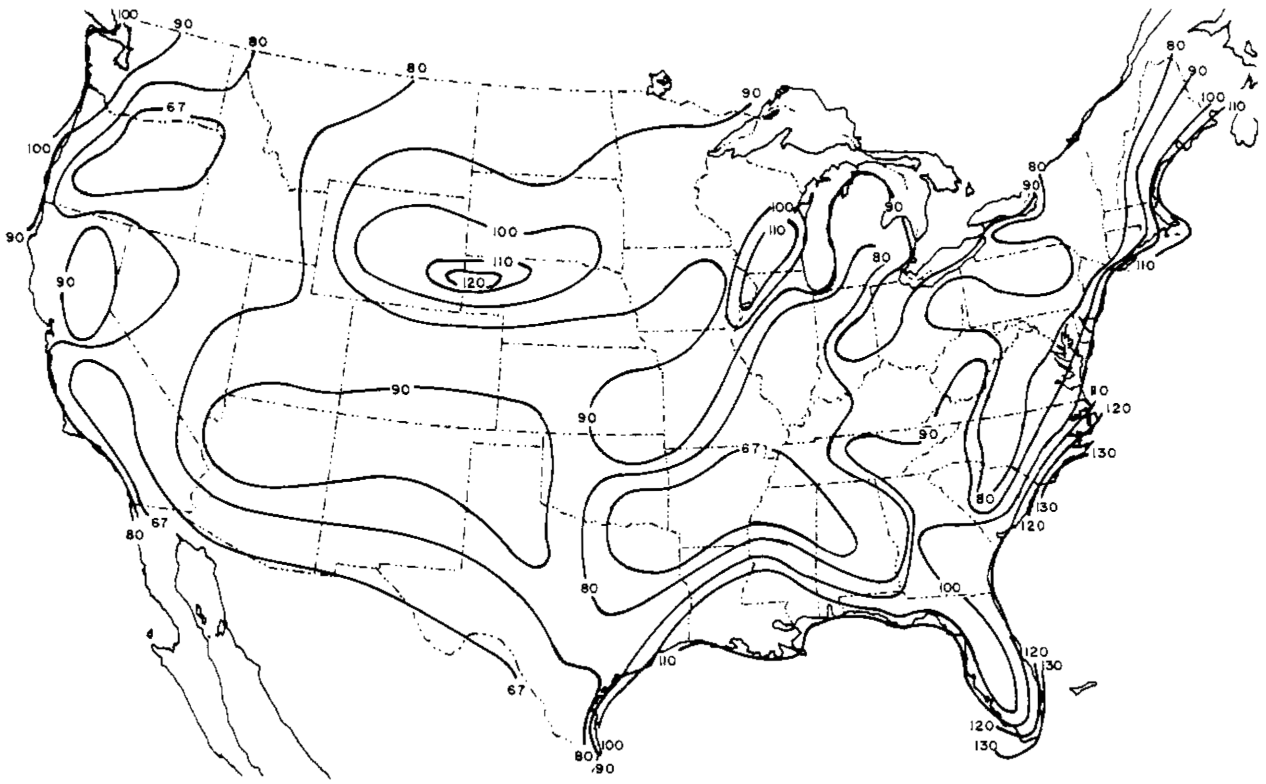


The hourly mean speed (in mph), 30 ft. above ground level over Exposure A terrain, of winds having a 30 year return period, is read off the map for any locality by interpolating between speed contours.

GRAPH 2: MAXIMUM HOURLY MEAN WIND SPEEDS (mph) IN CANADA FOR 30 YEAR RETURN PERIOD (from Ref. 1)



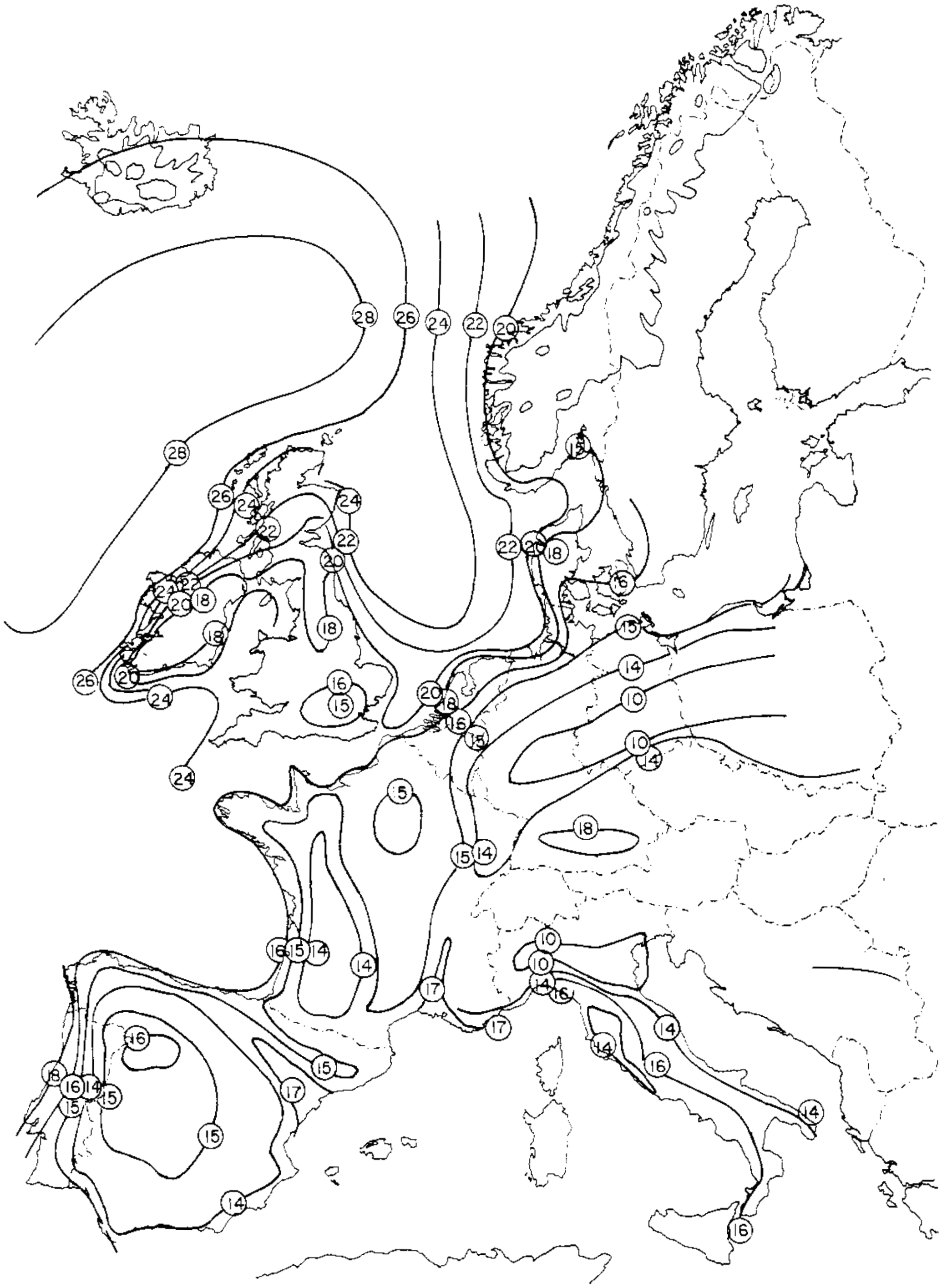
GRAPH 3a: 50 YEAR RETURN PERIOD



GRAPH 3b: 100 YEAR RETURN PERIOD

The speed (in mph), 30 ft. above ground level over Exposure A terrain, of the fastest mile of wind having the quoted return period, is read off the map for any locality by interpolating between speed contours.

GRAPH 3: FASTEST MILE WIND SPEEDS (mph) IN THE UNITED STATES FOR 50 AND 100 YEAR RETURN PERIODS (from Ref. 2)

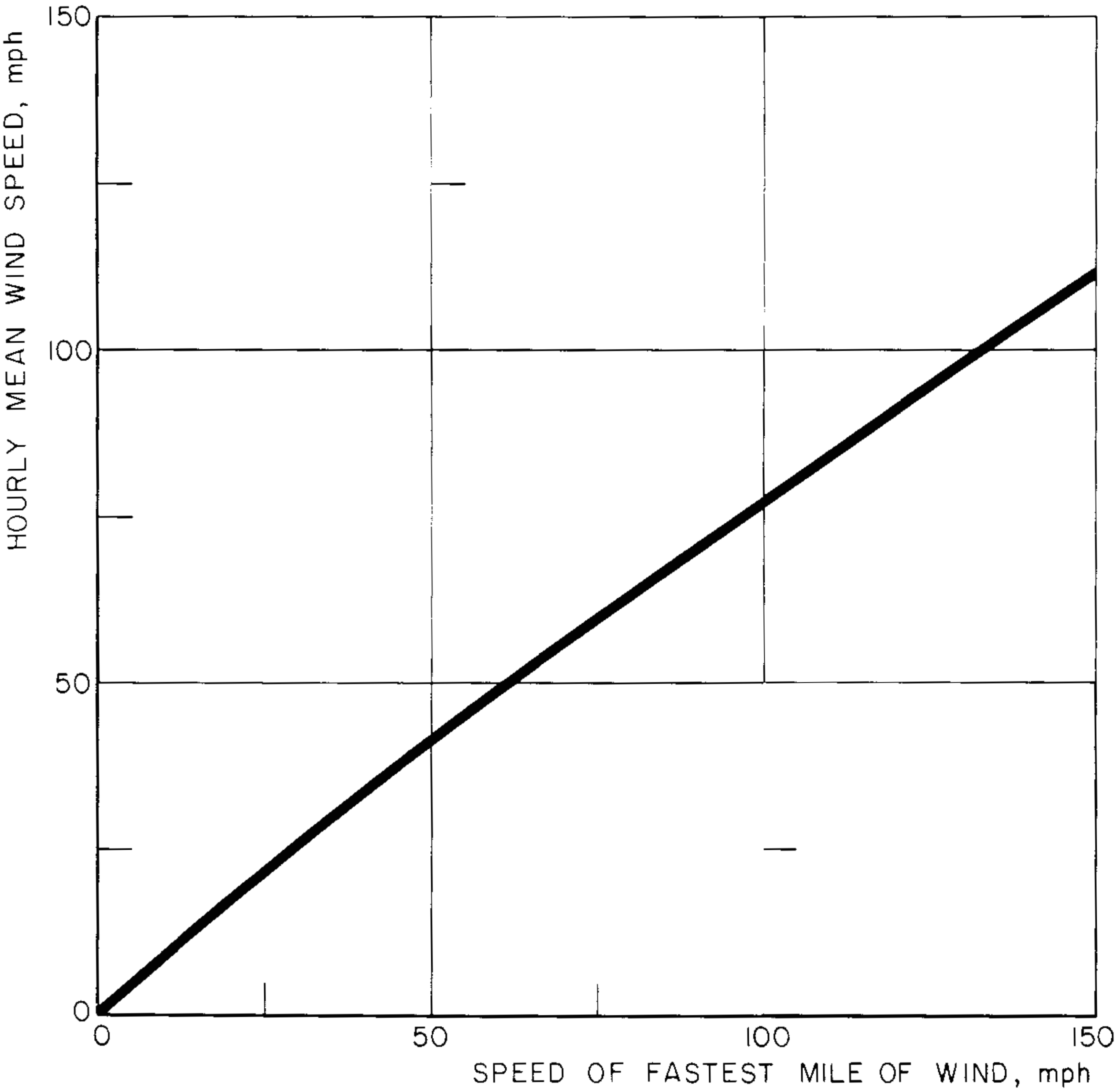


The mode of the annual maximum hourly mean wind speed (in m/s), 10m above ground level over Exposure A terrain, is read for any locality by interpolating between the speed contours. The hourly mean speeds for different return periods can then be determined from the relation $u = \bar{u}\,(1 + 0.1\,\ell n\,R)$

where R is the return period, in years
$\bar{u}$ is the wind speed read from the map, in m/s
u is the wind speed for return period R, in m/s

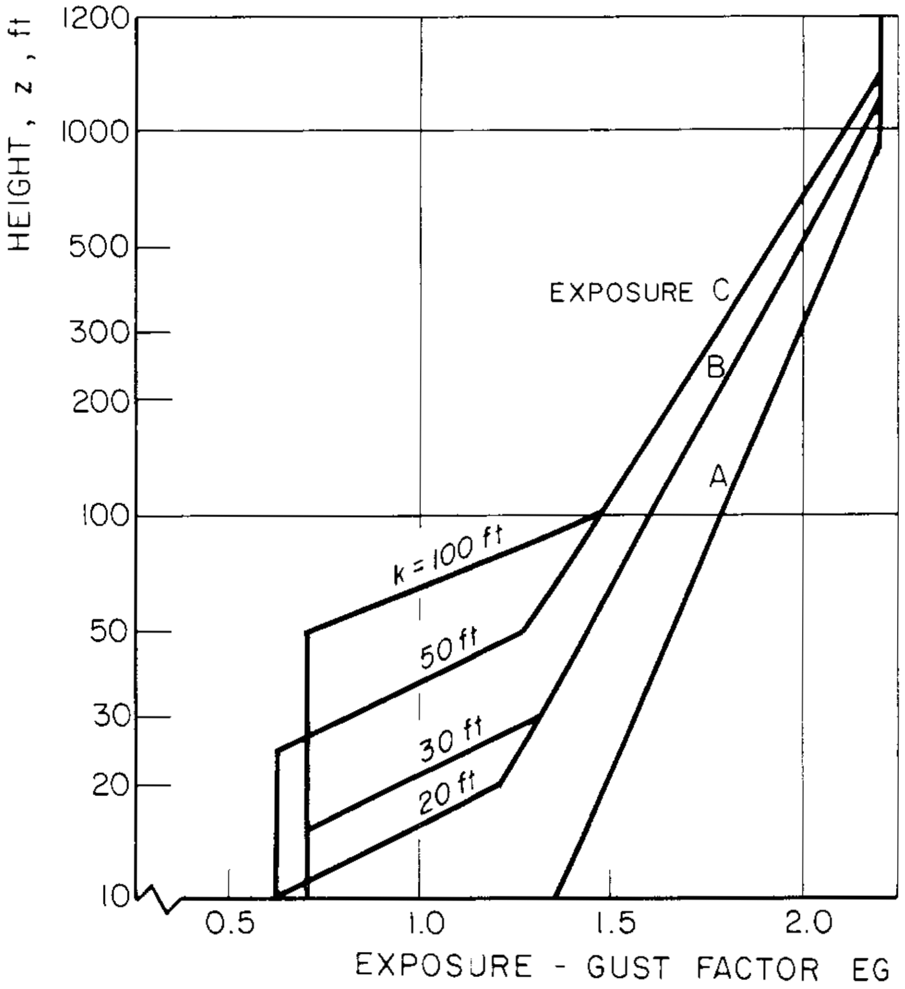
For example: if R = 30 years, $u = 1.34\bar{u}$
if R = 50 years, $u = 1.39\bar{u}$
if R = 100 years, $u = 1.46\bar{u}$

GRAPH 4: THE MODE OF THE ANNUAL MAXIMUM HOURLY MEAN WIND SPEEDS (m/s) IN EUROPE (from Ref. 3)



This graph is used to convert fastest mile wind speeds into equivalent hourly mean wind speeds. It is based on the experimental data of Figure 3, Appendix A.
Example: for fastest mile speed = 50 mph, hourly mean speed = 41 mph.

GRAPH 5: RELATION BETWEEN FASTEST MILE AND HOURLY MEAN WIND SPEEDS
(Exposure A; z = 30 ft.)

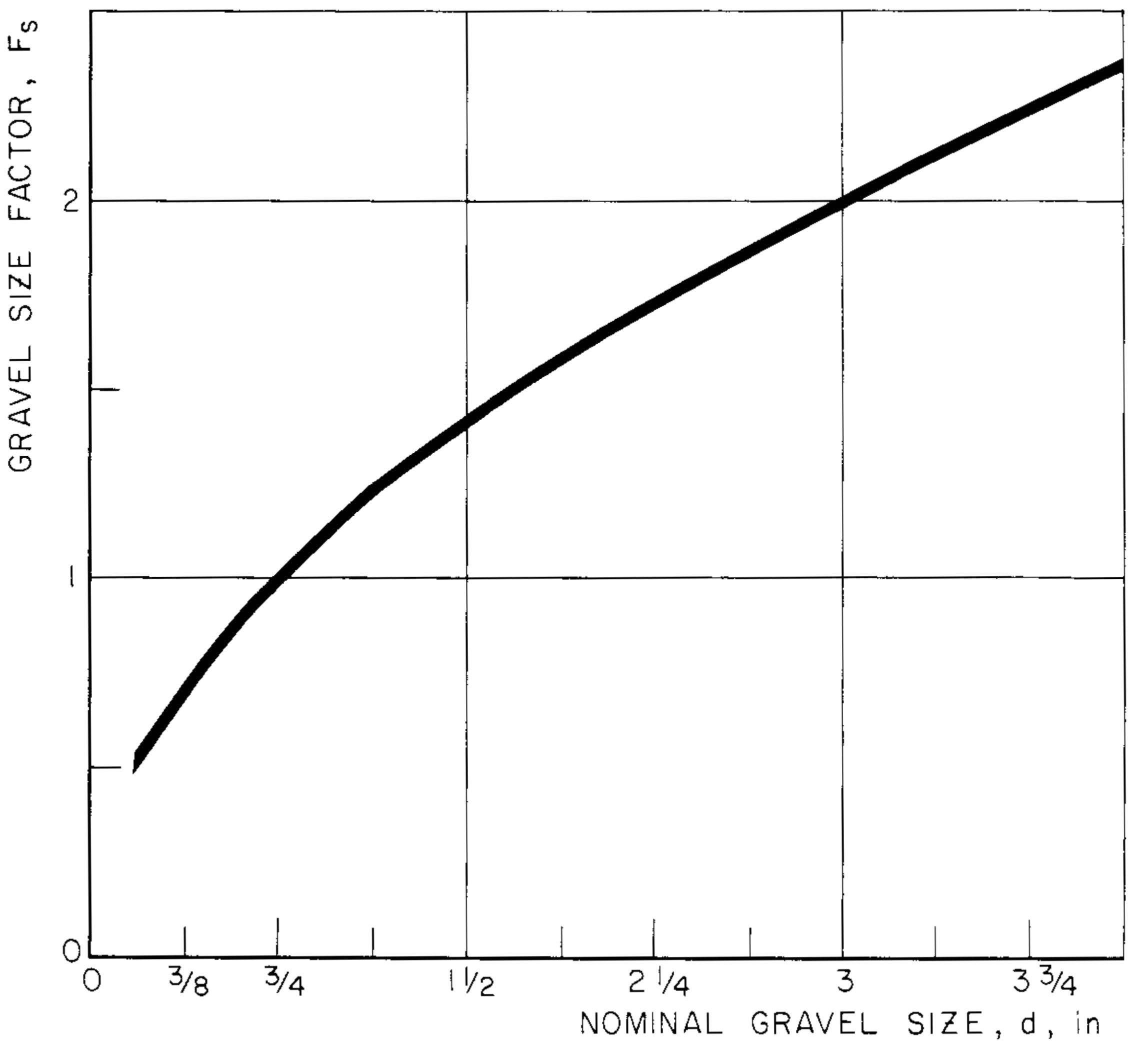


k ≡ height of roughness elements upwind of building site.

z ≡ height of rooftop above ground level.

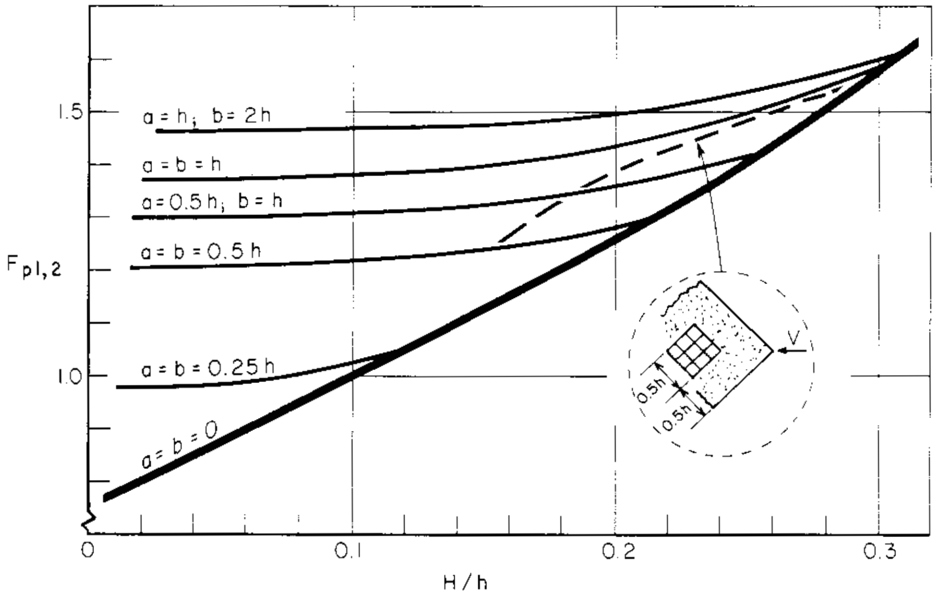
This graph should not be used when 'channelling' of the wind is apt to occur at rooftop level or within roughness which is not reasonably homogeneous (see Appendix A for details).
Before using this graph the designer must judge what exposure type (A, B or C) is appropriate (see Section 2.1) and, for relatively low buildings with Exposures B or C, what value of k is appropriate (see Section 2.1 and/or Appendix A).
The exposure-gust factor accounts for the effects of height, terrain type and gusts.
Example: for z = 40 ft., k = 50 ft., Exposure C, EG = 1.08

GRAPH 6: EXPOSURE-GUST FACTOR VS HEIGHT ABOVE GROUND LEVEL

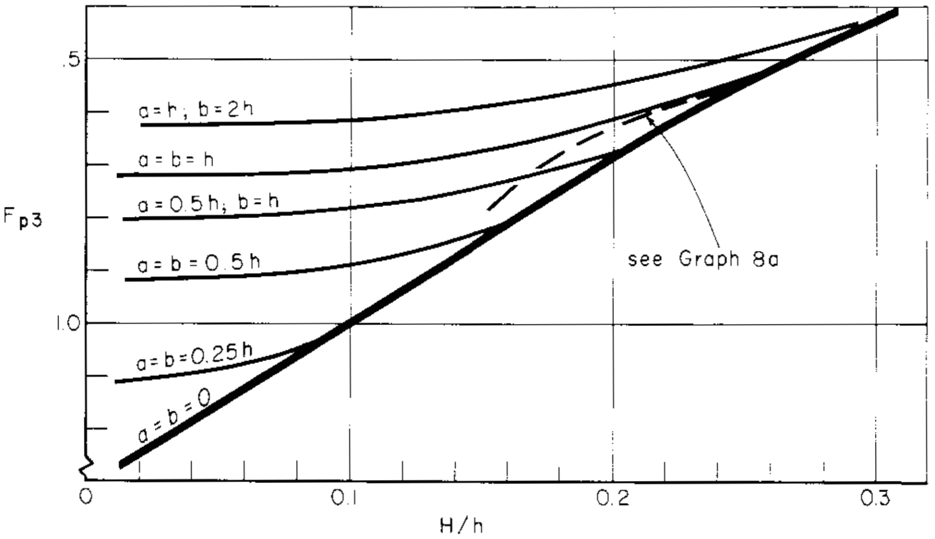


The gravel size factor accounts for the effects of using a gravel size different from 3/4 inch, the reference size. The graph applies for V_{c1}, V_{c2}, and V_{c3} only.
Example: for d = 1½ inch, F_s = 1.41.

GRAPH 7: GRAVEL-SIZE FACTOR VS GRAVEL SIZE



GRAPH 8a - for V_{c1} and V_{c2} only



GRAPH 8b - for V_{c3} only

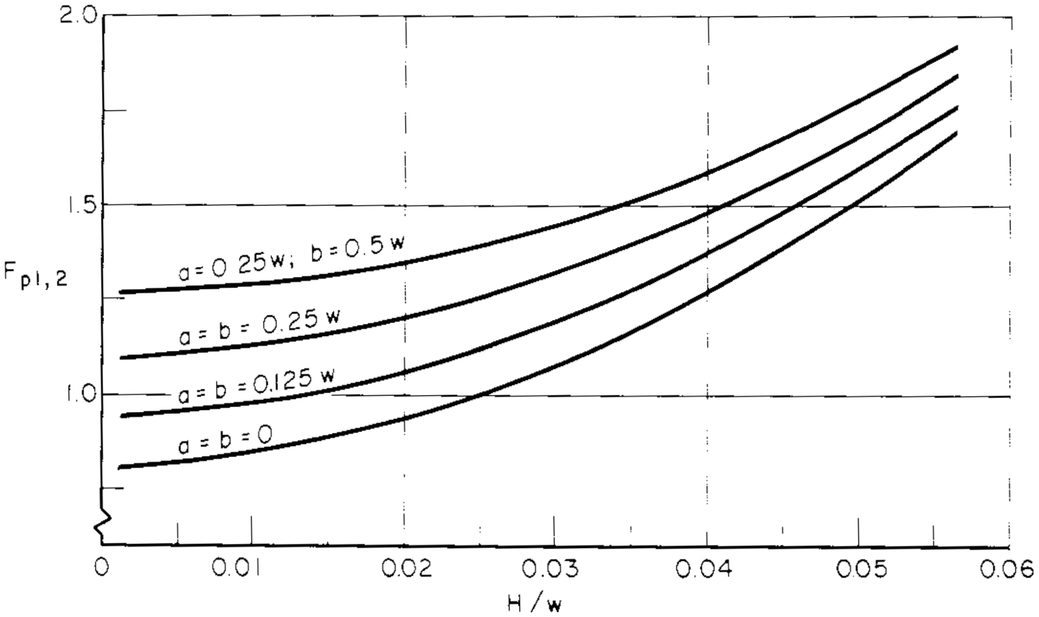
H ≡ parapet height (see Graph 1)

h ≡ building height (see Graph 1)

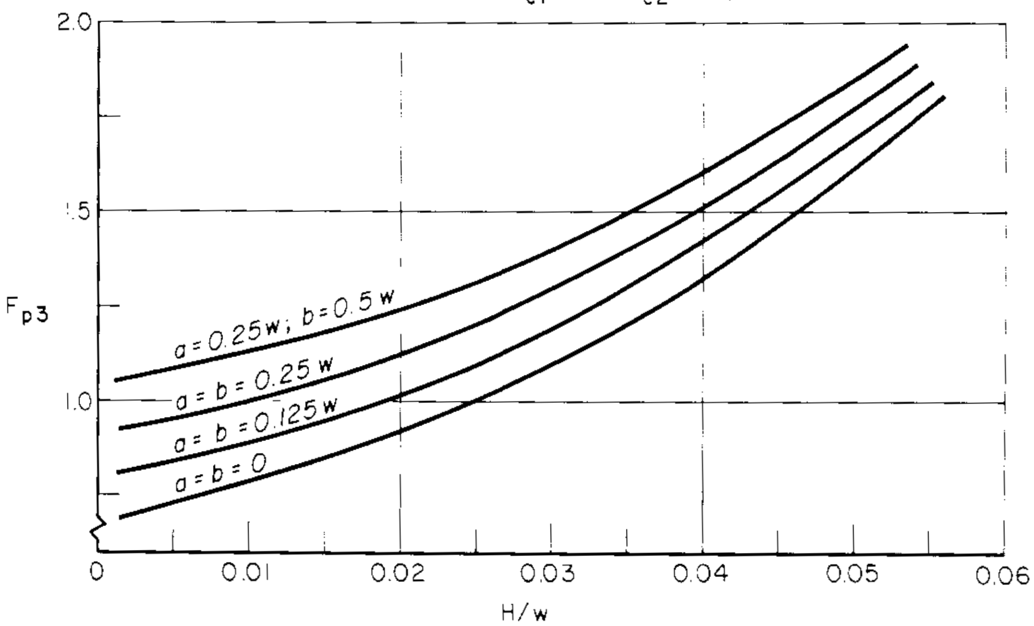
a, b ≡ dimensions of paving block array (see Graph 1)

This graph is only valid when $2.5\ (h + 3H) \lessapprox$ (ℓ and w) where ℓ and w are length and width of the building (see Graph 1). The wind direction angle α is assumed to be 45°.
The factor F_p is used to account for the combined effects of parapets and paving block arrays on the critical wind speeds.
Example: for (H/h) = 0.08, a = b = 0.5 h, $F_{p1,2} \simeq 1.21$ and $F_{p3} = 1.1$

GRAPH 8: PARAPET HEIGHT/PAVING BLOCK ARRAY FACTOR FOR LOW RISE BUILDING SHAPES



GRAPH 9a - for V_{c1} and V_{c2} only



GRAPH 9b - for V_{c3} only

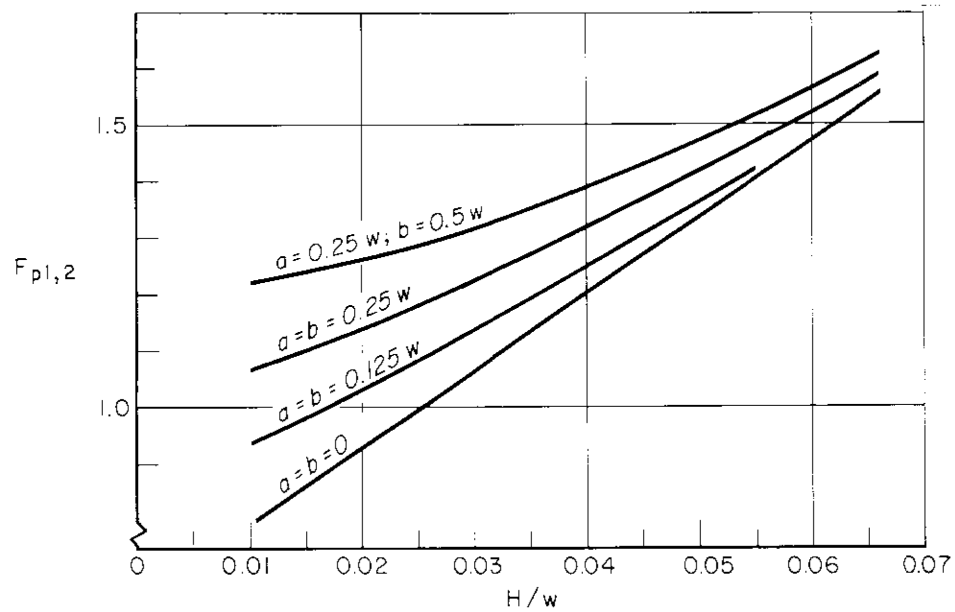
H ≡ parapet height (see Graph 1)

w ≡ building width (see Graph 1)

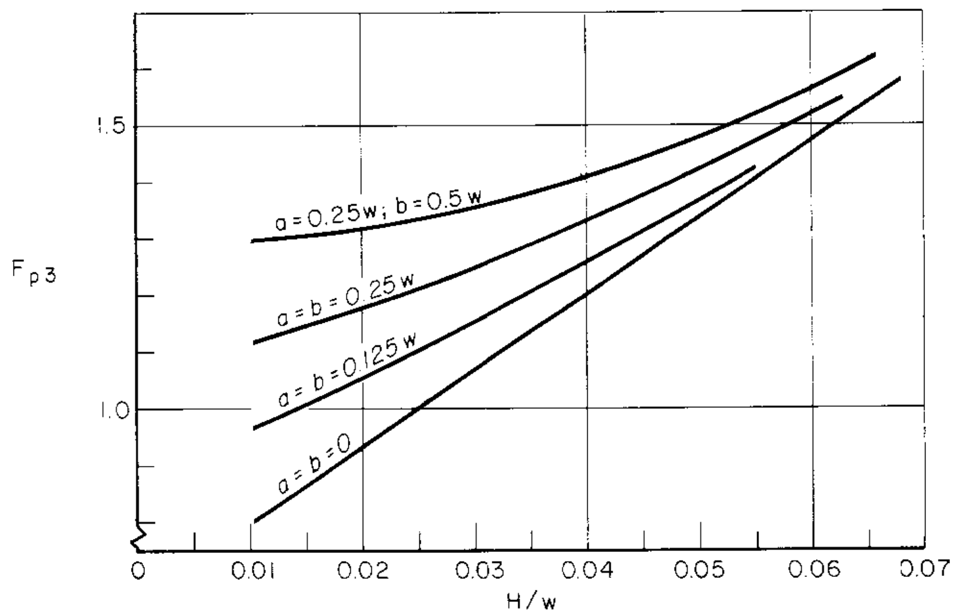
a, b ≡ dimensions of paving block array (see Graph 1)

This graph is only valid when the length:width ratio (ℓ/w) of the building is approximately 1 and when the building is at least twice as high as it is wide (i.e. h ≮ 2w). The wind direction angle α is assumed to be 45°.
The factor F_p is used to account for the combined effects of parapets and paving block arrays on the critical wind speeds.
Example: for (H/w) = 0.04, no paving blocks, $F_{p1,2}$ = 1.27 and F_{p3} = 1.32

GRAPH 9: PARAPET HEIGHT/PAVING BLOCK ARRAY FACTOR FOR HIGH RISE BUILDING SHAPES WITH ℓ = w



GRAPH 10a - for V_{c1} and V_{c2} only



GRAPH 10b - for V_{c3} only

H ≡ parapet height (see Graph 1)

w ≡ building width (the smaller of the two lateral dimensions – see Graph 1)

a, b ≡ dimensions of paving block array (see Graph 1)

This graph is only valid when the length:width ratio (ℓ/w) of the building is approximately 2 and when the building height h satisfies the relation h $\gtrsim$ (w + ℓ). The wind direction is assumed to be 45°.
The factor F_p is used to account for the combined effects of parapets and paving block arrays on the critical wind speeds.
Example: for (H/w) = 0.04, a = 0.25w, b = 0.5w, $F_{p1,2}$ = 1.39 and F_{p3} = 1.41

GRAPH 10: PARAPET HEIGHT/PAVING BLOCK ARRAY FACTOR FOR HIGH RISE BUILDING SHAPES WITH ℓ = 2w

2.3 Examples

To illustrate the use of the procedure it will be carried out for two hypothetical examples.

2.3.1 Low-Rise Building

Let the example building be 15 ft. high by 75 ft. wide by 100 ft. long. It is situated in suburban Toronto, Ontario. We wish to design the rooftop such that winds having a 30 year return period will not cause gravel blow-off.

- $h = 15$ ft.; $\ell = 100$ ft.; $w = 75$ ft.
- 30 year return period
- from Graph 2 the maximum probable hourly mean wind speed for a 30 year return period is 60 mph at Toronto
- exposure B is judged appropriate
- 20 ft. is the estimated value of the roughness height k
- from Graph 6, EG = 0.95
- $60 \times 0.95 = \underline{57 = V_d}$ (mph)
- tentatively select a gravel size of 3/4 in., a 3 in. high parapet (gravel-stop edge) and no paving blocks
- from Graph 7, $F_s = 1.0$
- $h \ll \ell, w$; therefore using Graph 8a we find $F_{p1,2} = 0.8$ ($H/h = 0.017$) and from Graph 8b, $F_{p3} = 0.75$
- $V_{c1} = 62 \times 1.0 \times 0.8 = 50$ mph
- $V_{c2} = 79 \times 1.0 \times 0.8 = 63$ mph
- $V_{c3} = 86 \times 1.0 \times 0.75 = 64.5$ mph

Thus the chosen design is safe because V_{c3} is greater than the design wind speed V_d of 57 mph. Since V_{c2} is also greater than V_d winds having a 30 year return period should not cause significant scouring.

2.3.2 High-Rise Building

The example building is 300 ft. high by 100 ft. wide by 125 ft. long. It is situated in downtown Detroit, Michigan. We desire that no stones will be blown off the rooftop by winds having a 50 year return period.

- $h = 300$ ft.; $\ell = 125$ ft.; $w = 100$ ft.
- 50 year return period
- from Graph 3a, the maximum probable fastest-mile wind speed for a 50 year return period is 80 mph
- exposure type C is judged appropriate

— from Graph 5, the corresponding hourly mean wind speed is 63 mph

— from Graph 6, EG = 1.75

— $63 \times 1.75 = \underline{110 = V_d}$ (mph)

— tentatively select a parapet height of 3 feet, a gravel size of 3/4 inch and no paving blocks

— from Graph 7, $F_s = 1.0$

— $h > (\ell + w)$; also $\ell \simeq w$; therefore using Graph 9a with H/w = 0.03
we find $F_{p1,2} = 1.08$
and from Graph 9b, $F_{p3} = 1.1$

— $V_{c1} = 62 \times 1.0 \times 1.08 = 67$ mph

— $V_{c2} = 77 \times 1.0 \times 1.08 = 83$ mph

— $V_{c3} = 80 \times 1.0 \times 1.1 = 88$ mph

— now $V_{c3} < V_d$ (recall $V_d = 110$ mph)

An increase of about 25% in V_{c3} is required; if 3/4 inch gravel is retained an increase of about 25% in F_{p3} is then required. Consulting Graph 9b, we see that this can be achieved by increasing the parapet height to 4 ft. and by using a paving block array of dimensions 12.5 ft. × 12.5 ft. (0.125w × 0.125w). This revised design gives a V_{c3} of about 114 mph which is satisfactory. It would also be satisfactory to use a parapet height of 4.3 ft. and no paving blocks; this gives a V_{c3} of about 112 mph. Other satisfactory combinations of parapet height and paving block array dimensions can also be found.

3.0 CONCLUSIONS

Design wind speeds relevant to scour or blow-off of rooftop gravel can be established from information available in the literature and the information and procedure for doing so have been presented.

The results of wind tunnel tests conducted to determine critical wind speeds for scour or blow-off of roofing gravel for a specific low-rise building shape can be generalized to apply to any low-rise rectangular building having a flat rooftop. Similar generalization is possible for high-rise shapes of any particular length:width ratio. This has permitted a reasonably general and easy-to-use procedure to be devised for estimating critical wind speeds required to cause scour or blow-off of roofing gravel from various building configurations.

4.0 REFERENCES

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APPENDIX A

BASIS OF METHODS USED IN THE ANALYSIS/DESIGN PROCEDURE

This appendix describes the methods used in each of the major steps of the analysis/design procedure and outlines their theoretical or experimental basis. The limitations of the assumptions and experimental data used in arriving at the various formulae and graphs are outlined and the consequent limitations of the information in this report are discussed.

A.1 Determination of Design Wind Speed

In many cases local building codes will specify the maximum wind speed which the building and its elements must be designed to withstand. In these cases the design wind speed is determined simply by consulting the local building code. In other cases the designer himself will have to determine a design wind speed on some rational basis. This section presents a method of doing this when blow-off cf rooftop gravel is of concern. The method is based on the best information currently available regarding the nature of the wind and the results are thought to be, if anything, a little conservative. Nevertheless the structure of the wind near the earth's surface is complex, highly variable and only imperfectly understood. Moreover winds are the result of 'weather', an imperfectly understood phenomenon, so that the wind climate of a particular region can only be predicted by extrapolation of previous records. 'Freak' occurrences of unexpectedly high winds are therefore not completely ruled out.

The probability that, in a given year, the wind speed will exceed a given value can be expressed in terms of the 'return period' or 'period of recurrence'. For example, if the return period of 70 mph winds is 30 years in a given locality, the probability that the wind speed will exceed 70 mph in any one year is 1/30 or 0.033. The designer must decide what return period represents an acceptable level of risk in any particular case. Data giving local values of the maximum probable wind speeds for various return periods can be found in publications such as References 1, 2 or 3.* The data in such publications normally provide mean wind speed (usually either hourly mean, or five-minute mean, or fastest-mile speed) at the standard reference height/terrain condition, namely 30 ft. or 10 meter height over level open terrain. Thus the designer can determine suitable maximum probable mean wind speeds for the reference height/terrain condition for any locality directly from this published data. For convenience, maps from References 1, 2 and 3 giving such wind-speed data are included in this report as Graphs** 1, 2 and 3. The designer must then apply suitable adjustment factors to these speeds to obtain the maximum probable gust speed at rooftop level appropriate to the nature of the terrain upwind of the building site.

Observation shows that up to the so-called gradient height, the wind speed varies in a power law fashion, as illustrated in Figure 1 (which is adapted from Ref. 4). Both the gradient height and the power law exponent depend on the roughness of the terrain over which the wind is blowing. The National Building Code of Canada (Ref. 5) classifies terrain roughness into three categories:

Exposure A (open or standard exposure) — open level terrain with only scattered buildings, trees or other obstructions, open water or shorelines thereof.

Exposure B suburban or urban areas, wooded terrain, or centres of large towns.

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* All references, including those referred to in this appendix, are listed in the body of this report, in Section 4.0.

** The designation 'Graph' is used to denote those diagrams which are used in the step-by-step calculation procedure of Section 2.0; all Graphs are collected in Section 2.0. The designation 'Figure' is used for all other diagrams, etc. which are part of this appendix. All Figures are at the end of this appendix.

Exposure C centres of large cities with heavy concentrations of tall buildings. At least 50 percent of the buildings exceed four storeys.

The values of gradient height and power law exponent adopted by the Code for these three exposures or terrain types appear in Figure 1. Relatively close to the rough surface, for example, near and below the rooftops of arrays of buildings, the wind speed no longer varies in a power law fashion. The average height, k, of the roughness elements is estimated to be about 3 ft. for Exposure A, 20 to 30 ft. for Exposure B and 50 to 100 ft. for Exposure C. Data in References 6, 7 and 8 suggest that within reasonably homogeneous roughness the mean wind speed remains approximately constant from ground level to about mid-height of the roughness elements; above this level the speed rises rapidly, the speed at the top of the roughness being approximately twice that near ground level. With the variation of mean wind speed established as outlined above, an 'exposure factor' E, defined as the ratio of the mean wind speed for any terrain/height combination to that for the standard reference terrain/ height combination, can be determined. This exposure factor is plotted in Figure 2 as a function of height above the ground for exposures or terrain types A, B and C.

Wind speeds within arrays of tall buildings can sometimes be exceptionally high due to 'channelling' of the wind; Figure 2 does not apply in such conditions.

The maximum mean wind speed for any given return period at rooftop level at any building site can be determined by multiplying the corresponding wind speed at the reference height/terrain condition by the exposure factor appropriate to the level of the rooftop and to the type of terrain upwind of the building. In judging whether Exposure A, B or C is appropriate it should be borne in mind that the corresponding terrain type should persist for a distance of at least one mile in the upwind direction. If doubt exists, it is conservative to choose a more open exposure, e.g. A rather than B or B rather than C. The exposure factor should be varied according to the terrain if the roughness differs from one direction to another. If the building is situated on a fairly abrupt and isolated hill the height used in determining the exposure factor should be measured from the general level of the surrounding terrain rather than from ground level right at the building site (Ref. 9). Unusual wind conditions can occur on peaks and in valleys in mountainous regions and the designer must proceed with extra caution; in particular he should attempt to get wind-speed data for the immediate locality (e.g. for the particular valley or peak in question).

As mentioned in the Introduction, an adjustment to account for the gustiness of the natural wind must also be made. This is done by the use of a gust factor, G, defined herein as the ratio of the maximum probable one-second gust speed to the hourly mean wind speed. Shellard (Ref. 9) quotes results given by Durst, for the standard reference height/terrain condition, of the ratio of maximum probable wind speed in gusts of various averaging time periods to the hourly mean wind speed. Durst's results are plotted in Figure 3. Similar results are given in Reference 10. In this report it is assumed that gusts having a period as short as one second are able to blow gravel off rooftops; Figure 3 shows that at the reference height/terrain condition the maximum speed of such gusts is about 60% greater than the hourly mean wind speed. This quantity is expected to vary with altitude and type of terrain. It is reasonable to assume that the excess of the gust speed over the mean wind speed is proportional to the intensity of the turbulence in the atmospheric boundary layer since it can be shown that the effect of the variation of the longitudinal scale of the turbulence with height is minor (Ref. 11). It is also reasonable to assume that the turbulence intensity is proportional to the square root of the Reynolds shear stress (Refs. 11 and 12). Between the top of the roughness elements and the 500 ft. level the variation of this shear stress can in turn be estimated using law-of-the-wall similarity theory (Ref. 13) and an eddy-viscosity correlation (constant eddy-viscosity Reynolds number) can be used at higher altitudes (Ref. 12). This approach was used together with Durst's result for the reference height/terrain condition to estimate the variation of the gust factor as a function of height and type of terrain. These results were compared with the recommendations of the Engineering Sciences Data Unit (Ref. 14) and the agreement was found to be reasonably good. Near the top of the roughness the calculated gust factor G has values of about 2 and 2.5 for Exposures B and C respectively. Measurements of turbulence intensity in Reference 6 indicate that the gust factor G reaches a maximum value of about 2 in the flow below the tops of the roughness elements. G was accordingly assumed to remain approximately constant at a value between 2 and 2.5 from ground level to the top of the roughness. The product of E and G gives a combined exposure-gust factor EG. The exposure-gust factors adopted in this report are plotted in Graph 6. The speed of one-second gusts at rooftop level is obtained simply by multiplying the hourly mean wind speed at the standard reference terrain/height condition by the appropriate value of EG. Graph 6 is not valid where 'channelling' of the wind occurs or within roughness which is not reasonably homogeneous.

To use Graph 6 for relatively low buildings with Exposures B or C the designer must estimate the average height k of the roughness elements just upwind of the building site. As mentioned earlier, k should have a value in the range 20 to 30 ft. for Exposure B and 50 to 100 ft. for Exposure C. If doubt exists, the lowest reasonable value of k should be adopted.

As can be seen from Figure 3, the value of the gust factor will depend on the gust duration and on the averaging time used in measuring the mean wind speed. As already mentioned, it is judged that gust durations as short as about one second are significant for gravel blow-off; Figure 3 shows that the gust factor is not overly sensitive to this judgement. Graph 6 gives the exposure-gust factor for one second gusts relative to hourly mean wind speeds. As mentioned in the Introduction, wind speed data at the standard reference height/terrain condition are commonly presented in terms of either hourly mean speeds, five-minute mean speeds or fastest-mile speeds. Before using Graph 6, five-minute mean speeds or fastest-mile speeds should be converted to equivalent hourly mean speeds by multiplication by (1/1.1) or by the use of Graph 5 respectively. Both the factor (1/1.1) and Graph 5 are based on Figure 3.

In summary, the design wind speed, if not specified by a local building code, is determined as follows:

(1) From meteorological data obtain the maximum probable wind speed at the reference height/terrain condition having the desired return period.

(2) If necessary convert this speed to an equivalent hourly mean wind speed.

(3) Multiply by the exposure-gust factor EG given by Graph 6 for the appropriate rooftop elevation and terrain type upwind of the building. The result is the design wind speed.

This procedure assumes that the derivative of wind speed with respect to height is unimportant, so that only the speed at rooftop level is significant. A check included in the experimental program indicated that this assumption is satisfactory for present purposes.

A.2 Estimation of Gust Speeds Required at Rooftop Level to Cause Scour or Blow-Off of Rooftop Gravel

Once the designer has determined the design wind speed, he must choose a rooftop design (i.e. gravel size, parapet height, and paving block array geometry) which will successfully withstand this wind speed. This is best done by somewhat arbitrarily choosing an initial design and analysing it to see if the design wind speed can be successfully withstood; if so, the design is acceptable; if not, a revised design must be chosen and analysed until an acceptable design is arrived at. This section will outline the analysis procedure and its basis. Virtually all the quantitative information used in the procedure was obtained from wind tunnel tests which are described in detail in References 15, 16 and 17.

A.2.1 Critical Speeds for a Reference Case

In this report the symbol V denotes the speed of gusts of wind at rooftop level. As in the earlier report (Ref. 16), four different critical speeds are identified:

V_{c1} the gust speed at which one or more stones are first moved an appreciable distance (say several inches) by the wind.

V_{c2} the gust speed above which scouring of stones would continue more or less indefinitely if the wind speed were maintained.

V_{c3} the gust speed above which an appreciable number of stones (say more than about five) leave the roof by going over the upstream parapet (AB in Graph 1).

V_{c4} the gust speed above which an appreciable number of stones leave the roof by going over the downstream parapet (BC in Graph 1).

Of course the values of these critical speeds will depend on the rooftop design and on the wind direction and the aim is to predict these values.

It is convenient for this purpose to arbitrarily choose certain cases as references or bench-marks. Critical speeds for other cases can then be determined by multiplying the corresponding critical speed for the reference case by appropriate factors to account for differing gravel size, parapet height and paving block array geometry. This approach allows the available results to be presented in a concise form and also allows full advantage to be taken of their universality. For example, the measurements taken on the specific low-rise building model used in the tests are applicable to any low-rise building and the results are presented in such a way that it is a straightforward matter to use them for any low-rise building. As mentioned in the Introduction, one expects the flow over the rooftops of low-rise buildings to be somewhat different from that over high-rise buildings. Consequently a separate reference case and set of results are required for low-rise building shapes and for each ℓ:w ratio for high-rise shapes. Medium-rise shapes would also require separate reference cases and sets of results but none of these were tested. Results are represented for three basic building shapes; the corresponding reference cases and reference critical speeds are tabulated in Table A-1. The critical speed V_{c4} does not appear in Table A-1 for reasons which are discussed later.

TABLE A-1

REFERENCE CASES AND REFERENCE CRITICAL SPEEDS

Building Shape	Reference Conditions				Reference Critical Speeds (mph)		
	Gravel Size d_{ref} (in.)	Parapet Height Ratio	Paving Block Array	Wind Angle α_{ref}	$V_{c1_{ref}}$	$V_{c2_{ref}}$	$V_{c3_{ref}}$
low rise ($h << \ell,w$)	3/4	H/h = 0.1	None	45°	62.0	79.0	86.0
high rise ($h >> \ell,w$) $\ell/w = 1$	3/4	H/w = 0.025	None	45°	62.0	77.0	80.0
high rise ($h >> \ell,w$) $\ell/w = 2$	3/4	H/w = 0.025	None	45°	54.0	67.0	68.0

The universality of the results only applies to V_{c1}, V_{c2} and V_{c3}, and not, unfortunately, to V_{c4}. This is because the events associated with V_{c1}, V_{c2} and V_{c3} occur near the upstream end of the building and these speeds do not, therefore, depend on the absolute length or width of the building, but only on its relative proportions. V_{c4} on the other hand involves the stones travelling the full length of the building so that V_{c4} most probably depends on this length. As a specific example, consider two low-rise buildings, one 75 ft. × 75 ft. × 15 ft. high and the other 150 ft. × 150 ft. × 15 ft. high, both with 1.5 ft. high parapets and 3/4 inch gravel with a wind angle of about 45°; one would expect V_{c1}, V_{c2} and V_{c3} to have the same values for both buildings while V_{c4} would be expected to have a higher value for the larger building. Because of this the experimental results for V_{c4} are restricted to the specific dimensions of the tested buildings while the results for V_{c1}, V_{c2} and V_{c3} are more widely applicable. Subsections A.2.2 to A.2.4 inclusive are only concerned explicitly with prediction of V_{c1}, V_{c2} and V_{c3}. Subsection A.2.5 deals with prediction of V_{c4}.

A.2.2 Effect of Wind Direction

The experiments clearly showed that the gravel scour and blow-off phenomenon is quite sensitive to the direction of the wind relative to the building. When the wind angle α (see Graph 1) is about 45° the critical speeds are much lower than for wind angles of about 90°. This point is illustrated by Figure 4. As mentioned in the Introduction, this behaviour is due to strong vortices which form along the upstream edges of the rooftop when $\alpha \simeq 45°$ (see Refs 15 and 16). In most localities winds are strongest from some particular direction but the sector of strongest winds usually covers an angular range of approximately 90°. Therefore at least one corner of any rooftop is likely to be exposed to the design wind speed with a wind angle of 45°. This then is the critical design case and the analysis procedure therefore deals only with this 'worst' case.

A.2.3. Gravel-Size Factor

As pointed out in Reference 15, the shear stress factor ($\tau_{max}/\frac{1}{2}\rho V^2$) is a constant for any particular building configuration;* in particular, this factor does not depend on gravel size, d, or on wind speed V. τ_{max} is the maximum shear stress acting on any gravel-covered area of the rooftop. Reference 15 also established that the shear stresses required to cause initial strong motion of the stones or to cause sustained scouring are proportional to d, the nominal gravel size. It follows then that V_{c1} and V_{c2} are proportional to $\sqrt{d}$ for any building configuration. Therefore the effect of gravel size being different from that in the reference case is easily accounted for by multiplying the reference critical speed by the gravel size factor F_s, where F_s is given by

$$F_s = \sqrt{d/d_{ref}} \qquad (1)$$

This is plotted in Graph 7 for the reference cases of Table A-1.

The experimental evidence and analysis give a firm indication that V_{c1} and V_{c2} are proportional to $\sqrt{d}$ as outlined above. In the case of V_{c3}, however, the stones must rise up over the parapet to leave the rooftop and dimensional analysis then suggests that the ratio d/H (gravel size: parapet height) might be significant. If d/H is significant V_{c3} cannot in general be proportional to $\sqrt{d}$ for a fixed building configuration. Fortunately, however, the limited available experimental evidence and some crude analysis do suggest that V_{c3} is in fact proportional to $\sqrt{d}$ so that the gravel size factor F_s given by Equation (1) can also be used for V_{c3}. The crude analysis which supports this is as follows:

For a fixed building configuration it is reasonable to assume that the stones travel the same distance to get over the upstream parapet regardless of stone size. This is reasonable because the particle path is determined mainly by the direction of the drag force which is determined by the fixed structure of the

* In this report the term 'building configuration' is meant to include such parameters as parapet height and paving block array geometry in addition to the basic building shape.

flow field. It is also reasonable to assume that the stones require a certain amount of kinetic energy to get over the parapets; that is $mgH \propto \frac{1}{2}mv^2$ where m is the mass of the stones, H is the parapet height and $\frac{1}{2}mv^2$ is the energy which the stones acquire from the airflow. It is reasonable to assume that the speed of the stones is much less than the local air speed which is proportional to V_{c3}.

Then $(\frac{1}{2}mv^2) \propto$ (drag coefficient) $\times V_{c3}^2 \times d^2 \times$ (distance travelled by stones) (2)

or
$$mgH \propto V^2 d^2 \qquad (3)$$

or, since $m \propto d^3$ and H is fixed

$$V_{c3} \propto \sqrt{d} \qquad (4)$$

An alternative analysis is to assume that the stone is lifted over the parapet when its weight is equalled by the upward component of the drag force. Since the direction of the drag force is fixed this gives

$$mg \propto (\text{drag coefficient}) \times V_{c3}^2 \times d^2 \qquad (5)$$

which again, since $m \propto d^3$, yields Equation (4).

Both analyses in effect assume that inertia forces on the stones are negligible so that only the ratio of drag force to gravity force on the stones is important. In fact this assumption, which seems quite reasonable for V_{c3}, considering the observed behaviour of the stones, leads directly to Equation (4). In this report it is assumed that Equation (4) is valid so that the gravel-size factor of Equation (1) can be used for V_{c3} as well as for V_{c1} and V_{c2}.

In the case of V_{c4} the stones must travel large distances to leave the rooftop via the downstream parapet. Therefore we cannot assume that the speed of the stones is negligible compared with the speed of the airflow and the above analyses do not apply. In the case of very long rooftops the speed of the stones will be approximately equal to that of the airflow and a revised version of the first analysis then suggests that V_{c4} is independent of stone size (i.e. $V_{c4} \propto d^0$). For less long rooftops the suggestion is that

$$V_{c4} \propto d^n \qquad (6)$$

where $0 < n < \frac{1}{2}$; n will depend on the length of the rooftop. The experimental data for the 75 ft. square by 15 ft. high low-rise buildings of the tests give $V_{c4} \propto d^{1/4}$ approximately. In any case it appears clear that the stone size factor of Equation (1) should not be used for V_{c4}. This is a further reason why V_{c4} cannot be dealt with as easily as V_{c1}, V_{c2} and V_{c3}.

A.2.4 Parapet Height/Paving Block Array Factor

For reasons stated in the Introduction, the effects of building shape, parapet height and paving block array geometry are interdependent and cannot be decoupled. A graph giving a combined parapet height/paving block array factor F_p has been prepared, on the basis of test results, for each of the three basic building shapes listed in Table A-1. Graphs 8, 9 and 10 present this information. The factor F_p represents, by definition, the following ratio:

$$F_p \equiv \left[\frac{(V_c)_{d = d_{ref}}}{V_{c_{ref}}}\right] \qquad (7)$$

As mentioned in Subsection A.2.3, the shear stress factor $(\tau_{max}/\frac{1}{2}\rho V^2)$ has a constant value for any given building configuration. Furthermore the magnitude of the shear stress required to cause initial strong motion of the stones or to cause sustained scouring is proportional to d, the nominal gravel size, and the constant of proportionality is independent of building configuration. It follows that for critical wind speeds V_{c1} and V_{c2} the factor F_p of Equation (7) can also be considered to represent the ratio

$$F_p = \left[\frac{(\tau_{max}/\frac{1}{2}\rho V^2)_{ref}}{(\tau_{max}/\frac{1}{2}\rho V^2)} \right]^{\frac{1}{2}} \tag{8}$$

This implies that the parapet height/paving block array factor F_p has the same value for both V_{c1} and V_{c2}. The magnitude of the shear stress associated with blowing of stones over the upstream parapets is expected to depend on building configuration because the trajectory of the stones will of course be dependent on this. Consequently the argument leading to Equation (8) does not apply to V_{c3} and we can expect that the values of the parapet height/paving block array factor F_p for V_{c3} will differ from corresponding values for V_{c1} and V_{c2}. Graphs 8a, 9a and 10a give values of F_p for critical speeds V_{c1} and V_{c2} while Graphs 8b, 9b and 10b give values of F_p for the critical speed V_{c3}.

For gravel size d_{ref} the critical wind speed for a particular building configuration is obtained by multiplying the corresponding reference critical speed (given in Table A-1) by the appropriate value of the factor F_p (obtained from Graph 8, 9 or 10 as appropriate). Judicious interpolation can be used if necessary. If the gravel size is in fact different from d_{ref}, the result is multiplied by the gravel-size factor of Graph 7.

The reader will note that all lengths (e.g. parapet height H and paving block array dimensions a and b), (see Graph 1 for nomenclature) appear in non-dimensionalized form as H/h, a/h, etc. in Graph 8. This is done in order to take advantage of the universality of the data. Graph 8 applies to any low-rise building shape ($h << \ell, w$) regardless of its actual height, length or width. This is because the structure of the flow in the upstream corner of the rooftop is independent of the length and width of the low-rise building; only the height h matters and its influence is that it establishes the size or length scale of the flow in the upstream corner. Therefore, because Reynolds number effects should be negligible, the flows in the upstream corners of low-rise buildings having different heights but the same H/h, a/h and b/h will be 'scale models' of one another. Consequently the shear stress factors and, for any given gravel size, the critical speeds V_{c1} and V_{c2} will have the same values. The same is true of V_{c3} if inertia forces on the stones are negligible as argued in Subsection A.2.3. As mentioned in Section A.1, the experiments indicate that the derivative of wind speed with respect to height above ground is unimportant in the present work. This condition is necessary for the data to be universal as outlined here.

For exactly similar reasons, the data for high-rise building shapes ($h >> \ell, w$) are also presented in non-dimensional form in Graphs 9 and 10. Since the height is much greater than either the length or width of the building it has no influence on the structure of the flow over the rooftop. The platform geometry of the rooftop influences the basic flow structure and establishes its size or length scale; the flow structure is different for different ℓ:w ratios. All lengths in Graphs 9 and 10 are accordingly non-dimensionalized by the width w of the rooftop and each graph only applies for the specified ℓ:w ratio.

No rigid criterion is known for distinguishing between low-rise, medium-rise and high-rise building shapes. For the present purposes the following criteria are suggested:

$$\text{low-rise:} \quad 2.5\,(h + 3H) \lesssim (\ell \text{ and } w) \tag{9}$$

$$\text{high-rise:} \quad \text{if } \ell/w = 1,\ h \gtrsim 2w$$

or more generally, [illegible] (10)

The parapet height H appears in Equation (9) because for a given building height, h, the length scale of the flow in the upstream corner becomes larger as the parapet height H is increased and the length and width of the low-rise building must be sufficiently large that this flow is not influenced by end effects. The value 3 for the coefficient of H in Equation (9) is suggested by Graph 8 which shows that a paving block array of dimensions h X h becomes ineffective when the parapet height reaches a value of about h/3.

Paving blocks placed in an upwind corner are effective in raising the critical wind speeds for wind angles of roughly 45°. They will not, however, raise the critical wind speeds for wind angles of roughly 90° unless they extend right across the rooftop. In the absence of paving blocks the critical wind speeds for wind angles of 90° are about 1.8 times those for wind angles of 45° (see Figure 4). Consequently if paving blocks were used to such an extent that the ratio of F_p with paving blocks to that for the same parapet height but no paving blocks exceeded 1.8, the rooftop gravel would be most vulnerable to 90° winds, rather than to 45° winds. None of the paving block arrays for which data are given in Graphs 8, 9 or 10 fall into this category; for low parapet heights, however, the data in Graph 8 for the largest paving block array are at about the limit set by this consideration.

A.2.5 Estimation of Critical Speed V_{c4}

As already discussed in Subsection A.2.1 and A.2.3, the results for the critical wind speed V_{c4} (stones leaving rooftop via downstream parapet) cannot be generalized in the same way as those for V_{c1}, V_{c2} and V_{c3}. The test results for V_{c4} are of course valid for the specific full-scale building dimensions, parapet height, paving block array dimensions and gravel size modelled in each test run but the data cannot be generalized to apply to all low-rise buildings or to all high-rise buildings of a given ℓ:w ratio, as the case may be. It appears from the tests however that V_{c4} is normally equal to or greater than V_{c3} and that for speeds equal to or greater than V_{c3} large quantities of stones are blown off the rooftops and many of these stones fly considerable distances downstream of the building where they are apt to cause damage. Therefore from a practical standpoint the relatively limited ability to predict V_{c4} is probably of little consequence. The results for the specific cases which were tested are presented in Figures 5a, 5b and 5c. The results are presented as the ratio of V_{c4}/V_{c3}; once V_{c3} is determined rough estimates of V_{c4} can then be obtained if desired by using Figures 5a, 5b and 5c as guides.

It should be noted that in those runs in which the largest paving block arrays were tested, V_{c3} was sometimes observed to be somewhat greater than V_{c4}. This tendency occurs because paving blocks have then replaced loose stones in the region where these are most likely to be blown over the upstream parapets. For the same reason the ratio (V_{c4}/V_{c3}) generally decreases when larger paving block arrays are introduced. In those few cases where (V_{c4}/V_{c3}) was observed to be less than unity, V_{c3} was taken equal to V_{c4} for purposes of Graphs 8, 9 and 10.

A.2.6 Tolerances of the Data Curves

Due to the randomness, within limits, of stone size, shape and placement and to the nature of the turbulence in the wind, the gravel scour and blow-off phenomenon is inherently random to a certain degree. This, together with experimental error, causes a considerable amount of unavoidable scatter in the data. All the data curves in this report represent estimated mean curves drawn through the scattered data points. Thus the critical wind speeds calculated from these graphs are mean values and in any particular instance the actual critical speed may be somewhat higher or lower than the calculated mean value. The individual data points scatter about the mean with a standard deviation estimated to be about 8% of the mean values. No account of this is taken in the analysis procedure because it is felt that the slight degree of optimism which this entails is compensated for by other, conservative, elements in the analysis procedure. In particular, the critical wind speeds are calculated for the most sensitive wind direction, $\alpha = 45°$. There is, therefore, a substantial probability that a wind speed much higher than the calculated critical value would be non-destructive because of the substantial probability that the direction of this wind would be considerably different from 45°. A probabilistic analysis showed that the design wind speed could be reduced by roughly 10 percent if this factor were considered; these estimates were made using the assumption that a bi-variate Gaussian distribution adequately described the probability distribution of the wind in terms of speed and direction. The conservatism inherent in assuming that the wind angle is always 45° thus tends to balance the slight optimism inherent in neglecting the scatter of the data.

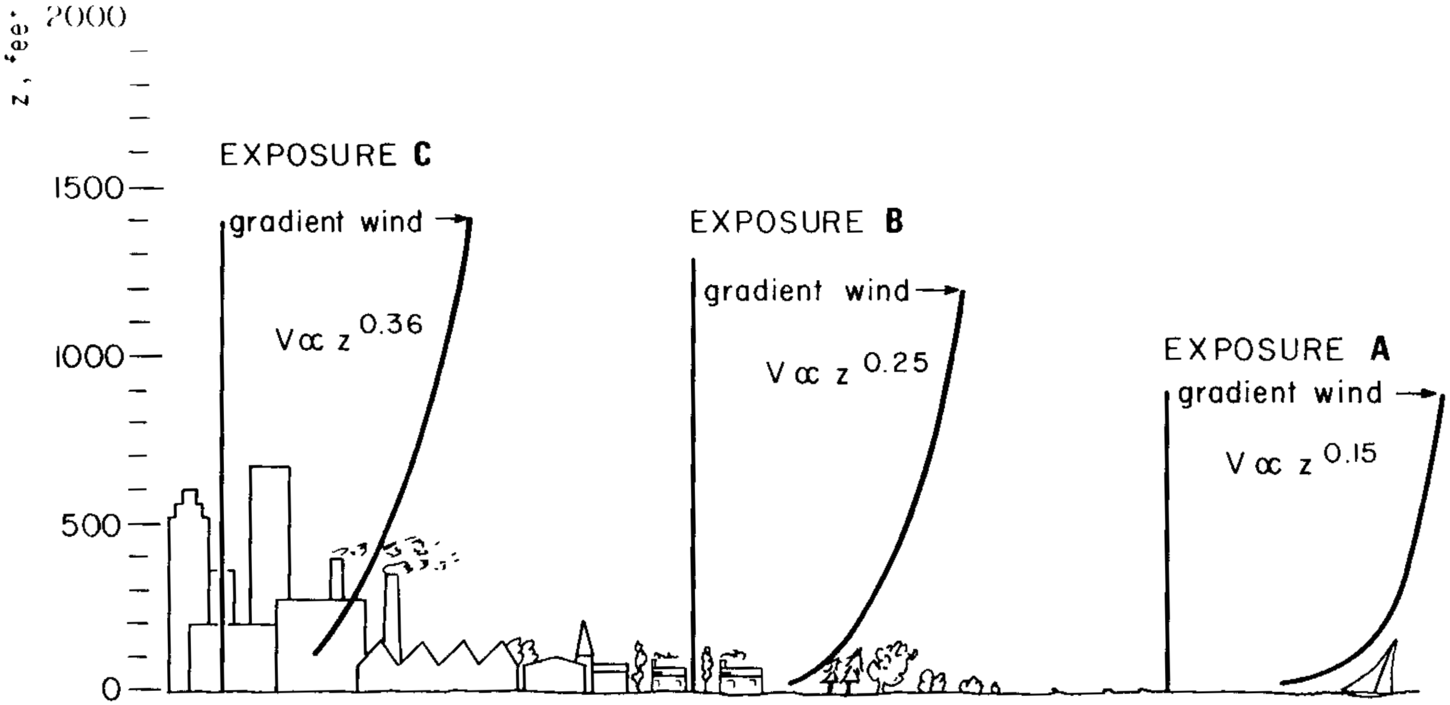

FIG. 1: PROFILES OF MEAN WIND SPEED OVER LEVEL TERRAINS OF DIFFERING ROUGHNESS
(adapted from Ref. 4)

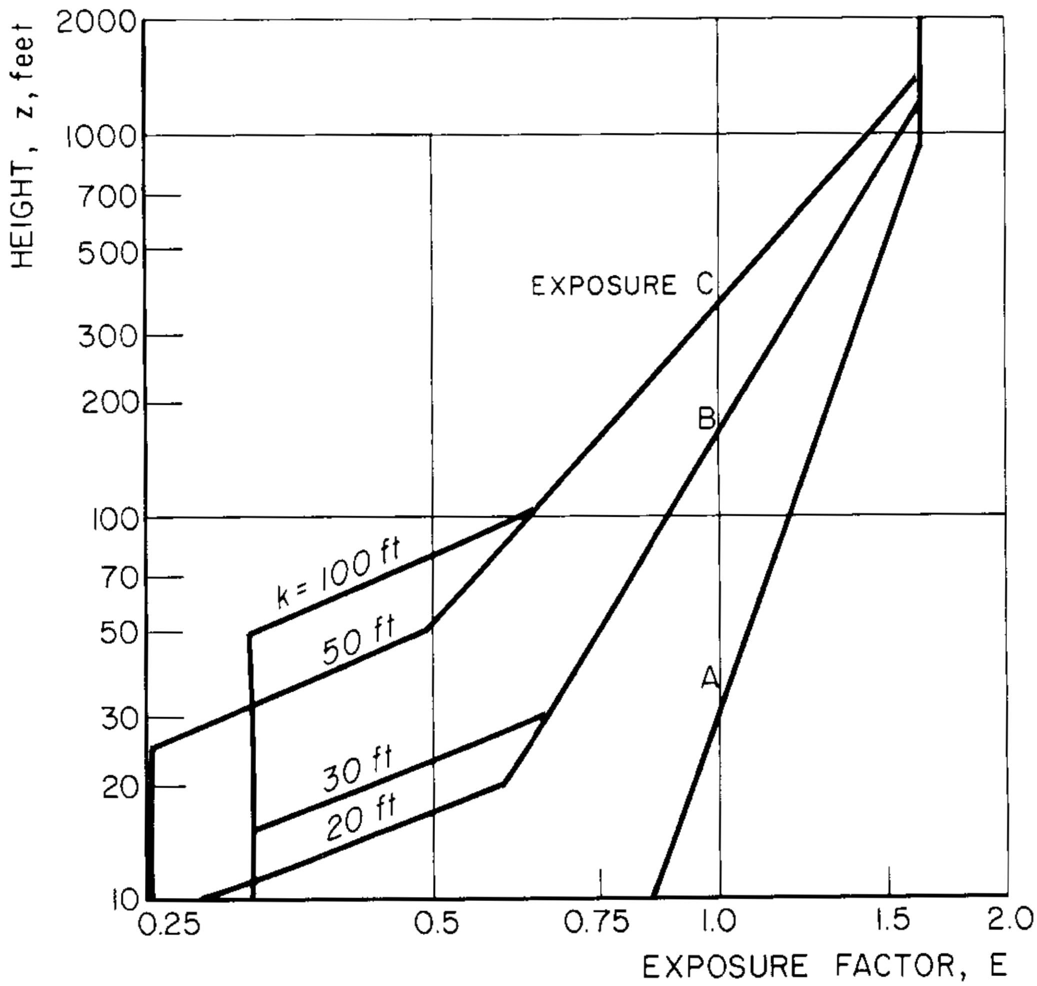

FIG. 2: EXPOSURE FACTOR VS HEIGHT ABOVE GROUND LEVEL

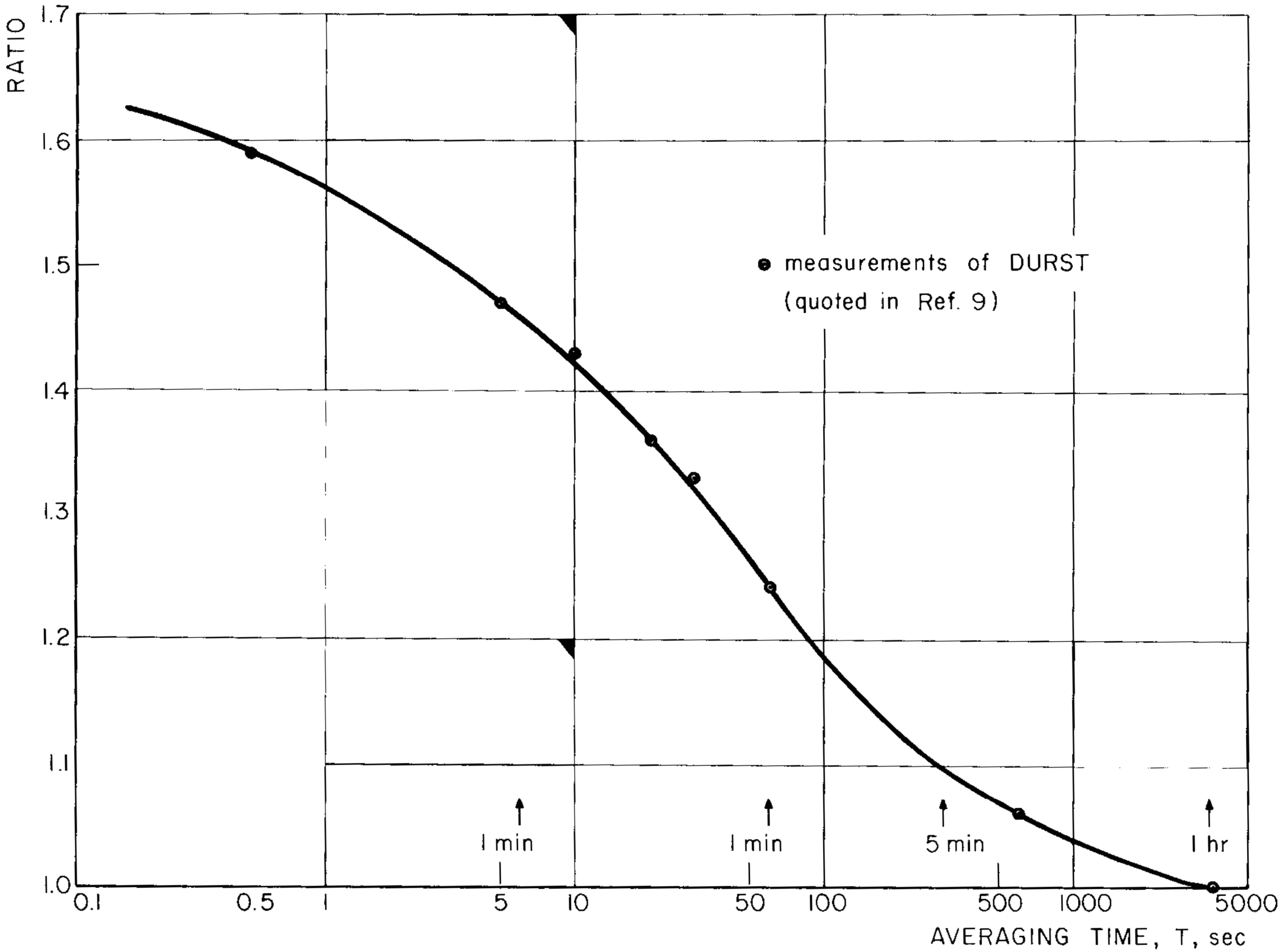

FIG. 3: RATIO OF PROBABLE MAXIMUM WIND SPEED AVERAGED OVER TIME T TO THAT AVERAGED OVER ONE HOUR (z = 30 ft.; Exposure A)

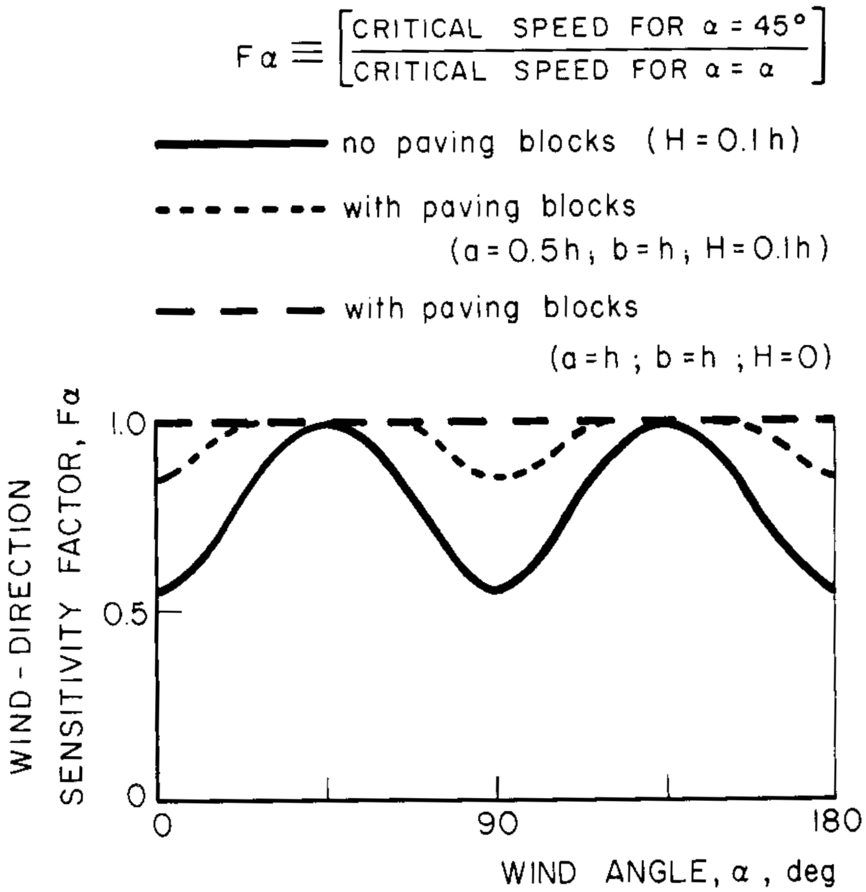

FIG. 4: WIND-DIRECTION SENSITIVITY FACTOR FOR LOW RISE BUILDINGS

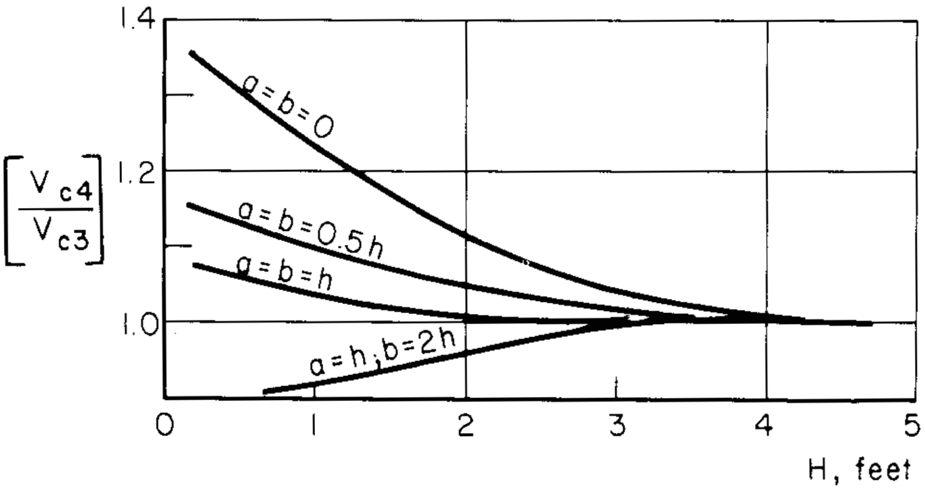

FIG 5a: h x ℓ x w = 15' x 75' x 75'; d = 0.9 → 1.5 in; α = 45°

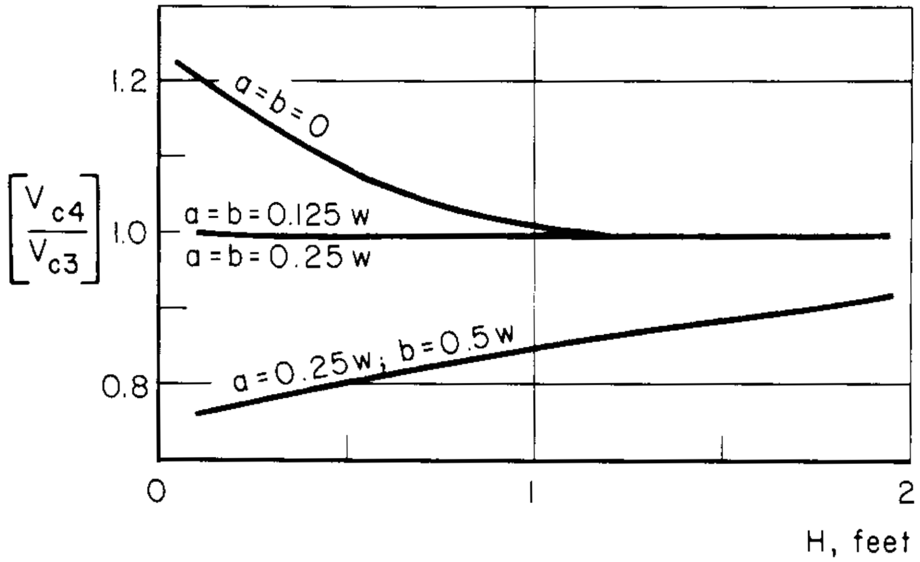

FIG 5b: h x ℓ x w = 75' x 30' x 30'; d = 0.9 in; α = 45°

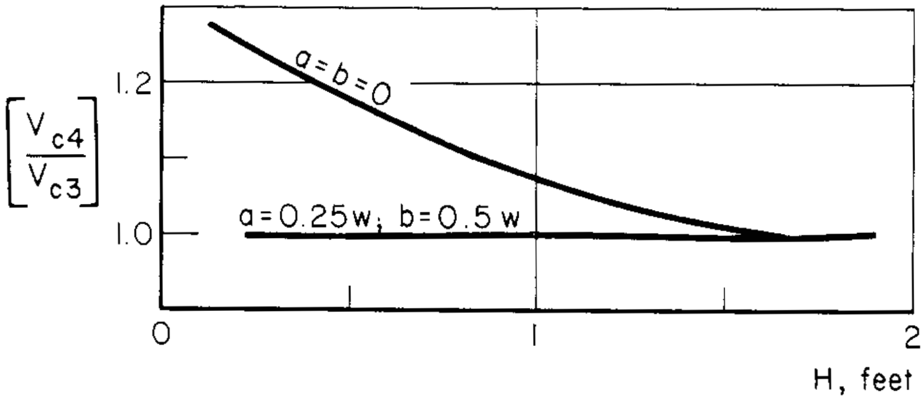

FIG 5c: h x ℓ x w = 75' x 60' x 30'; d = 0.9 in; α = 45°

FIG. 5: RESULTS FOR $[V_{c4}/V_{c3}]$