F. R. Note No. 443

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

ROOF VENTING OF BURNING ENCLOSURES

PART III A

NOMOGRAMS APPLICABLE TO THE VENTING OF FIRES OF CONSTANT HEAT OUTPUT

by

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Summary

Equations given in a previous report in this series[1] can be used to calculate the depth and temperature of the layer of hot gases beneath the ceiling and the rate of discharge of heat through the vent. In this report nomograms of these equations are given for determining these quantities and also the area of roof vent required to ensure that all low level openings in an enclosure full of hot gas are inlets for cold air.

F.1000/12/346

September 1960

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HERTS.

Notation

Symbol	Meaning
A_f	Area of fire
A_i	Area of inlet
A_i'	Effective area of inlet
A_v	Area of vent
A_v'	Effective area of vent
C_d	Coefficient of discharge through the vent
C_d'	" " " beneath the curtain
C_p	Specific heat at constant pressure
d	Depth of layer of hot gases
d_c	Depth of hot air measured from bottom of curtain
d_n	Distance between top of highest opening and ceiling (i.e. stack height)
f	Distance from effective point source of plume to floor
g	Acceleration due to gravity
h	Height of opening
h_c	Depth of curtain
h_n	Distance between top of opening and the level of the highest opening
H	Height of compartment
H_c	Distance from floor to bottom of curtain
H'	$H + f$
H_c'	$H_c + f$
Q_f	Rate of heat output of fire
T	Absolute temperature in the enclosure
T_H	Absolute temperature beneath the ceiling
T_o	Absolute ambient temperature
w	Width of inlet
θ	Temperature above ambient in the enclosure
θ_H	" " " beneath the ceiling
ρ_o	Density of gases at ambient temperature

Introduction

Part III of this series of notes[1] discussed the venting of small fires with a constant area and constant rate of heat output. This situation is illustrated in fig. 1 which shows a compartment separated from the rest of a single storey building by curtains extending part of the way to the floor. There is a vent in the roof of the compartment and the building has low level openings in its outside walls which allow air to enter the building. A fire on the floor produces a plume of hot combustion products which entrains air as it rises and a hot layer of a mixture of combustion products and air collects beneath the ceiling. After a short time (usually of the order of a minute) this layer attains a stable thickness determined by the equilibrium between the flow of hot gases into the layer from the plume and out of the layer through the vent and under the edge of the curtain. Formulae were given which enabled the depth and temperature of the layer of hot gases and the rate of discharge of heat through the vent to be calculated. These formulae are difficult to use, and accordingly they can be profitably represented by nomograms as in this report.

Reference was also made in the previous note to the theory developed by Yokoi[2] for the case of an enclosure full of hot gas. This enabled a calculation to be made of the size of vent required to ensure that any low level openings in the walls of the enclosure acted as inlets for cold air. Nomograms are given in this note to facilitate this calculation. They may be used for example to determine the area of vent required over the stage in a theatre.

It should be noted that the theory given here and in Part III refers to both the small fire in a large enclosure and a fully developed fire. It does not deal with the spreading fire, but when the rate of spread is slow, at any instant a spreading fire may, if not too large, be regarded as a constant localized fire.

Scheme of Nomograms

Six nomograms are outlined below and the quantities they relate are specified. In a following section, notes on the method of use are given. The equations from which they are derived are given in the Appendix. Their construction follows the general principles outlined by Allcock & Jones[3].

Nomograms for the case of a small fire

Nomograms 1a and 1b. The effective vent area

It is shown in the Appendix that restricting the area of the inlet to the building is equivalent to reducing the area of the vent. In all the subsequent nomograms the concept of an effective vent area is used which takes into account both the actual area of the vent and the inlet. Nomogram 1 may be used to find either the actual vent area or the effective vent area if the other is known. It can also be used to determine the minimum area of inlet which will not impair the efficiency of the vent.

Nomogram 2. The depth of the layer of hot gases when this is less than the depth of the curtains

This nomogram expresses the relation between the depth of the layer of hot air, the area of the vent and the area of the fire when the height of the building is known. It may be used to find

(1) the depth of the layer of hot air when the areas of the vent and of the fire are known;

(2) the area of vent required to confine a fire of a given area within curtains of a given depth;

(3) the maximum area of fire which a given area of vent will confine within curtains of a given depth.

When the depth of the layer of hot gases is greater than the depth of the curtain, nomogram 3 must be used.

Nomogram 3. The depth of the layer of hot gases when this is greater than the depth of the curtains

When the layer of hot gases extends below the bottom of the curtains, Nomogram 3 must be used since as well as the curtain depth, the perimeter must also be taken into account. This nomogram may be used to find

(1) the depth of the layer of hot gases when the area of the vent is known;

(2) the area of the vent required to keep the depth of the hot air layer below a certain maximum.

Nomogram 4. The temperature of the layer of hot gases

This nomogram enables the temperature of the hot gas layer to be found after its depth has been calculated from nomograms 2 or 3..

Nomogram 5. The fraction of the heat output of the fire exhausted by the vent

When the layer of hot gases extends below the bottom of the curtains, only part of the heat output of the fire is exhausted through the vent. This nomogram enables the heat exhausted by the vent to be calculated as a fraction of the heat output of the fire.

Nomograms for the case of a compartment full of hot gases

The use of nomograms 6a and 6b can best be illustrated by considering the venting of the stage of a theatre, although they can be used for other analogous situations. It is necessary to ensure that, should a large fire occur on the stage, hot gases will not pass into the auditorium round the edges of the safety curtain or through any other openings between the stage and auditorium. When the stage compartment is full of hot gases, the pressure near the roof will be higher than that in the auditorium, while the pressure near the floor will be lower; in one horizontal plane the pressure in the stage compartment will be equal to that in the auditorium. In order to prevent hot gases flowing from the stage to the auditorium it is necessary to ensure that this plane lies above the top of the highest opening between the stage and auditorium. The size of vent required to fulfil this condition may be calculated using nomograms 6a and 6b.

Acknowledgments

The author would like to thank Mr. C. R. Theobald and Mrs. S. Pascalutti for undertaking the computations and drawing the nomograms.

References

1. THOMAS, P. H., SIMMS, D. L., HINKLEY, P. L., and THEOBALD, C. R. Roof venting of burning enclosures. Part III. Venting fires of constant heat output. Joint Fire Research Organization F. R. Note No. 419, 1960.

2. YOKOI, S. A study on dimensions of smoke vent in fire resistive construction. Report of the Building Research Institute, Tokyo, Japan. No. 29. March, 1959.

3. ALLCOCK, H. J. and JONES, J. R. The Nomogram. London, 1950 (4th Edition) Sir Isaac Pitman and Sons Ltd.

APPENDIX

Formulae from which nomograms are derived

Equations in Part III are referred to by asterisk*

Nomogram 1

Equation (25)* in Part III[1] for the depth of the layer of hot gases when the inlets are restricted is

$$C_d \; d^{\frac{1}{2}} = 0.043 \left\{ \frac{1}{A_i^2} \frac{T_o}{T_H} + \frac{1}{A_v^2} \right\}^{\frac{1}{2}} (H' - d)^{5/2} \qquad (1)$$

This is equivalent to equation (14)* for the case when the inlets are large, i.e.

$$C_d \; d^{\frac{1}{2}} = 0.043 \; \frac{1}{A_v} \; (H' - d)^{5/2} \qquad (2)$$

if A_v is replaced by an effective vent area (A_v') given by

$$\left(\frac{1}{A_v'}\right)^2 = \frac{1}{A_i^2} \frac{T_o}{T_H} + \frac{1}{A_v^2} \qquad (3)$$

Writing $\frac{1}{A_i^2} \frac{T_o}{T_H} = \left(\frac{1}{A_i'}\right)^2$ (4)

$$\left(\frac{1}{A_v'}\right)^2 = \left(\frac{1}{A_i'}\right)^2 + \left(\frac{1}{A_v}\right)^2 \qquad (5)$$

Equations (4) and (5) are represented by nomograms 1a and 1b respectively. To is taken as 500°R.

Nomogram 2

This represents equation (14)* i.e.

$$C_d \; A_v' \, d^{\frac{1}{2}} = 0.043 \; (H' - d)^{5/2} \qquad (6)$$

where $C_d = 0.6$.

Nomogram 3

Equation (17)* is

$$C_d \; A_v \; d^{\frac{1}{2}} + \tfrac{2}{3} C_d' \; w(d - h_c)^{3/2} = 0.043 \; (H' - d)^{5/2} \qquad (7)$$

This cannot be represented by a convenient nomogram and is therefore rewritten as

$$C_d \, A_v \, (d_c + h_c)^{\frac{1}{2}} + \tfrac{2}{3} C_d' \; w \, d_c^{3/2} = 0.043 \; (H_c' - d_c)^{5/2} \qquad (8)$$

The number of variables is reduced to 4 by writing

$$\frac{A_v}{H_c'} = A_v'' \qquad \frac{d_c}{H'_c} = d_c' \qquad \frac{h_c}{H_c'} = h_c' \text{ and } \frac{w}{H'_c} = w'$$

Then $C_d \; A_v'' \; (d_c' + h_c')^{\frac{1}{2}} + \tfrac{2}{3} C_d' \, w' \, (d_c')^{3/2} = 0.043 \; (1 - d_c')^{5/2}$ (9)

This equation is represented by nomogram 3.

$$C_d = C_d' = 0.6.$$

Nomogram 4

Nomogram 4 represents equation (11)* i.e.

$$\frac{\theta_H}{(\theta_H + T_o)^{\frac{2}{3}}} = \frac{6.5}{(\rho_o\ c_p)^{\frac{2}{3}}\ (g\ T_o)^{\frac{1}{3}}\ (H' - d)^{5/3}}\ Q_f^{\frac{2}{3}} \qquad (10)$$

T_o is taken as 500°F. and

$$\frac{6.5}{(\rho_o\ c_p)^{\frac{2}{3}}(g\ T_o)^{\frac{1}{3}}} = 3.4 \quad \text{B.t.u.}^{\frac{2}{3}}\ s^{-\frac{2}{3}}\ {}^{o}F^{-\frac{1}{3}}$$

Nomogram 5

Equation (19)* can be written

$$Q_v = C_d\ A_v'\ \ \rho_o\ c_p\ \left(\frac{To}{To + \theta_H}\right)\ \theta_H\ \frac{2g\ d\ \theta_H}{To} \qquad (11)$$

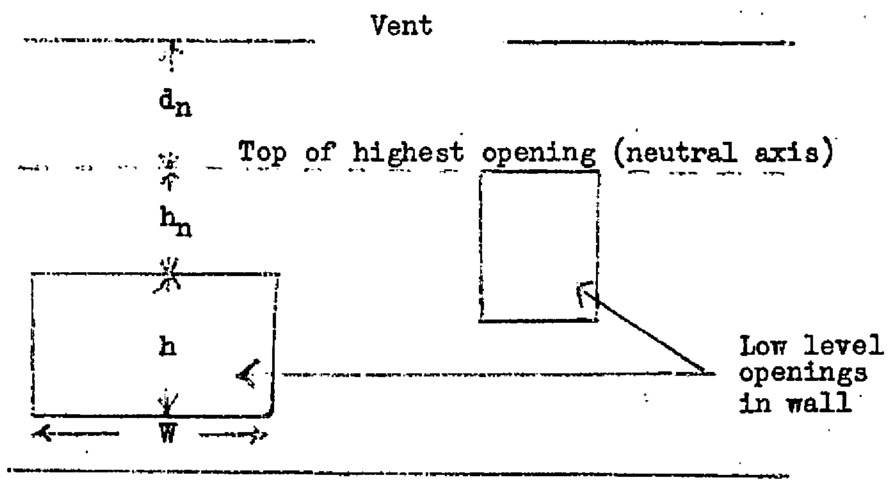
Combining this with equation (10) above

and putting $C_d = 0.6$ gives

$$\frac{Q_v}{Q_f} = 14.15\ \ A_v'\ \frac{d^{\frac{1}{2}}}{(H' - d)^{5/2}} \qquad (12)$$

This is represented by nomogram 5.

Nomogram 6



Equating the mass entering the enclosure with that passing out through the vent[2] gives

$$1.2 \sum \tfrac{2}{3}\ C_d'\ W\ \ \rho_o \left\{ (h + h_n)^{3/2} - h_n^{3/2} \right\} \sqrt{\frac{2g\ \theta}{T}}$$

$$= C_d\ \ A_v\ \ \rho_o\ \ \frac{To}{T} \sqrt{\frac{2gd_n\ \theta}{T_o}} \qquad (13)$$

The factor 1.2 takes into account the volume of hot gas produced by a fire in the enclosure allowing for a fuel/air ratio of 0.2.

Equation (13) reduces to

$$A_v \sqrt{\frac{To}{To + \theta}\, d_n} = 1.2 \sum \tfrac{2}{3} W h^{3/2} \left\{ \left(1 + \frac{h_n}{h}\right)^{3/2} - \left(\frac{h_n}{h}\right)^{3/2} \right\} \qquad (14)$$

Writing $N = \tfrac{2}{3} W h^{3/2} \left\{ \left(1 + \frac{h_n}{h}\right)^{3/2} - \left(\frac{h_n}{h}\right)^{3/2} \right\}$ (15)

$$A_v \sqrt{\frac{To}{To + \theta_H}\, d_n} = 1.2 \sum N \qquad (16)$$

Nomograms 6a and 6b represent equations (15) and (16) respectively.

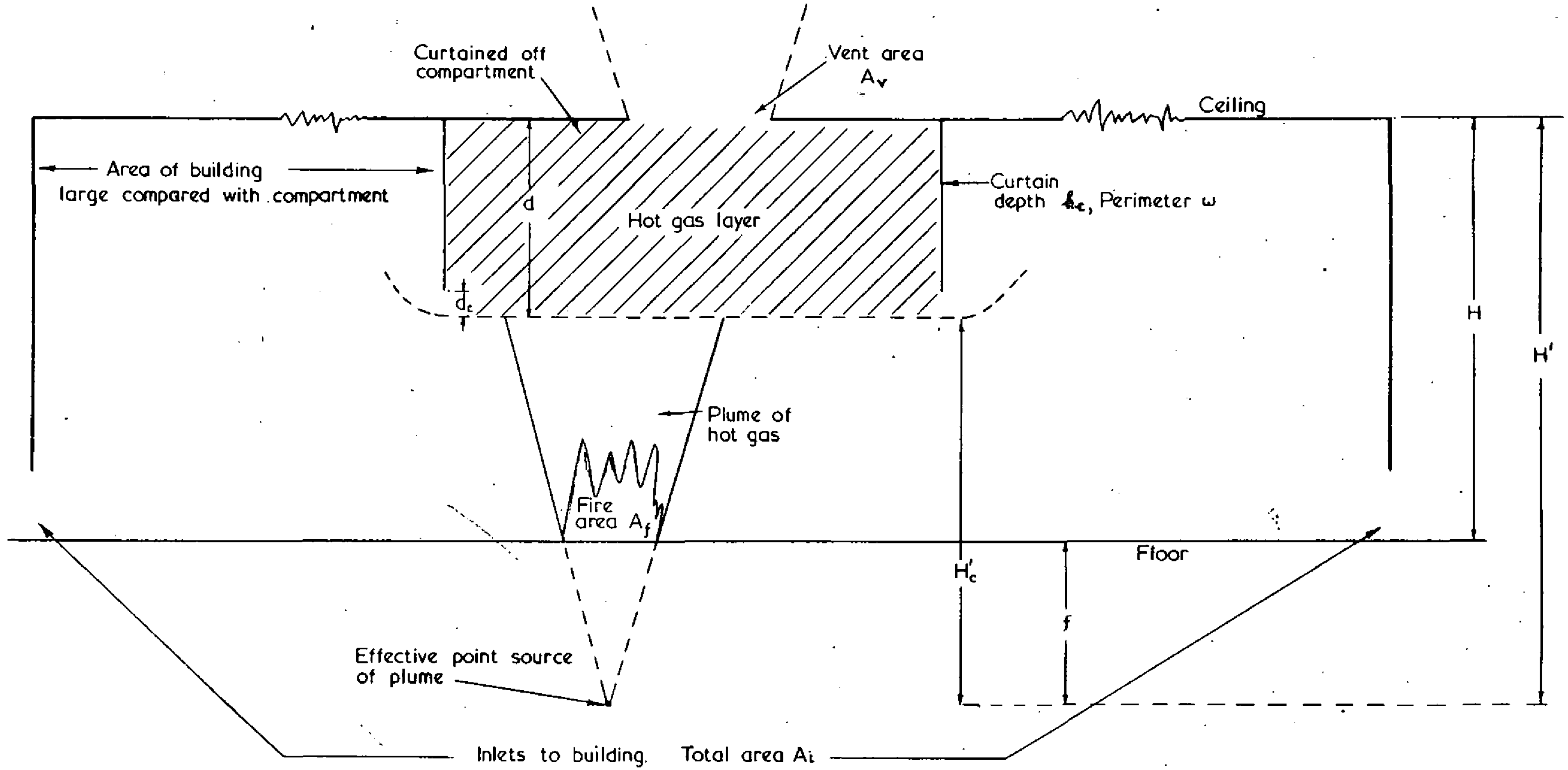


FIG.1. TO ILLUSTRATE VENTING OF A SMALL FIRE

NOMOGRAMS 1a AND 1b

The effective vent area allowing for the size of the inlets to the building

The first step is to calculate an intermediate quantity which for convenience we call the effective inlet area A_i1 which must first be determined using Nomogram 1a.

Scales (Nomogram 1a)

θ_H Temperature beneath ceiling in ^oF

A_i Actual inlet area

A_i' Effective inlet area.

No units are given for the areas; the effective area will have the same units as the inlet area. The range of the area scales may be extended by multiplying them both by the same power of 10.

Effective vent area when actual vent area is known

The ratio $\frac{\text{Effective inlet area}}{\text{Actual vent area}}$ must be determined. If this is greater than 4, the inlets do not appreciably affect the flow and the effective vent area is the same as the actual vent area. If it is less than $\frac{1}{4}$, the flow is controlled by the inlet and the effective vent area is given by the effective inlet area. For values of the ratio between $\frac{1}{4}$ and 4 the effective vent area can be obtained from nomogram 1b.

Actual vent area when effective vent area is known

The ratio $\frac{\text{Effective vent area}}{\text{Effective inlet area}}$ must be determined. This can never be greater than unity. It can be shown from Apperdix equation (5) that if it lies between 0.97 and unity the actual vent area is very large. If it is less than 0.25 the actual vent area is equal to the effective vent area. For values of the ratio between 0.25 and 0.97, the actual vent area can be determined from nomogram 1b.

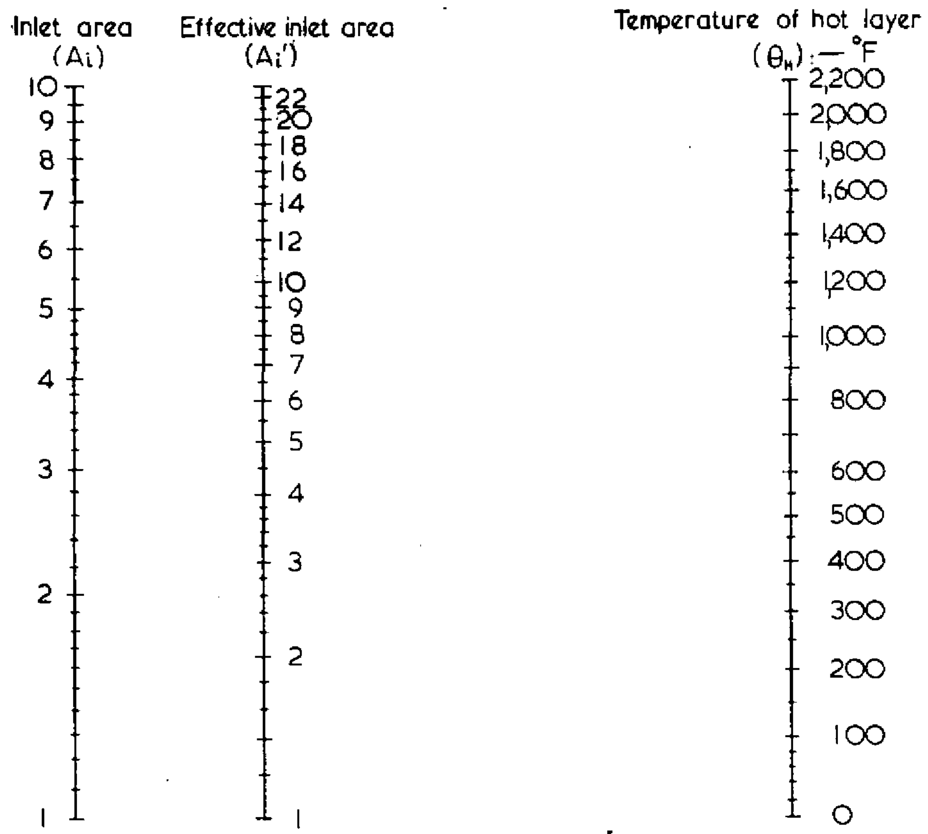
Scales (Nomogram 1b)

A_i' Effective inlet area

A_v Actual vent area

Av' Effective vent area

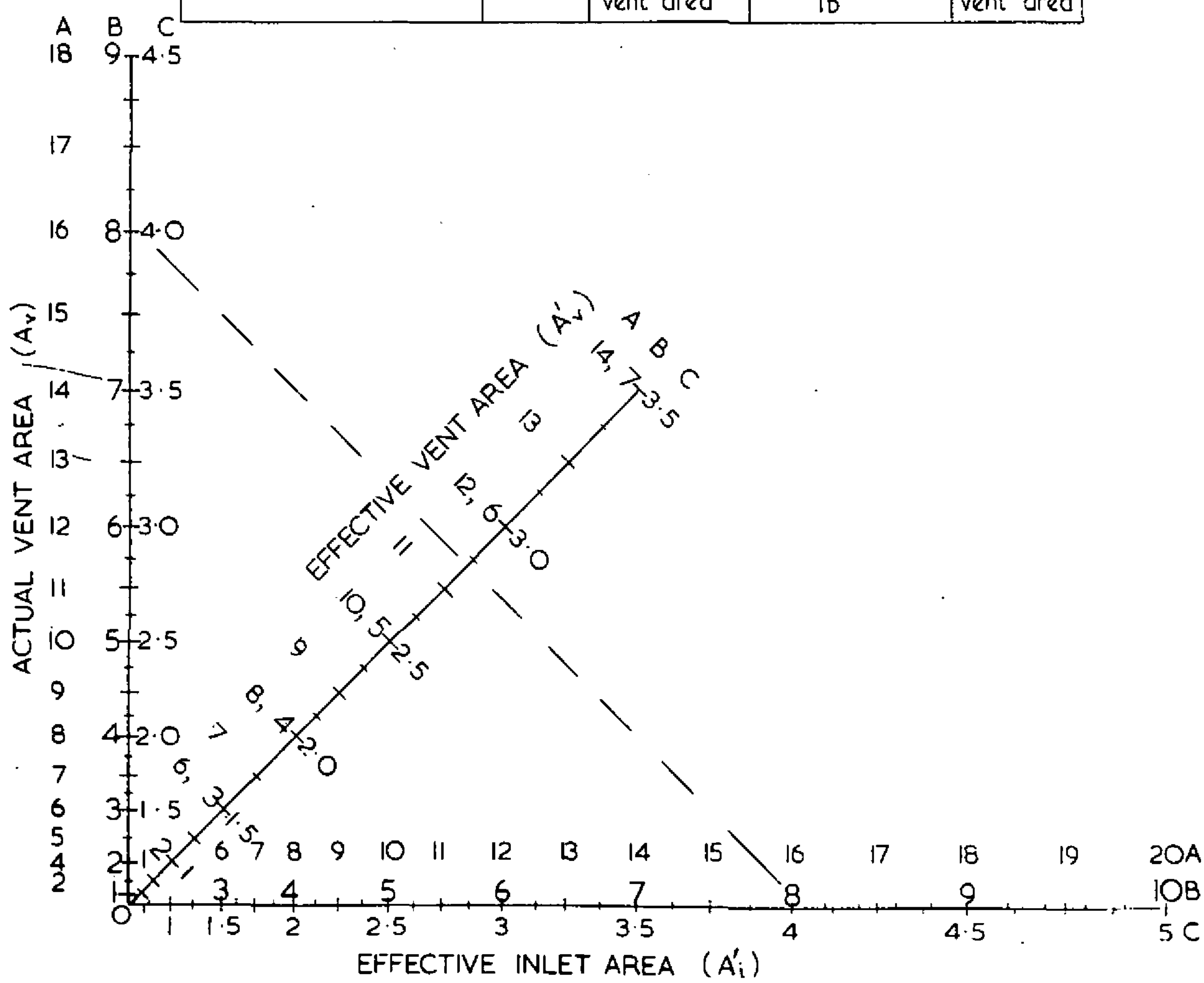
Each line has three scales A, B and C. The same scale must be used on all three lines. The range of this nomogram may be extended by multiplying all the scales by the same power of 10.



NOMOGRAM 1a

$\frac{\text{Effective inlet area}}{\text{Actual vent area}}$	Less than $\frac{1}{4}$	$\frac{1}{4}$ – 4	Greater than 4
Effective vent area	Effective inlet area	Use nomogram 1b	Actual vent area

$\frac{\text{Effective vent area}}{\text{Effective inlet area}}$	1	0·97	0·97–0·25	Less than 0·25
Actual vent area	Infinite	4 x effective vent area	Use monogram 1b	Effective vent area



NOMOGRAM 1b

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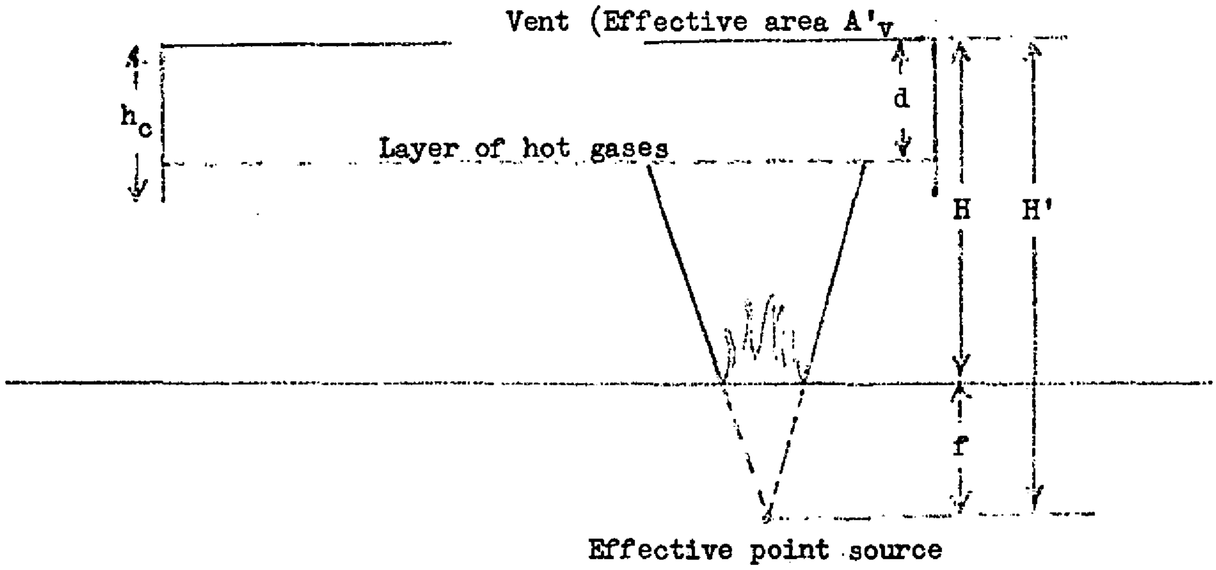
NOMOGRAM 2

The depth of the layer of hot gases when this is less than the depth of the curtains



Scales

$\sqrt{A'_v}$ Square root of effective vent area.

d Depth of layer of hot gases beneath the ceiling.

H' Distance between ceiling and effective point source of the fire = H + f

where H is ceiling height, f is the distance between the floor and the effective point source of the fire. For a circular fire on the ground (1)

$$F \doteq 1.5 \quad A_f$$

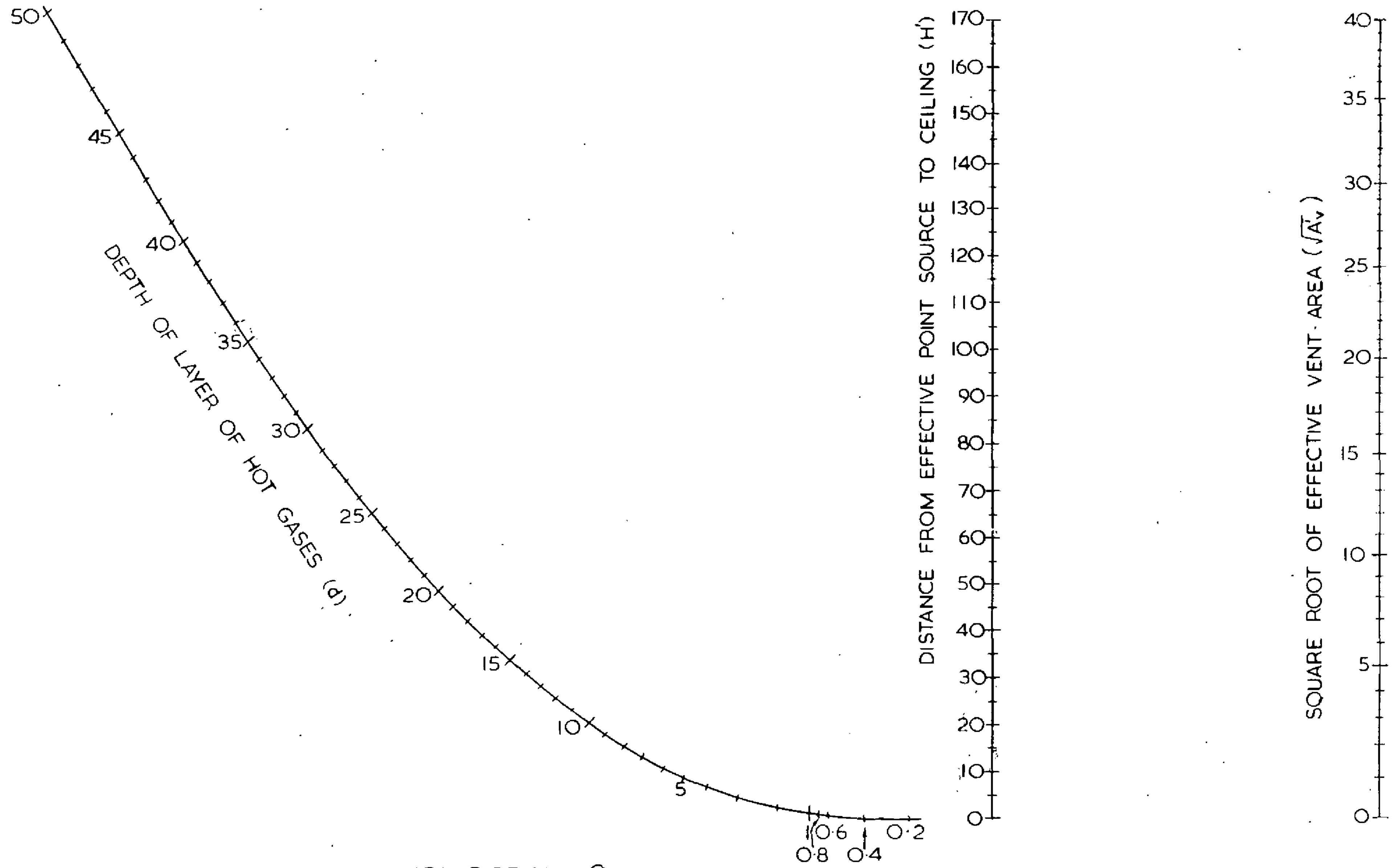
where A_f is the area of the fire.

Units

There are no units given in this nomogram. Any units may be used but they must be the same for all three scales.

Note:

If the value of d obtained from this nomogram is greater than the curtain depth (h_c) nomogram 3 must be used.

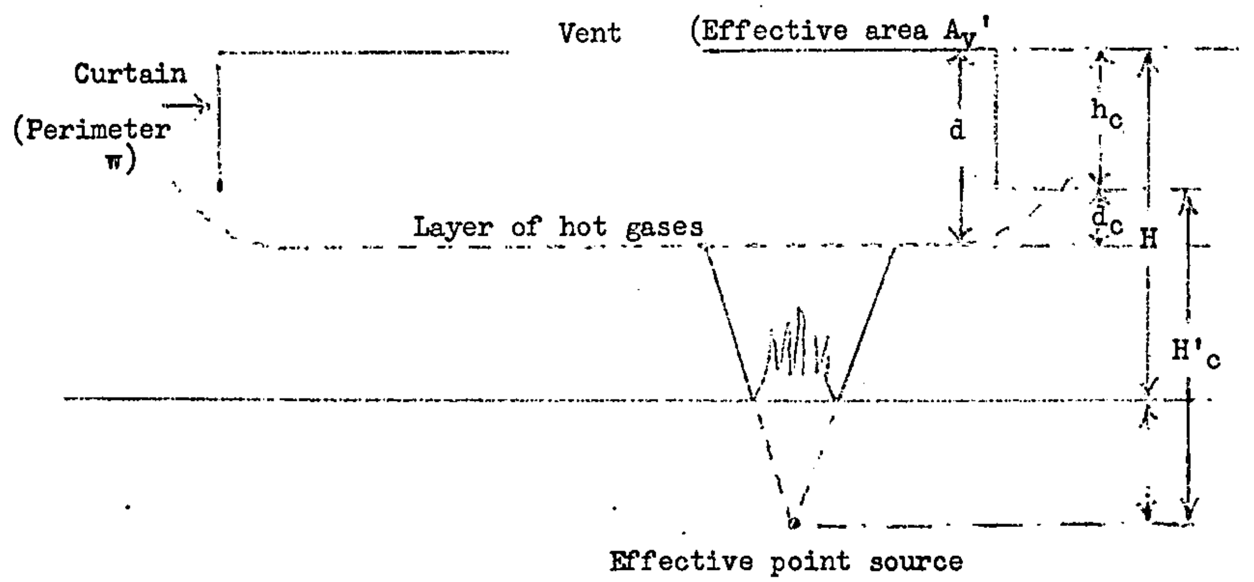


DEPTH OF LAYER OF HOT GASES (d)
50
45
40
35
30
25
20
15
10
5
1
0·8
0·6
0·4
0·2
DISTANCE FROM EFFECTIVE POINT SOURCE TO CEILING (H')
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
SQUARE ROOT OF EFFECTIVE VENT·AREA ($\sqrt{A'_v}$)
40
35
30
25
20
15
10
5
0

NOMOGRAM 2

NOMOGRAM 3

The depth of the layer of hot gases when this is greater than the depth of the curtains



H'_c — distance between bottom of curtain and effective point source

$= H - h_c + f$

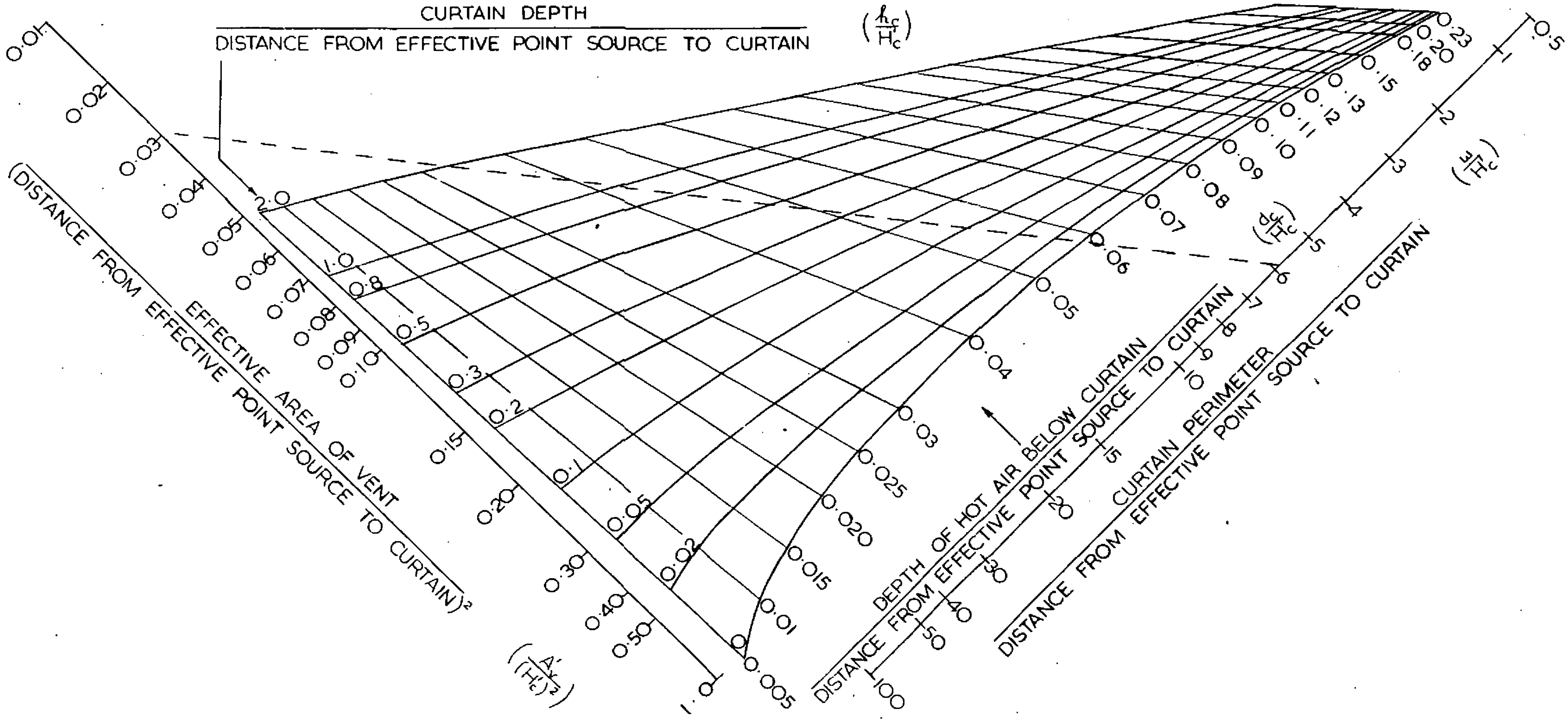
where
- H is ceiling height
- h_c is curtain depth
- f is distance between floor and effective point source of the fire (calculated as for nomogram 2).

Scales

$\frac{A_v'}{H_c'^2}$	Effective area of vent divided by $H_c'^2$
$\frac{h_c}{H_c'}$	Curtain depth divided by H_c'
$\frac{w}{H_c'}$	Curtain perimeter divided by H_c'
$\frac{d_c}{H_c'}$	Distance between bottom edge of curtain and bottom of hot gas layer divided by H_c'.

Units

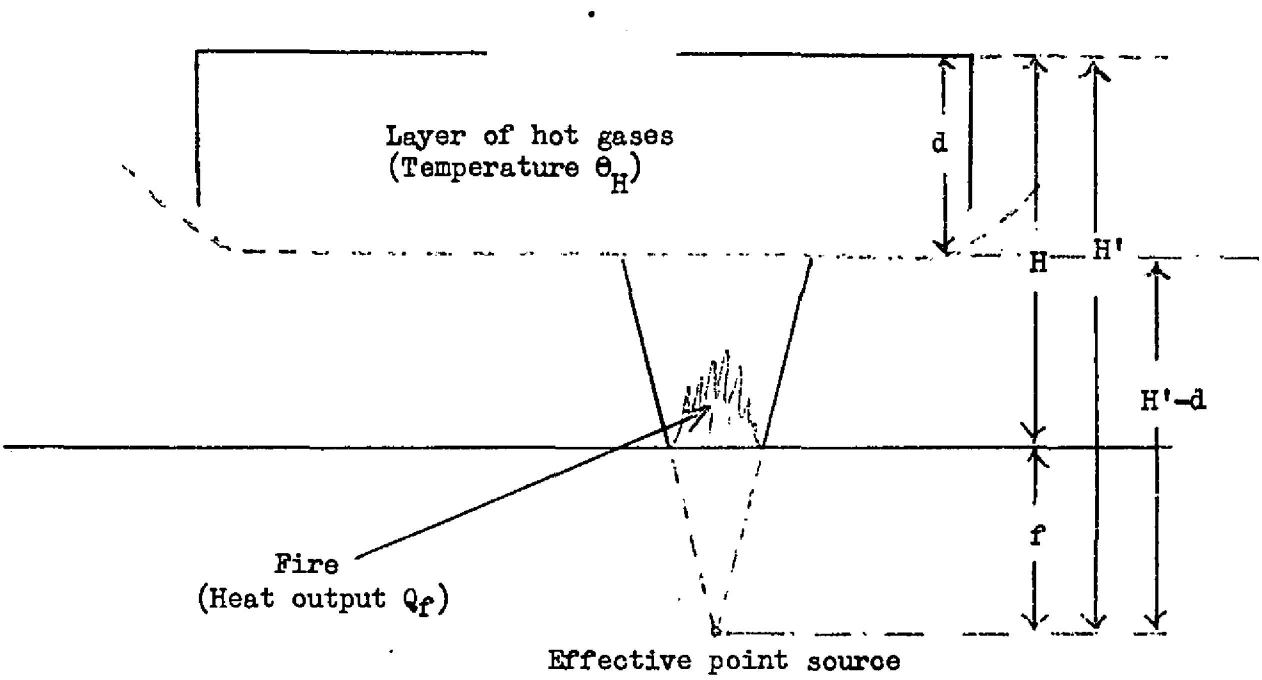
The quantities represented by the scales in this nomogram are dimensionless. H_c', h_c, w and d_c must have the same units of length and A_v must have the corresponding units of area.


CURTAIN DEPTH
DISTANCE FROM EFFECTIVE POINT SOURCE TO CURTAIN
$\left(\frac{h_c}{H_c}\right)$
EFFECTIVE AREA OF VENT
(DISTANCE FROM EFFECTIVE POINT SOURCE TO CURTAIN)²
$\left(\frac{A'_v}{(H'_c)^2}\right)$
DEPTH OF HOT AIR BELOW CURTAIN
DISTANCE FROM EFFECTIVE POINT SOURCE TO CURTAIN
$\left(\frac{d_c}{H_c}\right)$
CURTAIN PERIMETER
DISTANCE FROM EFFECTIVE POINT SOURCE TO CURTAIN
$\left(\frac{l}{H_c}\right)$

NOMOGRAM 3

NOMOGRAM 4

The temperature of the layer of hot gases



Scales

$(H' - d)$: distance in feet between effective point source and bottom of hot gas layer.

$= H + f - d$

Calculate f as in note to nomogram 1.

Obtain d from nomogram 2 or 3.

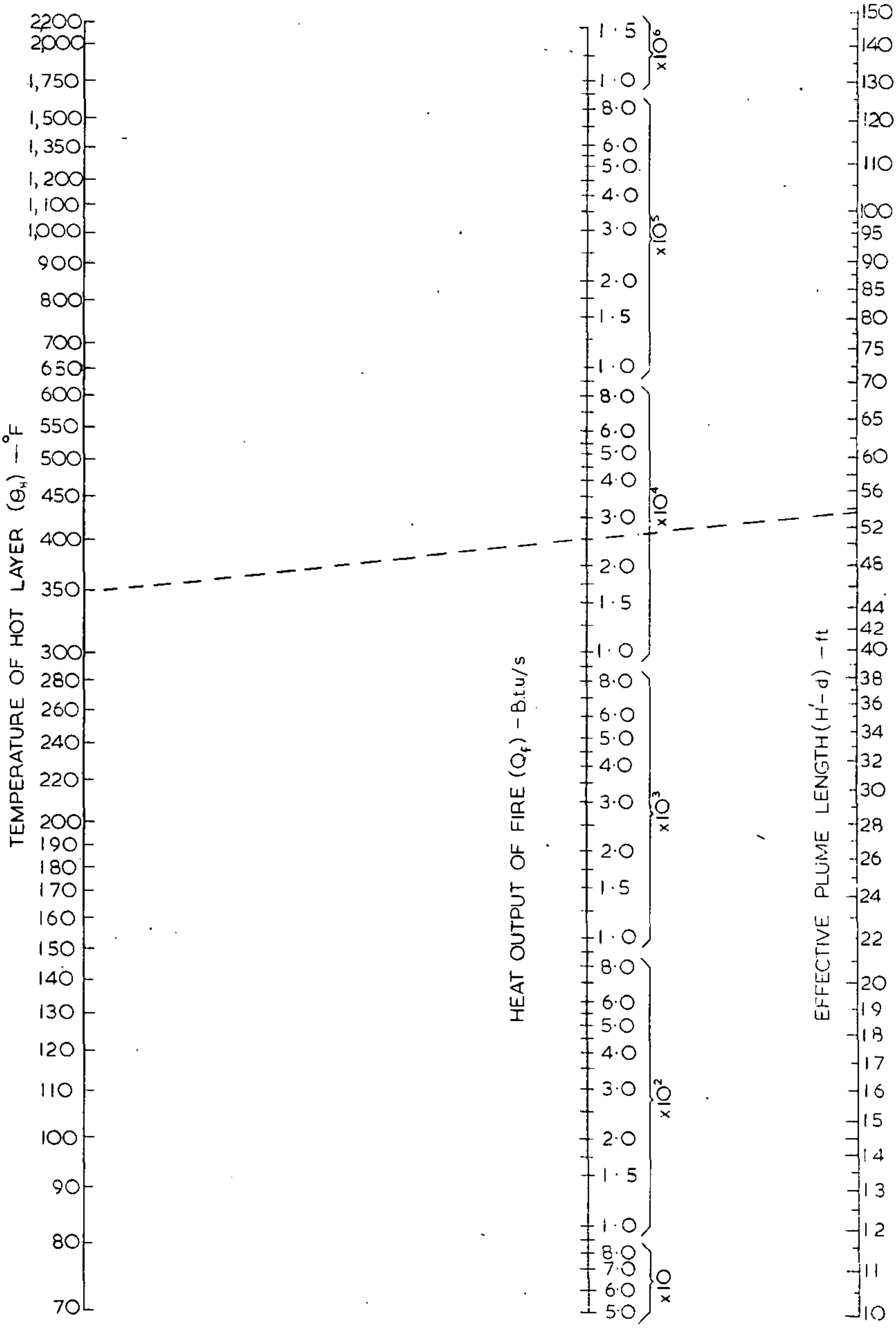
Q_f : Convective heat output of fire in B.t.u.

= (Total heat output) - (Radiation heat output).

θ_H : Temperature of hot gas layer (^oF).

Note:

In some cases the temperatures given by this nomogram will be above the flame temperature. This is absurd and in such cases the maximum temperature of the hot layer will be the flame temperature. All temperatures above about 700^{o}F. may be erroneous.



NOMOGRAM 4

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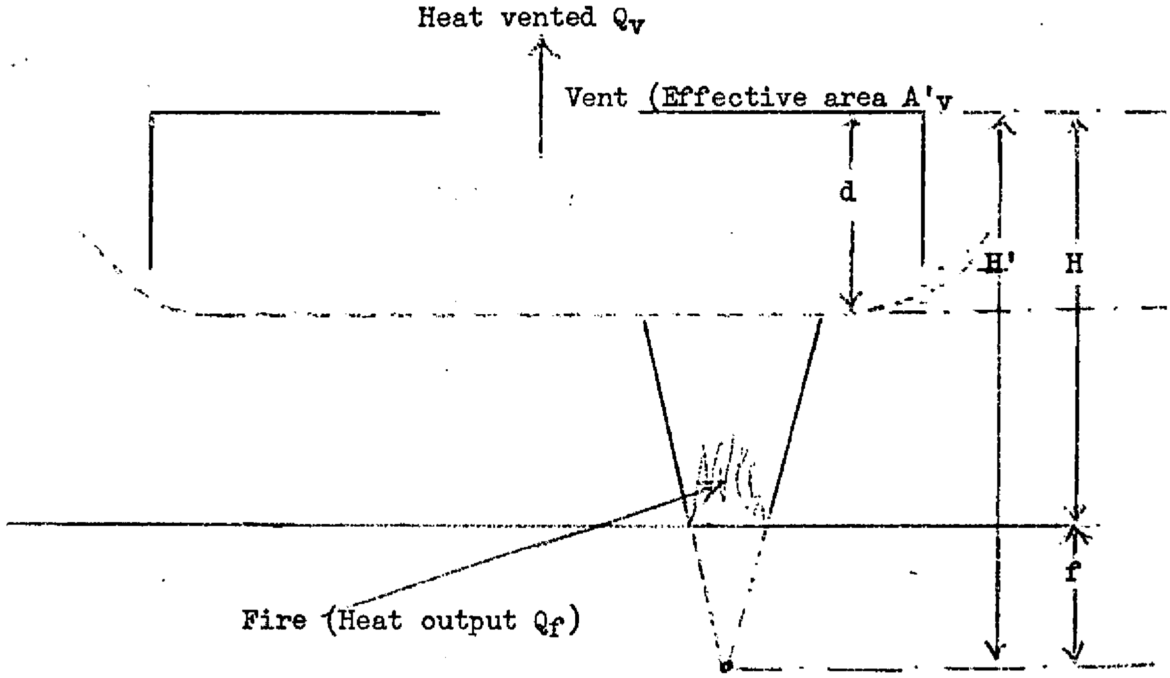
NOMOGRAM 5

The fraction of the heat output of the fire exhausted by the vent



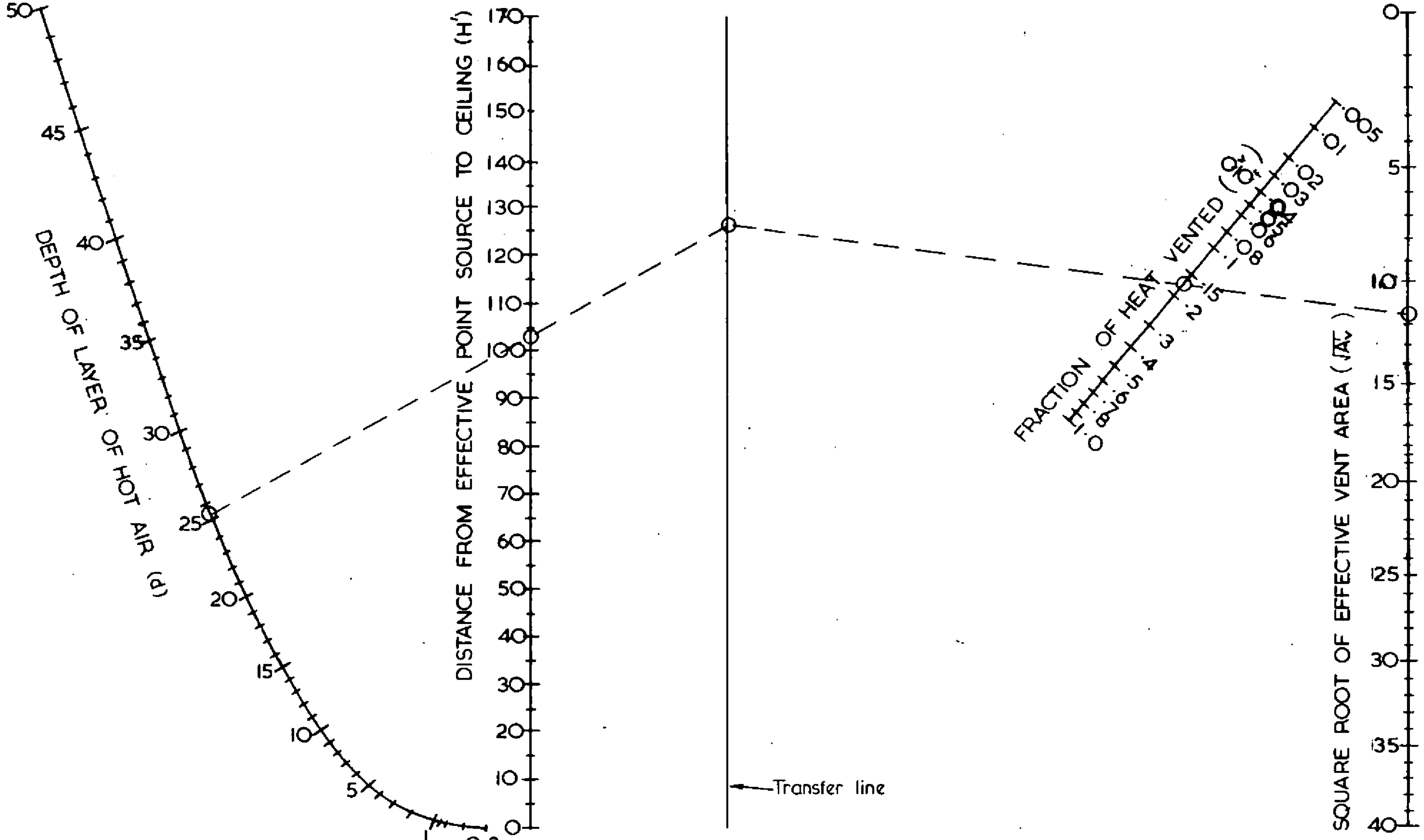
Scales

$\sqrt{A'_v}$	Square root of effective vent area.
d	Depth of layer of hot air beneath the ceiling.
H'	Distance between ceiling and effective point source = H + f.
	f is obtained as note on nomogram 1.
$\frac{Q_v}{Q_f}$	Fraction of heat produced by the fire which passes through the vent.

Units

There are no units given on this nomogram. $\frac{Q_v}{Q_f}$ is dimensionless.

Any units may be used for the other scales, but they must be the same for all three. The range of this nomogram may be extended by multiplying all scales by the same power of 10.



DEPTH OF LAYER OF HOT AIR (d)
DISTANCE FROM EFFECTIVE POINT SOURCE TO CEILING (H')
Transfer line
FRACTION OF HEAT VENTED (Q_v/Q_f)
SQUARE ROOT OF EFFECTIVE VENT AREA ($\sqrt{A_v}$)

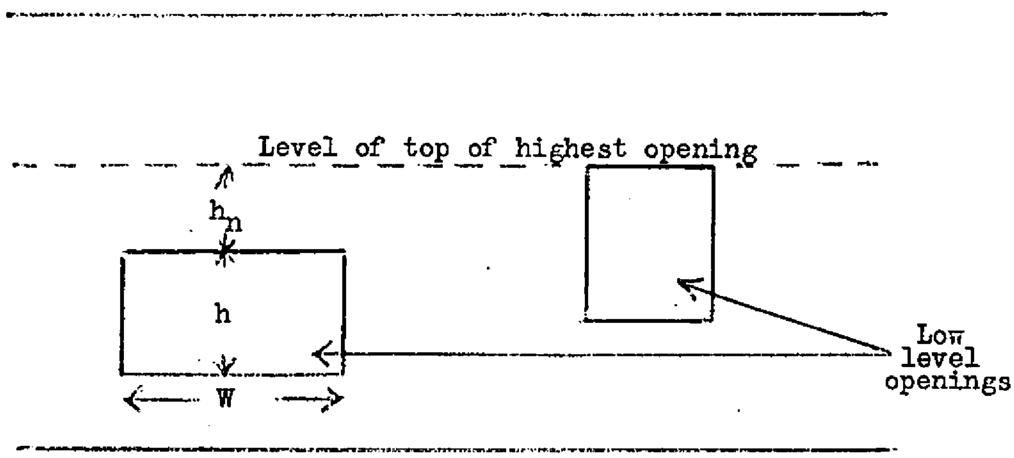
NOMOGRAM 5

NOMOGRAMS 6a and 6 b

Venting of an enclosure full of hot gas

Nomogram 6a is first used to calculate a quantity "N" (Appendix, Equation (15)) for each of the low level openings in the building. The sum of the "N"s for each opening is then used in nomogram 6b to calculate the effective vent area required.

NOMOGRAM 6a



Scales

W = Width of opening

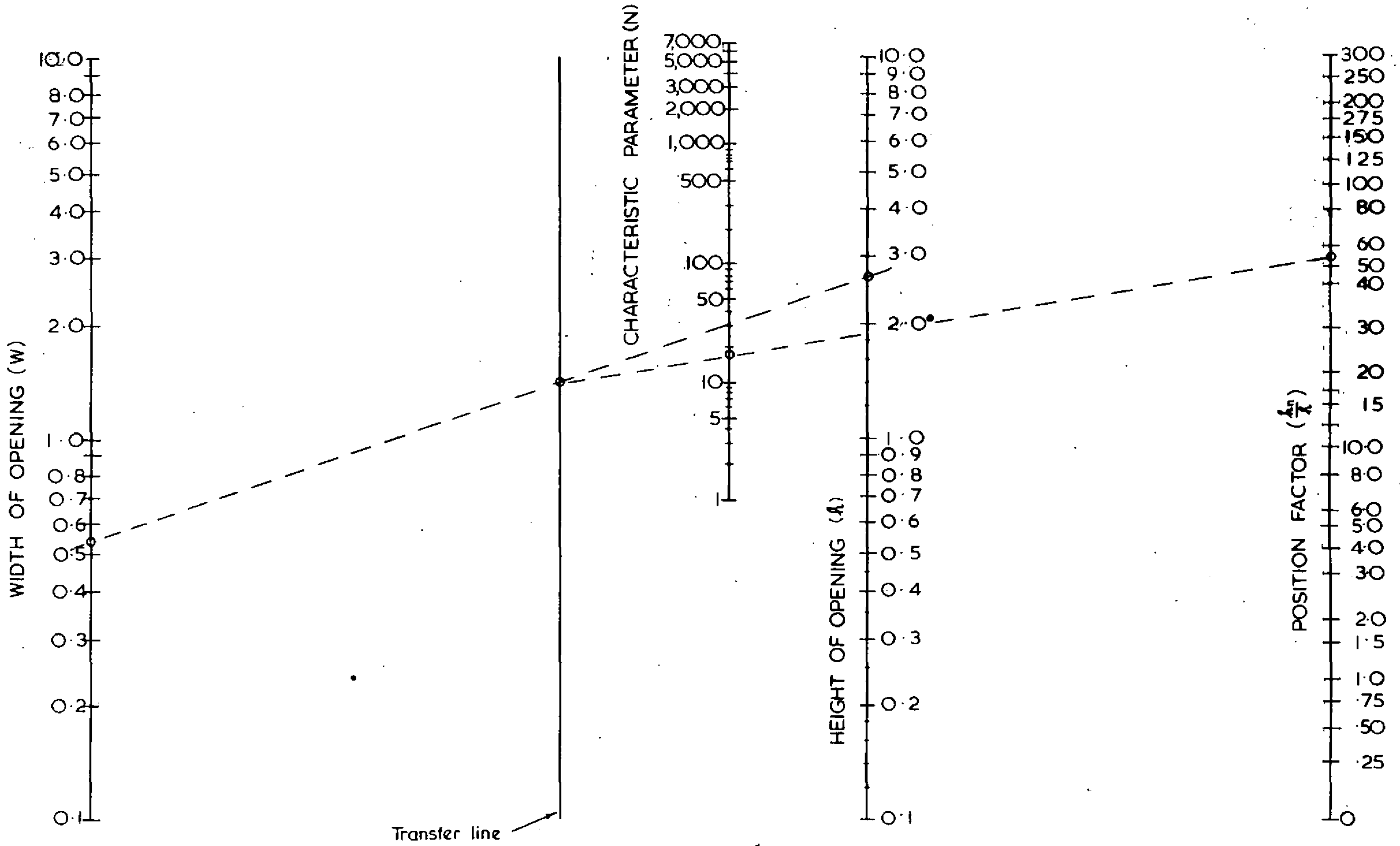
h = Height of opening

$\frac{h_n}{h}$ Position factor = Distance from top of opening to level of the top of the highest opening divided by the height of the opening.

N = Parameter characteristic of opening.

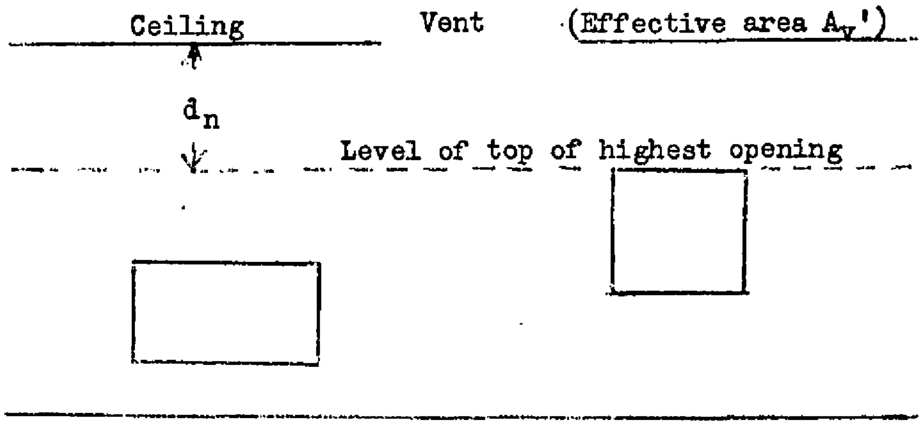
Units

No units are given on this nomogram. The same units must be used for h, h_n and W throughout these calculations.


WIDTH OF OPENING (W)
10·0
8·0
7·0
6·0
5·0
4·0
3·0
2·0
1·0
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
Transfer line
CHARACTERISTIC PARAMETER (N)
7,000
5,000
3,000
2,000
1,000
500
100
50
10
5
1
HEIGHT OF OPENING (h)
10·0
9·0
8·0
7·0
6·0
5·0
4·0
3·0
2·0
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
POSITION FACTOR
300
250
200
275
150
125
100
80
60
50
40
30
20
15
10·0
8·0
6·0
5·0
4·0
3·0
2·0
1·5
1·0
·75
·50
·25
0

NOMOGRAM 6a

NOMOGRAM 6b



Scales

d_n Distance from ceiling to top of highest opening (i.e. stack height).

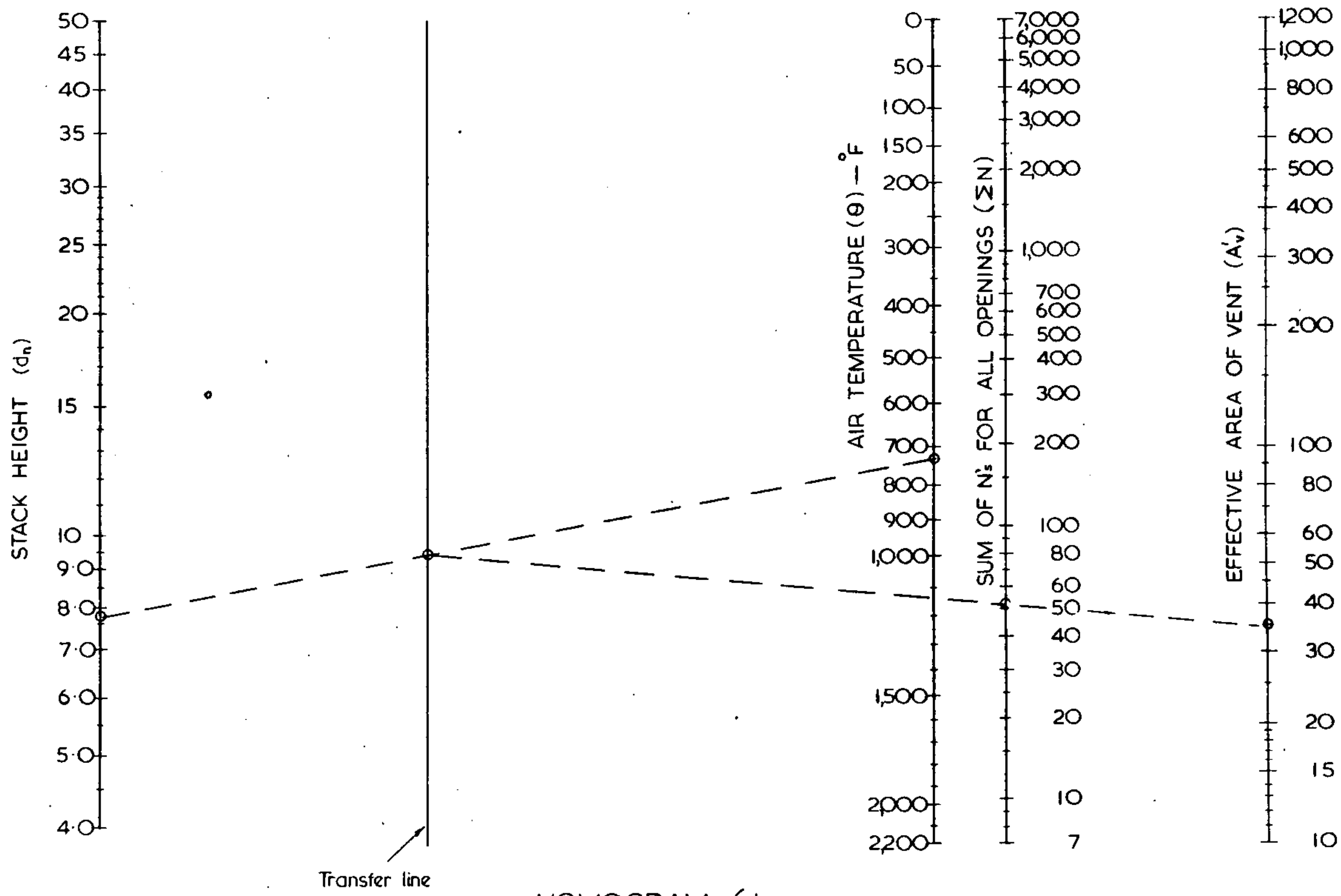
$\sum N$ Sum of "N"s for all the openings at low level.

θ Temperature inside the building in ^oF.

A_v' Effective vent area.

Units

Temperatures are in ^oF. No units are given for lengths and areas. The same units must be used for this nomogram as were used for nomogram 6a.


STACK HEIGHT (d_n)
50
45
40
35
30
25
20
15
10
9·0
8·0
7·0
6·0
5·0
4·0
Transfer line
AIR TEMPERATURE (θ) — °F
0
50
100
150
200
300
400
500
600
700
800
900
1,000
1,500
2,000
2,200
SUM OF N's FOR ALL OPENINGS (ΣN)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
700
600
500
400
300
200
100
80
60
50
40
30
20
10
7
EFFECTIVE AREA OF VENT (A'_v)
1,200
1,000
800
600
500
400
300
200
100
80
60
50
40
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NOMOGRAM 6b