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GASP! WHEEZE! UGH! WHERE IS THAT SMELL COMING FROM?

By

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KEY WORDS:

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ABSTRACT:

At a time when good engineering practice for large pollutant sources is to propose stacks 1.5 times the height of associated buildings, there is still a large use of mini-chimneys and flush vents on buildings to disperse effluents from small process activities. Such designs may result in problems ranging from offensive odors, fire hazards, product corrosion, to even re-entry of toxic contaminants. Most prediction procedures and measurements relate to long time average concentrations, but flammability, toxicity, and odor are short time problems and intermittent in nature. Recent measurements of fluctuating concentration statistics near model buildings in the wind-engineering laboratory together with probability mathematics permits estimation of odor hazards and a positive design response.

INTRODUCTION:

Re-entry of furnace effluents, smoke, air-conditioning exhausts, or chemical hood exhausts into occupied building areas often results in complaints of stench and odor. Numerous investigations of serious odor complaint conditions have revealed no direct physiological harm due to the odors themselves; however, to the degree that the odor is a mental irritant and one develops symptoms, such as nausea, headache, irrational behavior, and loss of appetite, caused by the sheer unpleasantness of the odor, it may not matter whether the air is toxic. In addition the perceived intensity of an odor decreases less sharply than the absolute concentration; hence, the efficacy of dilution of an odorant by ventilation or atmospheric dispersion is reduced. Thus odor control often requires the largest ventilation rates and dominates equipment choice (ASHRAE, 1980, 1981).

A model is proposed to calculate permissible exhaust concentrations for odorant effluents when ventilation inlets are located at various points about a building. Measurements of mean and root-mean-square (rms) concentrations about model buildings in environmental wind tunnels are combined with probability models for concentration variation and odor annoyance threshold information to predict source strengths which will produce acceptable frequencies of high odor levels.

Human Response to Environmental Odors

Odorants are chemical substances and can be analyzed by chemical methods, but odor sensations must be assessed by measuring human responses. Human responses to odors have often been expressed in terms of thresholds. The detection threshold is the minimum concentration of odorant at which a response is elicited, the recognition threshold is the minimal concentration at which an odorant can be identified, and the annoyance threshold is the minimal concentration at which the public expresses resentment about the odor. Since the use of minimum thresholds are subject to variability due to the human context of measurement, such as "false alarms" and expectation, it is customary to define the "50% thresholds" as the minimal concentrations at which half the subjects in a population respond to or identify an odor--this definition is parallel to the concept of a "median", "average", or "standard" nose. Testing by odor panels has resulted in published tables of such threshold levels for many odorants (Leonardos, 1969; Hellman and Small, 1974; National Research Council, 1979; ASHRAE, 1981). (Since there is a wide variability in testing method and threshold definition some care must be taken when using these tables.)

Odor concentration can be expressed as the number of unit volumes which a unit volume of odorous sample will occupy when diluted to the odor threshold with nonodorous air (ASTM D1366-67a). Odor units (ou) are widely used to express legal limits for odoriferous materials.

Past experience suggests that, regardless of the particular odorant characteristics, the threshold of distraction for most persons occurs at approximately 5 ou/scf. The complaint level odor concentration has been found to be approximately twice the distraction threshold, or 10 ou/scf. This concentration of odor is apparently sufficient to be totally demanding of conscious attention and to cause the psychological stress commonly associated with odor complaints. At the present time, there seem to be no federal regulations for the control of odors, and odors have been classified as non-criteria pollutants by the Environmental Protection Agency. Nonetheless, some state and local agencies do control odorants. At least seven states have stipulated that odors should not be recognized by an "average" person when sample air is dilulted seven times (<7 ou/scf) as measured at a location just off the pollutant producers property. Of course the optimal solution is to produce an agreeable odor level both on and off the property site.

Estimating Odor Levels

The ASHRAE 1981 Fundamentals Handbook recommends ventilation, adsorption, chemical reaction, and odor modification in air-conditioning for odor removal (Chapter 12). In planning the use of ventilation air for odor control the required diluting volume of ventilation air to prevent re-entry at odorous levels is required. In Chapter 14, Air Flow Around

Buildings, algorithms to predict minimum average dilution levels are provided; unfortunately these are for average dilutions levels; thus they are not sufficient to estimate odor frequencies. Several authors have proposed to use conventional Gaussian dispersion models to predict downwind odors from point and area sources, but they fail to account for the statistical variability of the scent with time (Clarenburg, 1973; Cheremisinoff, 1975; Balling and Reynolds, 1980;etc.). Others recognize the effect of plume meandering and adjust for it by using puff models and wind rose statistics (Hgstrom, 1972; Feldstein et al., 1974; Murray et al., 1978) or correct for it by adjusting the averaging times (Summer, 1971). None of these models are suitable for estimating odor levels and their frequencies on or in the wake of buildings.

AIR FLOW AROUND BUILDINGS

There is a relatively high level of misunderstanding of how wind flows around buildings, probably caused by conceptual extensions of two-dimensional flows. For example, frequently authors assume that the separation zones about three-dimensional obstacles are bounded by streamlines connected to the building corners such that the separated cavities are closed (See figure 1, Chapter 14, ASHRAE 1980 Fundamentals Handbook). In actuality upwind flows continually flush into the downwind wake (cavity) and leave by complicated interaction with free standing vortices with vertical axes forming an arch at the back corner and by entrainment into the surface level horseshoe vortex which surrounds the building complex (See figure 1). For this reason transport of pollutants into or out of the vicinity of a building is primarily accomplished by convection and not by turbulent dispersion (Meroney, 1982; Peterka et al., 1984).

Mean Surface Concentration Levels

Transport of effluents from surface vents or stacks back to surface inlet ventilators is equally complex. Li and Meroney (1983a) examined diffusion about a model box-shaped building in a meteorological wind tunnel. Their measurements included mean and fluctuating surface and wake concentrations for various source locations and model building orientations. Figures 2, 3 and 4 display typical concentration-coefficient isopleths, K, for roof mounted exhaust vents. Similar measurements for other building shapes but with fewer orientations are reported by Wilson (1976, 1977). Since the wind may be expected to blow from all quadrants at some time, figure 5 recommends surface coefficients to use during ventilator design. When dilution levels , K_e/K, are plotted versus the minimum normalized separation distance (string distance), $r/\sqrt{A_c}$, between exhaust and sampling point a bounding line for minimum dilution levels can be specified. Li and Meroney suggest a revised version of the ASHRAE expression:

$$D_{min} = \frac{0.11\, K_e\, (r/\sqrt{A_c})^2}{(1 + 4\,\theta/\pi)} \qquad (1)$$

where

D_{min} = Minimum dilution of exhaust gases,
K_e = $(C_e A_c U)/Q_e$,
C_e = Concentration of exhaust gas at source,
A_c = Crosswind cross-sectional area of the building for the $\Theta = 0^o$ orientation, and
U = Approach wind velocity at height of building.

This expression provides a lower bound to 99% of all surface measurements of mean concentration. When an odorous plume impinges on a building from a source upwind or downwind of the building Wilson et al.(1984) recommend alternative calculation procedures. If the receptor is in the wake of the building see the works of Kothari et al. (1981a, 1981b, 1981c).

Concentration Fluctuation Measurements

Li and Meroney (1983b) reviewed recent measurements of concentration fluctuations in plumes released from isolated sources and near buildings. Both field and laboratory measurements suggest centerline concentration fluctuations are largest near the source where the plume is narrow but diminish as the plume broadens due to dispersion. The absolute concentration intensity, $i_c = \sqrt{\overline{c'^2}}/C_{\text{℄}}$, is relatively constant near plume center and decreases rapidly near the edge of the plume. Csanady (1973) proposed that concentration fluctuations are log-normally distributed about the mean for a continuous ground-level point source. Wilson (1976) measured concentration fluctuations on a sharp-edged building surface for a source released from different roof vent locations. He reported that the concentration statistics are in good agreement with the log-normal probability distribution and the fluctuation intensity decreases as the distance from the vent increases. Li and Meroney (1983b) report measurements of concentration fluctuation intensity and peak-to-mean concentration ratios in the wake region of a block-shaped model building (See their figure 5). The decay of concentration intensity with string-distance is correlated by expressions suggested by Wilson (1976) and Meroney (1982):

$$i_c = 0.71\,(r/\sqrt{A_c'})^{-0.81}, \qquad \text{Wilson (1976)} \qquad (2)$$

$$i_c = 0.35 + 3.65\exp(-2\,r/\sqrt{A_c'}), \qquad \text{Meroney (1982)} \qquad (3)$$

STATISTICAL CHARACTER OF ODOR PROBLEMS

Odor fluctuations in a dispersing gas cloud are caused by the inherent turbulent character of the medium in which it disperses. The distinctive character of turbulence is its randomness. The results of two separate realizations of odor dispersion will inevitably be different from one another no matter what precautions are taken to ensure that initial conditions are the same. Several authors have reviewed the basic statistical terminology and relations required to describe the variability of gas dispersion (Netterville, 1980; Meroney, 1982, 1984; Chatwin, 1982; Jones, 1983). They conclude that, at a minimum, one requires the form of the probability density function (p.d.f.), p(C;x,t), the mean, $\overline{C}(x,t)$, and the variance, $\overline{c^2}(x,t)$, of the ensemble of concentration realizations to predict the probability of odors exceeding some threshold odor level.

Let the odor units/volume of the dispersing odorant at position x and time t be $\chi(x,t)$. The statistical properties of $\chi(x,t)$ can be meaningfully defined only for an ensemble of possible trials. The p.d.f. of χ defines the proportion of the trials for which χ lies between C and C + dC, or

$$p(C;x,t) = \text{prob}(C < \chi(x,t) < C + dC) \qquad (4)$$

where prob is an abbreviation for probability. Since concentrations and proportions are essentially positive, the p.d.f. must never be negative. Since $\chi(x,t)$ must lie between zero and one, the integral of the p.d.f. must be unity. The ensemble mean concentration may be defined as

$$\overline{C}_m(x,t) = \int_0^{1.0} p(C;x,t)dC, \qquad (5)$$

and the mean square fluctuation or standard deviation will be denoted by

$$\overline{c^2}(x,t) = \int_0^{1.0} (C - \overline{C}_m(x,t))^2 p(C;x,t)dC. \qquad (6)$$

Since the range of concentrations, C, is limited to between zero and one, it is frequently suggested that the p.d.f. is normally distributed at middle-range concentrations and is log-normally distributed at the two ends of the concentration range. Both distributions are uniquely defined in terms of their mean values and standard deviations. Since threshold odor concentrations are typically very small (≃ ppm to ppb), the log-normal distribution proposed for odor use is

$$p_{ln}(C) = 1.0/((2\pi)^{0.5}\sigma_{ln}C)\cdot\exp(-(\ln(C/C_{med}))^2/(2\sigma_{ln}{}^2)) \qquad (7)$$

where σ_{ln} is the log-normal standard deviation and C_{med} is the median concentration, or

$$\sigma_{ln}{}^2 = \ln(\overline{c^2}/\overline{C}_m{}^2 + 1), \text{ and}$$

$$C_{med} = \overline{C}_m/(1 + \overline{c^2}/\overline{C}_m{}^2)^{0.5}.$$

Predicting Probability of an Odorous Situation

When a gaseous effluent contains odorous material, one is interested not only in the average levels of such odors, but in their instantaneous magnitudes. In particular, one is concerned with the total probability, Ω, that $\chi(x,t)$ remains below a specified maximum odor level, C_{max}, where

$$\Omega(\chi<C_{max}) = \int_0^{Cmax} p(C;x,t)dC. \tag{7}$$

When the p.d.f. is well approximated by a log-normal curve with mean and variance known, then

$$\Omega(\chi<C_{max}) = \tfrac{1}{2}\left\{ 1+ \text{erf}[\ln(C_{max}/C_{med})/(\sqrt{2}\sigma_{ln})]\right\} \tag{8}$$

The total probability, Ω, can be evaluated using standard error function tables. For odorous gases C_{max} may be specified in terms of some multiple, N_{max}, of a threshold concentration, i.e. $C_{max} = N_{max} \cdot C_{th}$.

Predicting Maximum Permissible Odor Levels in Ventilator Exhausts

Alternatively, it is possible to predict exhaust odor levels, C_e, which will not produce inlet odor levels, C_{max}, more than some prespecified percentage of time using the p.d.f., mean concentration, and variance information. Again assuming a log-normal p.d.f for odors and empirical information about mean concentration and variance distributions about the building one finds that exhaust levels in odor units must be less than

$$\begin{aligned} N_e &= C_e/C_{th} = \\ &= \frac{A_c U N_{max}}{KV_e}\left\{\exp[-\sigma_{ln}(\sqrt{2}\, \text{erf}^{-1}(2\Omega - 1) - 0.5\sigma_{ln})]\right\}, \end{aligned} \tag{9}$$

where

C_{th} = Threshold odor level for specific scent,

Ω = Total probability concentrations remain below C_{max},

A_c = Cross section of building normal to wind,

U = Wind speed at building height,

N_{max} = Maximum permissible odor level,

V_e = Exhaust volume flow rate at source vent,

K = Mean concentration coefficient, and

σ_{ln} = Log-normal standard deviation.

The dimensionless concentration coefficient, K, may be estimated from displays like those shown in figures 2 through 5 or calculated from empirical expressions such as equation 1, where $K = K_e/D_{min}$. Estimation of the log-normal standard deviation requires information about concentration fluctuation variance or concentration intensity, i_c. Li and Meroney (1983b) found that

$$i_c \leq 0.57\ K, \qquad (10)$$

but this may also be a function of K_e. If one eliminates $r/\sqrt{A_c}$ between equations 1 and 2 or 1 and 3 alternative expressions can be calculated such as,

$$i_c = 0.29\ K^{0.405}. \qquad (11)$$

Thus, the log-normal standard deviation is

$$\sigma_{ln} = \ln(0.08\ K^{0.81} + 1). \qquad (12)$$

ODOR CALCULATIONS FOR BUILDING VENTILATORS

Evidence now exists that concentrations are distributed about their mean values in a log-normal manner, mean concentrations may be reliably predicted by simple empirical expressions, and variances can be simply related to centerline plume concentrations. This information has been used together with the approach discussed in proceeding paragraphs to produce estimates of maximum exhaust odor unit levels which avoid nuisance level odors. Figure 6 predicts the total probability, $\Omega(C_{max})$, that peak concentrations during a release situation will lie below disturbing odor levels. A value of $\Omega = 0.998$ implies a three minute odor episode may occur once a day. Odor events are also dependent upon wind direction; hence, to the extent that winds remain in quadrants which do not produce the expected mean concentrations odorous situations are even less likely.

Since $N_e/(K_e N_{max}) = f(K, \Omega)$ it is possible to re-scale the isopleths in figures 2 to 5 to specify required exhaust odorant levels to avoid re-entry of detectable odors. Figure 7 displays exhaust odor number isopleths for one event a day episode levels, where

$$XN = \text{Exhaust Number} = N_e/(K_e N_{max})$$

ranges from near zero near the source to large values near the ground.

Example Calculation for Exhaust of Ammonia

A 10 story building is presumed to exhaust ammonia from a roof center ventilator. The roof area is 100 ft by 100 ft and the building is 100 ft tall. Ammonia has a particularly noxious pungent odor which causes a stinging burning sensation in the nose and eyes and becomes recognizable at a fairly high concentration of 47 ppm (ASHRAE, 1981). The ventilator used has an exit area of two square feet and exhausts at 10 ft/s. The average wind speed at building height is expected to be 20 ft/s, but the wind may blow from any quadrant. The building owner needs to know if it is necessary to pre-treat the exhaust air if the effluent is laden with 50,000 ppm ammonia. The nearest inlet ventilator is half way down the side of the building. The owner desires to avoid odor episodes exceeding 5 ou/scf occurring more than once a day.

Sample Calculations:

$C_{th} = 47$ ppm

$N_{max} = 5$

$\Omega = 0.998$

$A_c = (100)\cdot(100) = 10{,}000 \text{ ft}^2$

$U = 20$ ft/s

$V_e = (2)\cdot(10) = 20$ cfs

$K_e = (10000)\cdot(20)/(20) = 10000$

$r/\sqrt{A_c} = 100/\sqrt{10000} = 1.0$

hence

$D_{min} = (\text{Equation 1}) = 0.11\ (10000)(1.0)^2/(1) = 1100$

$K = K_e/D_{min} = 10000/1100 = 9.1$

$i_c = (\text{Equation 11}) = 0.29\ (9.1)^{0.405} = 0.71$

$\sigma_{ln} = \ln(i_c{}^2 + 1) = \ln((0.71)^2 + 1) = 0.41$

$$XN = K^{-1}\{\exp[-\sigma_{ln}\{\sqrt{2}\ \text{erf}^{-1}(2\Omega - 1) - 0.5\sigma_{ln}\}]\}$$

$$= \{\exp[-0.41\{\sqrt{2}\ \text{erf}^{-1}(2(0.998) - 1) - 0.5(0.41)\}]\} \div 9.1$$

$$= 3.35 \times 10^{-2}.$$

$$N_e = XN \cdot K_e \cdot N_{max} = (0.0335)(10000)(5) = 1676$$

$$C_e = N_e C_{th} = (1676) \cdot (47) = 78,763 \text{ ppm.}$$

Thus the actual exhaust concentrations are low enough to avoid frequent odor episodes at the building ventilator inlets.

CONCLUSIONS

Combining information about odor physiology, dispersion statistics, and plume behavior near buildings in the atmospheric surface layer suggests that it is quite possible to design ventilator systems to minimize odor impact from building related sources. The equations and figures provided here should make it possible to assess odor impact on comfort of conditioned building spaces. The method recommended above will also work for receptor locations located in the building wake out to distances of $5\sqrt{A_c}$. Odor levels calculated for greater transport distances should be adjusted for variability in wind direction and thermal stratification.

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LIST OF FIGURE TITLES

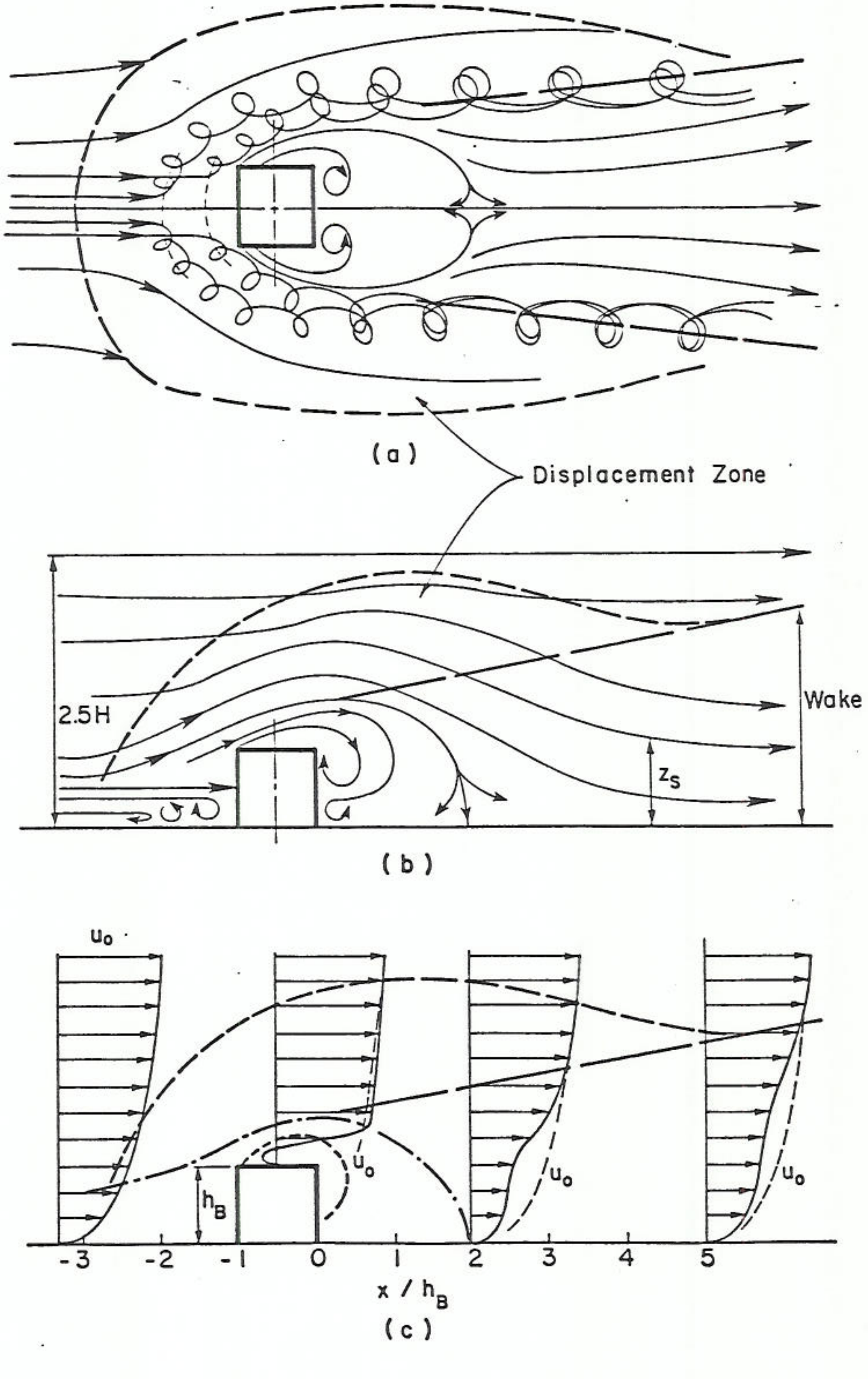


Figure 1. Mean streamline patterns about a block building (Meroney, 1982).

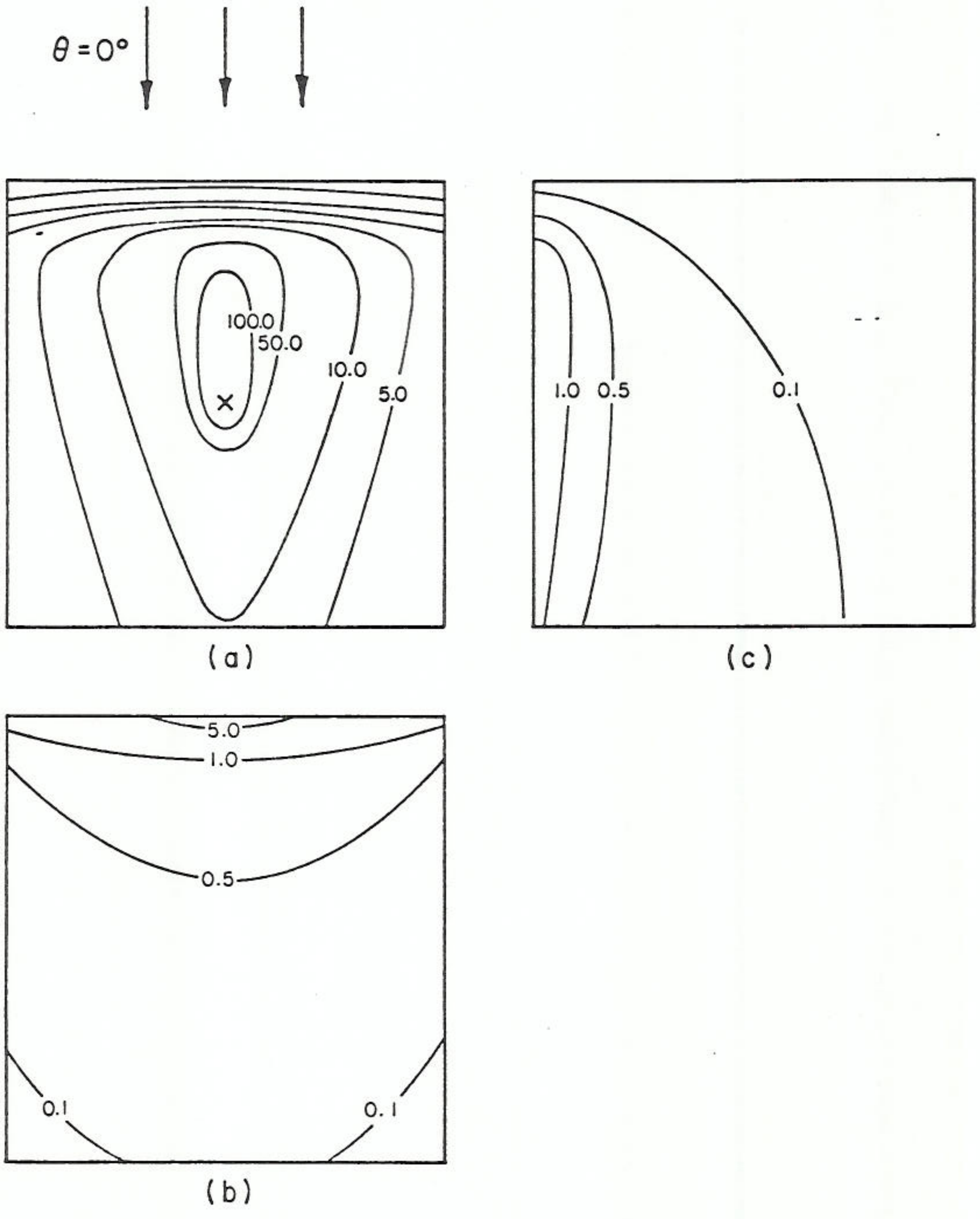


Figure 2. Concentration coefficient isopleths on a cubical model building (θ = 0°, central roof vent release) (Li and Meroney, 1983a).

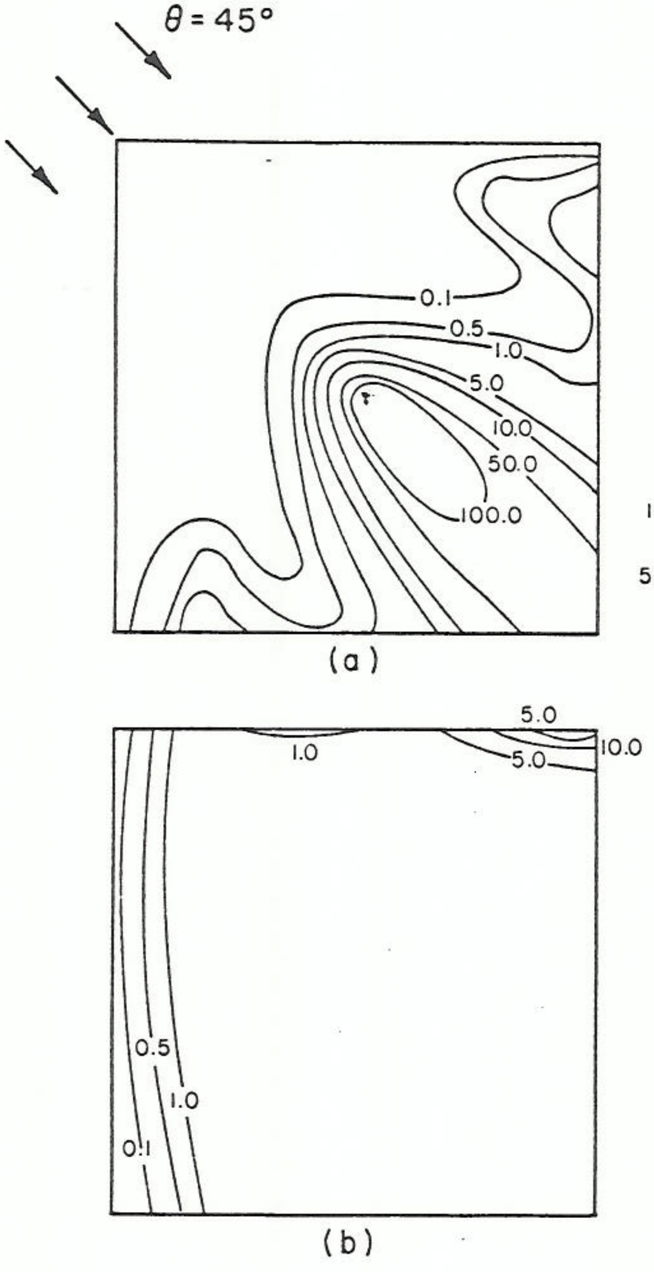


Figure 3. Concentration coefficient isopleths on a cubical model building (θ = 45°, central roof vent release) (Li and Meroney, 1983a).

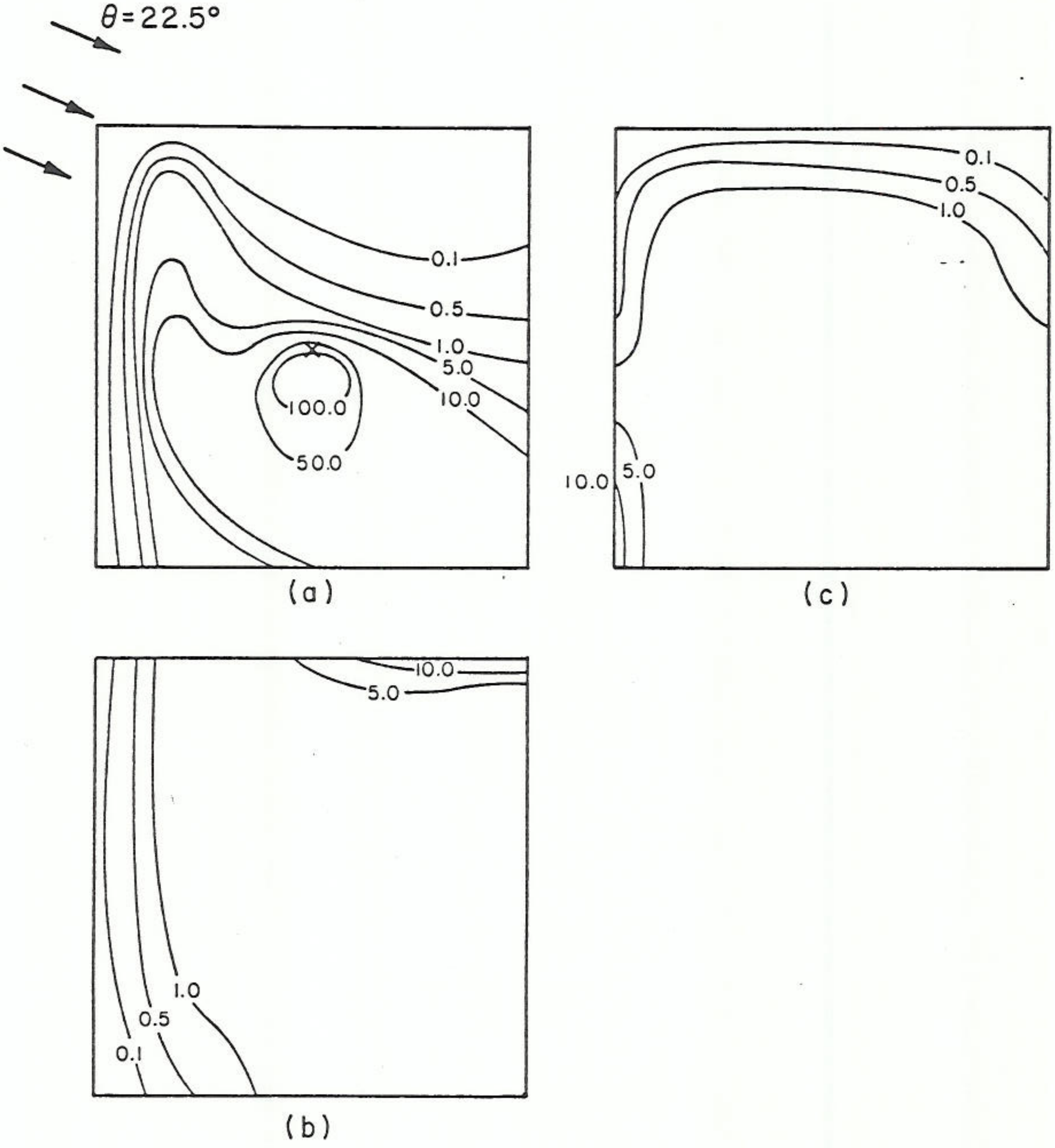
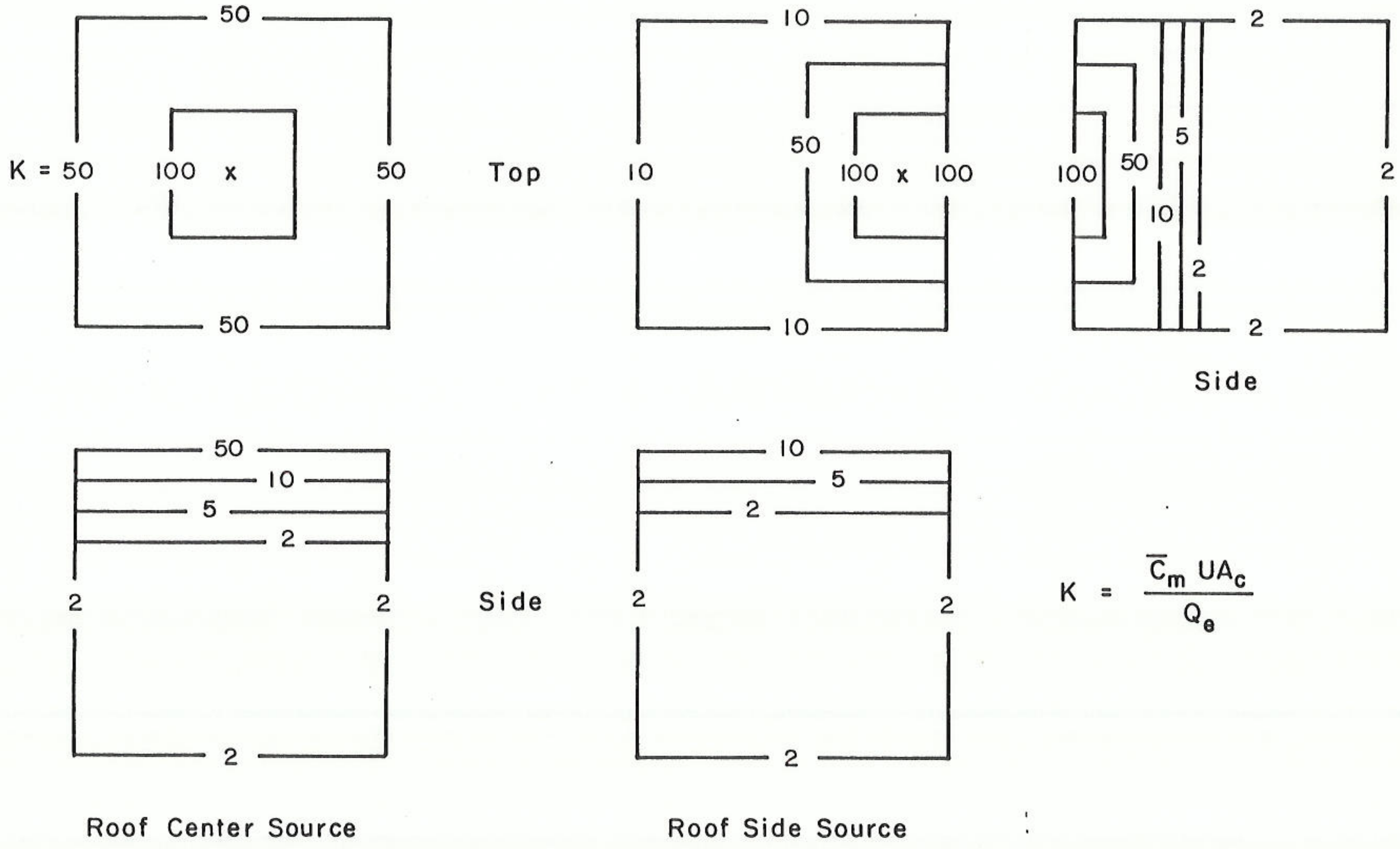


Figure 4. Concentration coefficient isopleths on a cubical model building (θ = 22.5°, central roof vent release (Li and Meroney, 1983a).



$$K = \frac{\overline{C}_m U A_c}{Q_e}$$

Figure 5. Resultant all wind quadrant concentration coefficient isopleths for roof central and roof edge vent release.

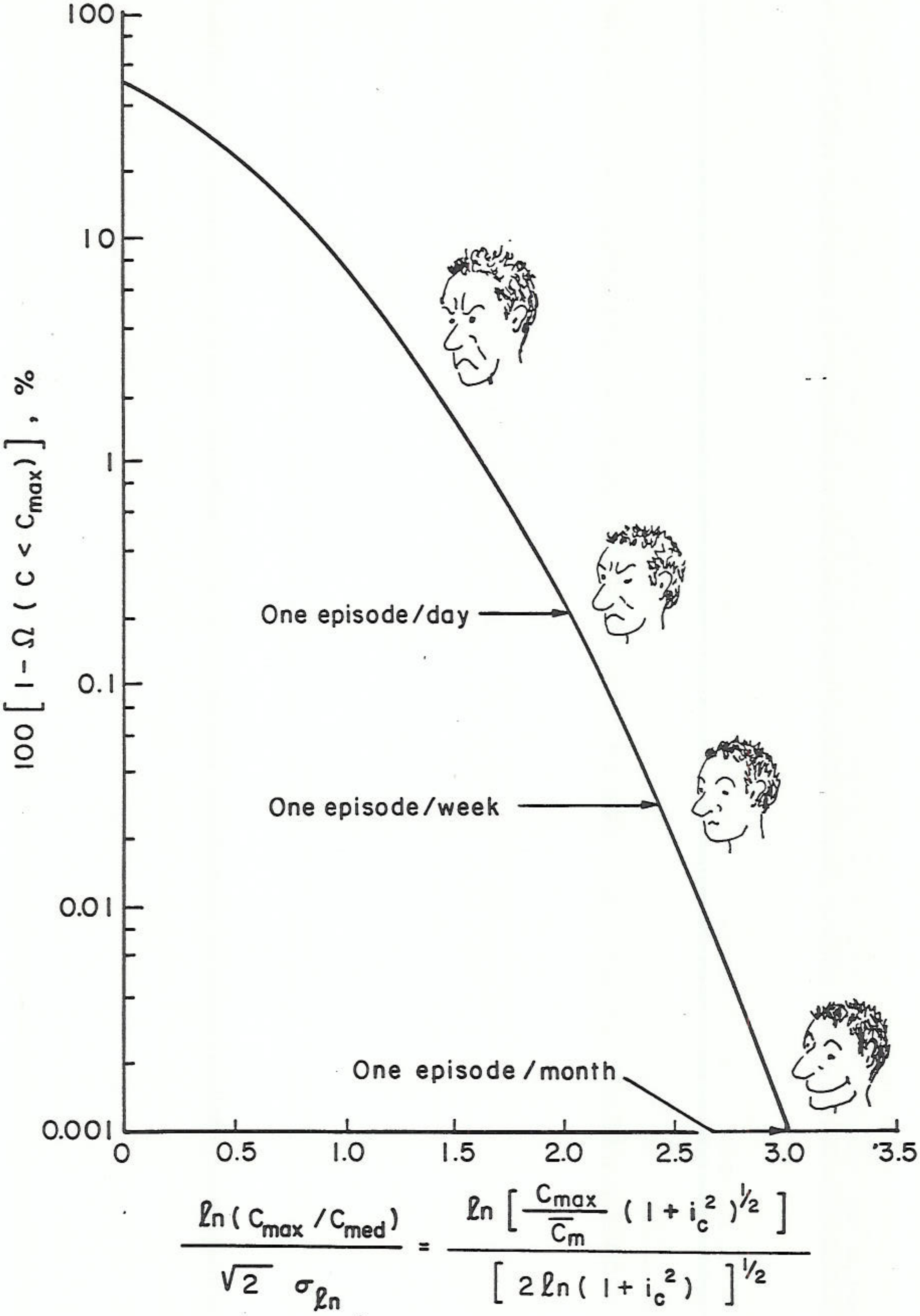


Figure 6. Total probability, Ω, that peak concentrations exceed a prespecified maximum concentration, C_{max}.

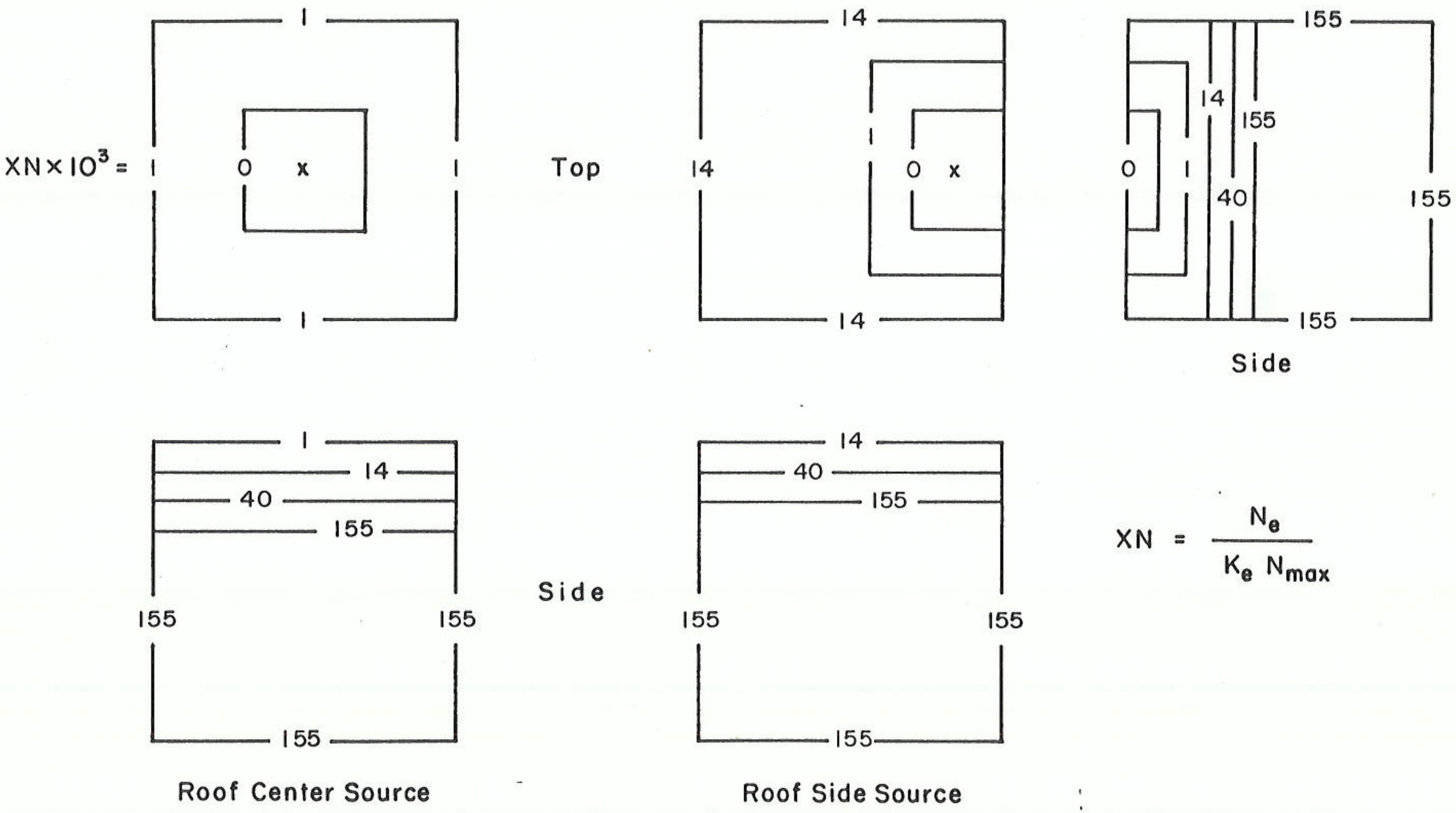


Figure 7. Resultant exhaust numbers, XN, for all wind quadrant releases from roof central and roof edge vent release required to maintain odor levels below maximum odor numbers, N_{max}, with a probability $\Omega = 0.998$.