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PRELIMINARY DRAFT

DIFFUSION ESTIMATION FOR SMALL EMISSIONS

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Corrections and Additions

p. 5, ℓ.21 - $H' = (h'-h_b)/\ell_b$

p. 9, ℓ.7 - "full distance" should be "fall distance"
ℓ.10 - $|F|^{u4}$ should be $|F|^{1/4}$

p. 11, bottom - "300" should be one mark to the right on "F" scale

p. 16, ℓ.9 - "35 m/sec" should be "3.5 m/sec"

p. 25, eq. (12) - " = " in the denominator should be " + "
eq. (14) - "F" should be "f"
ℓ.11 - "f" should be "F"

p. 29, ℓ.1 - "4/3" should be "3/2"
ℓ.8,9 - "3" should be "2"

p. 36, ℓ.5 - "$h_b = 1.5\ell_b$" should be "$h_b + 1.5\ell_b$"

DIFFUSION ESTIMATION FOR SMALL EMISSIONS

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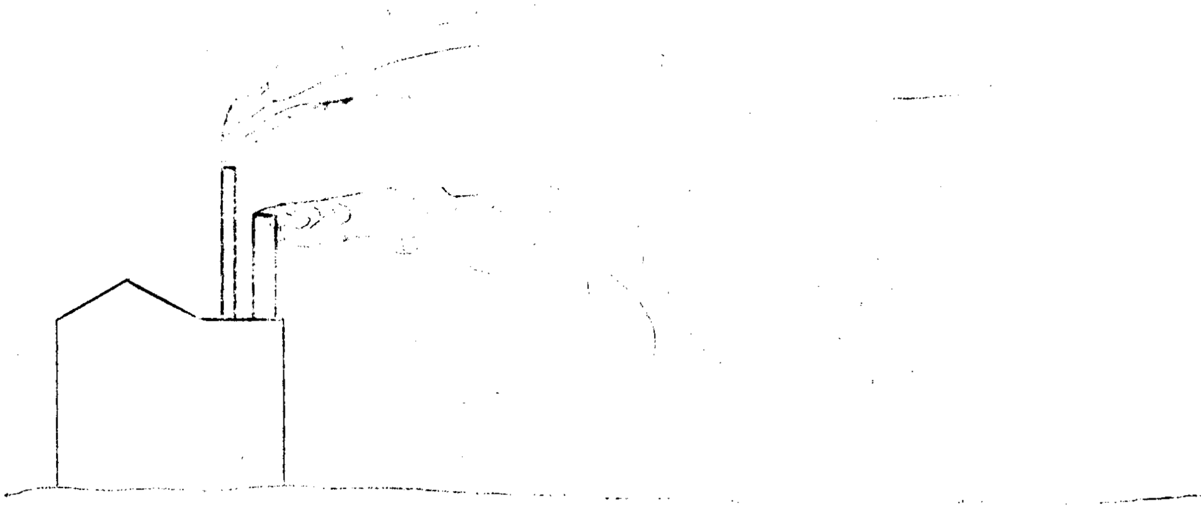
1.0 INTRODUCTION

This is a simplified approach to the calculation of ground level concentrations of effluents from small industrial and fuel burning installations. It is intended to serve as a first approximation to a very complex process. Because each stack, building, and terrain configuration is different, actual ground concentrations may frequently differ from the values calculated here by a factor of two. Nonetheless, this procedure should be useful for determining whether ambient air quality standards are likely to be met, exceeded, or only marginally obtained. It also predicts the locations where the highest and most frequent ground concentrations are likely. Sampling at several such locations is very advisable, unless the predicted concentrations are quite low. In addition, consultation with a specialist in air pollution meteorology may be desirable in the long run, especially in marginal or unique situations.

The procedures given here were designed especially for source heights of less than 100 m; some of the simplifications made are not valid for large emissions. In the few cases where more than arithmetic formulas are necessary, simple nomograms are provided. It is important to note that all lengths are in meters (m) and velocities are in meters per second (m/sec) in these formulas; this avoids needless reiteration of the formulas for different units. Appendix B provides all necessary conversion factors.

Chapter 2 gives a method for calculating the effective height of a plume of effluent, if it escapes the "downwash" effect of the stack and buildings, and for predicting the occurance of downwash. The latter is a common occurance with small emissions, and greatly increases ground concentrations in the immediate vicinity downwind of the source. If downwash is avoided, it is important to make a reasonable estimate of the plume's effective height, as this greatly affects the maximum ground concentration. Chapter 3 simplifies somewhat the "classical" methods for predicting ground concentrations, for both elevated sources and ground sources, and gives correction factors for various averaging periods up to 24 hours. Chapters 4 and 5 outline ways to extend the above procedures to predict the average ground concentration and total deposition of particulates over extended periods, 30 days to a year. Chapters 6, and 7 note important features of diffusion at sites that are not flat and rural that differ from the classical diffusion model, and suggests means of accounting for them.

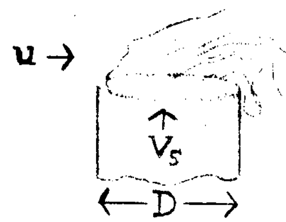
Further guidance can be found in the ASME "Recommended Guide for the Prediction of the Dispersion of Airborne Effluents" (1968, presently being revised).



2.0 ELEVATED SOURCE OR GROUND SOURCE?

The answer to this question can mean either a zero concentration or a very high concentration of effluent at the ground in the neighborhood of an emission. Does the plume keep its distance from the ground-and if so, what is its effective height - or, is the plume brought to the ground very near the source? The latter can happen if the efflux velocity is too low, the stack is too short, or the emission is denser than air. Downwash of the plume due to terrain is also possible, particularly if there is an escarpment upwind of the source, but this case is relatively rare.

The answer to the above question can depend on the wind speed, as will be seen below. It also can depend on the location of the stack relative to buildings and the wind direction. The great variety of possible building geometries gives ample reason for not expecting great accuracy from the following "rules-of-thumb."



2.1 Stack Aerodynamic Effect:

An effluent emitted vertically from a stack can rise due to its momentum or can be brought downward by the low pressure in the wake of the stack. Which occurs depends on the ratio of the efflux velocity, v_s, to the crosswind velocity, u. Make the following computation, where D is the inside stack diameter and h_s is the source height above the ground:

$$h' = h_s + 2(v_s/u - 1.5)D \quad . \qquad (1)$$

It is suggested that this be done for the following values of u: 1, 2.5, 4.5, 7, and 10 m/sec. The efflux velocity can be determined from direct measurement, from the amount of forced draft, from the rate of the process and relative proportions of its gaseous product (thermal expansion should be taken into account), or from visual or cinematographic estimates (if there are visible tracers in the effluent.) Building and stack measurements can be made directly, taken from drawings, or scaled from photographs. All dimensions should be converted to meters, and v_s and u should be in meters per second, as these units are used throughout this guide. Conversion factors are given in Appendix B

If the effluent is emitted from a non-vertical stack or vent, set $h' = h_s$.

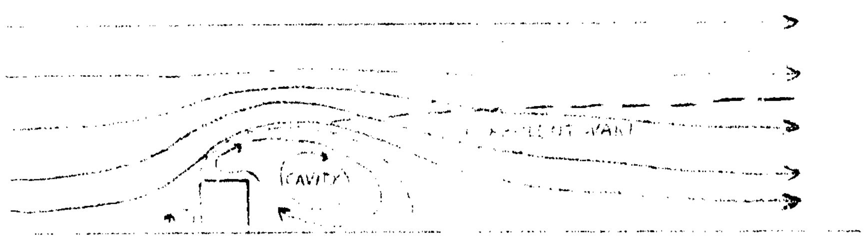
2.2 Building Effect:

If the effluent is emitted from a stack or vent on or near a building, it may be brought downward by the flow of air over and around the building.

Let ℓ_b equal the lesser of the building height, h_b, or the building width perpendicular to the wind direction, w_b. If h' is less than $(h_b + 1.5\ell_b)$ and the point of emission is on the roof, anywhere within $\ell_b/4$ of the building, or within $3\ell_b$ directly downwind of the building, the plume can be considered to be within the regional of building influence. If this is not the case, set h" = h' and go on to Section 2.3. If the plume is within the region of building influence, there are several possibilities:

(1) If h' is less than $(h_b + 0.5\ell_b)$, part or all of the effluent is likely to circulate within the aerodynamic "cavity" that forms in the lee of the building (see the sketch below.) This cavity usually begins at the upwind edge of a flat roof or at the crest of a pitched roof (unless the crest is parallel to the wind). It grows to a height of about $(h_b + 0.5\ \ell_b)$ and a width a little greater than w_b, and extends over all lee sides of the building and downwind 2 to 3.5 ℓ_b. Thus, effluents in the cavity region may affect persons on the ground and in the building. One must especially consider the placement of intake vents providing ventilation within the building. Following are some rough guidelines for estimating the concentration (χ) experienced in the cavity region. Let $\chi = KQ/(u\ \ell_b^2)$, where Q is defined in Section 3.1. If H' > 0.35, K is generally 1 or less throughout the cavity. If H' < 0.35, K is typically 1.5 and at most is 3.0, except on the side of the building where the effluent is emitted (for instance, the roof). Here, K can range up to 100. The concentration along the axis

of the plume can be roughly approximated by $\chi = 4Q/(us^2)$, where s is the distance from the source measured along the axis. The airflow near buildings is complicated and it is difficult to predict the trajectory of the plume axis. For example, in the cavity within $\ell_b/4$ of the roof, the flow is usually upwind.



(2) If $h' > h_b$, compute $h'' = 2\,h' - (h_b + 1.5\,\ell_b)$

If $h' < h_b$, compute $h'' = h' - 1.5\,\ell_b$ (2)

(3) If h'' is greater than $\ell_b/2$, the plume remains an elevated source. Go on to Section 2.3.

If h'' is less than $\ell_b/2$, treat the plume as a ground source with an initial cross-sectional area $A = \ell_b^2$. Go on to Chapter 3.

The above rules reduce to a simpler form in the case of a squat building, i.e. when $h_b < w_b$: if $h' \geq 2.5\,h_b$, the plume escapes the region of building influence and $h'' = h'$; if $h' \leq 1.5\,h_b$, the plume downwashes into the building cavity (see (1) above) and also becomes a ground source with $A = h_b^2$ (see (3) above); for inbetween values of h', the plume remains elevated and $h'' = 2\,h' - 2.5\,h_b$ (see (2) above).

.2.3 Buoyancy Effect:

If the procedure just given in Section 2.2 indicates that the plume is still elevated, the plume height can be significantly altered by buoyancy if the density of the effluent differs from the density of the ambient air by more than 1%. This is nearly always true, unless the effluent is more than 98% air and its temperature is within 5°F of the ambient temperature; in this latter case, it is permissible to set h = h'', where h is the effective source height, and go on to Chapter 3.

To determine whether an effluent is heavier or lighter than air, calculate $\Delta = \Delta_T + \Delta_m + \Delta_w$, where Δ_T is the temperature contribution to the relative density difference, Δ_m is the molecular weight contribution, and Δ_w is the liquid water contribution (after evaporation occurs). $\Delta_T = -(c_{po}/c_p)\ (\Delta T/T)$, where c_{po} is the specific heat capacity at constant presure of the effluent, c_p is the specific heat capacity of air (c_p = 0.24 cal/gm -°K).
ΔT is the difference between the effluent and ambient temperatures, and T is the ambient absolute temperature (°K = °C + 273°).
For the products of combustion of the hydrocarbon fuels, $(c_{po}/c_p) \doteq 1$.
Except in arctic winters, 288°K = 518°R is an adeqate approximation for T.
If ΔT is not convenient to measure, an alternative expression is $\Delta_T = -Q_H/(M_o\ c_p\ T)$, where Q_H is the amount of dry heat emission carried by the effluent (not latent heat) and M_o is the mass flux of the effluent (if Q_H is in cal/sec, c_p should be in cal/gm - °K, T in °K, and M_o in gm/sec),

$\Delta_m = (1 - 28.9/m_o)$, where m_o is the mean molecular weight of the effluent ($1/m_o$ is the sum of the fraction, by weight, of each component gas times the inverse of its molecular weight). For Products of combustion of the hydrocarbons, Δ_m is negligible compared to Δ_T as long as at least 10% of the heat of combustion is carried by the effluent as dry heat. Finally, $\Delta_w = 8\ Q_w/M_o$, where Q_w is the estimated mass flux of liquid water in the effluent; Q_w/M_o is just the fraction by weight of liquid water in the effluent. Except for scrubbed or washed plumes, Δ_w is usually negligible. (When there is water vapor present in the effluent, it is also possible to get a temporary increase in buoyancy due to latent heat release if condensation occurs; in practice, the condensation stage is usually short-lived for small emissions and all water soon evaporates.)

If Δ is positive, the plume is denser than air (negatively buoyant) and may fall to the ground very near the source; the next section applies in this case. If Δ is negative, the plume is lighter than air (buoyant) and may rise significantly; go on to Section 2.3.2 in this case.

2.3.1 Dense Plumes:

If $\Delta > 0$ the plume is heavier than air, and may fall to the ground rather close to the source if $u < 0.22\ C \sqrt{g\ \Delta\ D}$, where C is given by

		Urban Site	Rural Site
Day ,	$u < 3.5$ m/sec	3	5
Day ,	$u > 3.5$ m/sec	5	10
Night ,	$u > 3.5$ m/sec	7	15
Night ,	$u < 3.5$ m/sec	10	35

If u is greater than the above value, set the effective source height equal to h" (i.e. h = h") and go on to Chapter 3. If u is less than the above, the plume falls to the ground at a distance roughly equal to $4.5\ h_s\ u/\sqrt{g\ \Delta\ D}$ downwind of the source, and should be treated as a ground source (h = 0) with an initial cross-sectional area $A = 0.2\ h_s^2$.

The exception to this rule is the rural source at night when $u < 3.5$ m/sec; in this case, the full distance is limited to approximately $100\ |F|^{1/4}$, where F is defined in the next section. Therefore, in this particular case treat the plume as above only if $(h_s - 100\ |F|^{1/4}) < 0.2\ h_s$; if $(h_s - 100\ |F|^{u4}) > 0.2\ h_s$ but is less than $0.5 \ell_b$, in association with a building, treat it as a ground source with $A = \ell_b^2$. If neither of these conditions hold, treat it as an elevated source with

$$h = h_s - 100\ |F|^{1/4} \quad .$$

Complete absence of wind does not imply that the effluent reaches the ground with an infinite concentration, since the plume does mix with air as it falls. To allow for this, in this calculation procedure consider that there is an "effective minimum wind speed" equal to $|F/h_s|^{1/3}$. If this speed is greater than $0.22\ C\ \sqrt{g\ \Delta\ D}$, the density effect may be neglected altogether; set h = h" and go on to Chapter 3.

Since very low wind speeds may be of great concern in the case of dense plumes, the following very rough guideline is offered for estimating the frequency of low winds:

Terrain Type	Frequency of u < 1 m/sec
Flat	2 to 5%
Rolling	5 to 10%
Hilly	10 to 20%
Mountain region	20 to 30%
Mountain sheltered	30 to 40%

These low winds occur predominantly at night.

For the Frequency of winds less than 1 m/sec, multiply the above frequencies by u^2, where u is the upper limit in m/sec. Obviously, the nature of the site has a strong influence here.

2.3.2 Buoyant Plumes:

If $\Delta < 0$, the effluent may rise appreciably owing to its buoyancy, resulting in substantially reduced concentrations at the ground. To determine this rise, first calculate

$$F = -2.6 \, \Delta \, M_o, \qquad (3)$$

where M_o is the mass flux of effluent in kgm/sec. An alternative expression for effluents in which molecular weight and liquid water do not contribute significantly to Δ is

$$F = 3.7 \cdot 10^{-5} \, Q_H \, , \qquad (4)$$

where the dry heat emission, Q_H, is in cal/sec (Appendix A gives conversion factors for other units). This expression is quite adequate for unwashed effluents resulting from the combustion of hydrocarbon fuels.

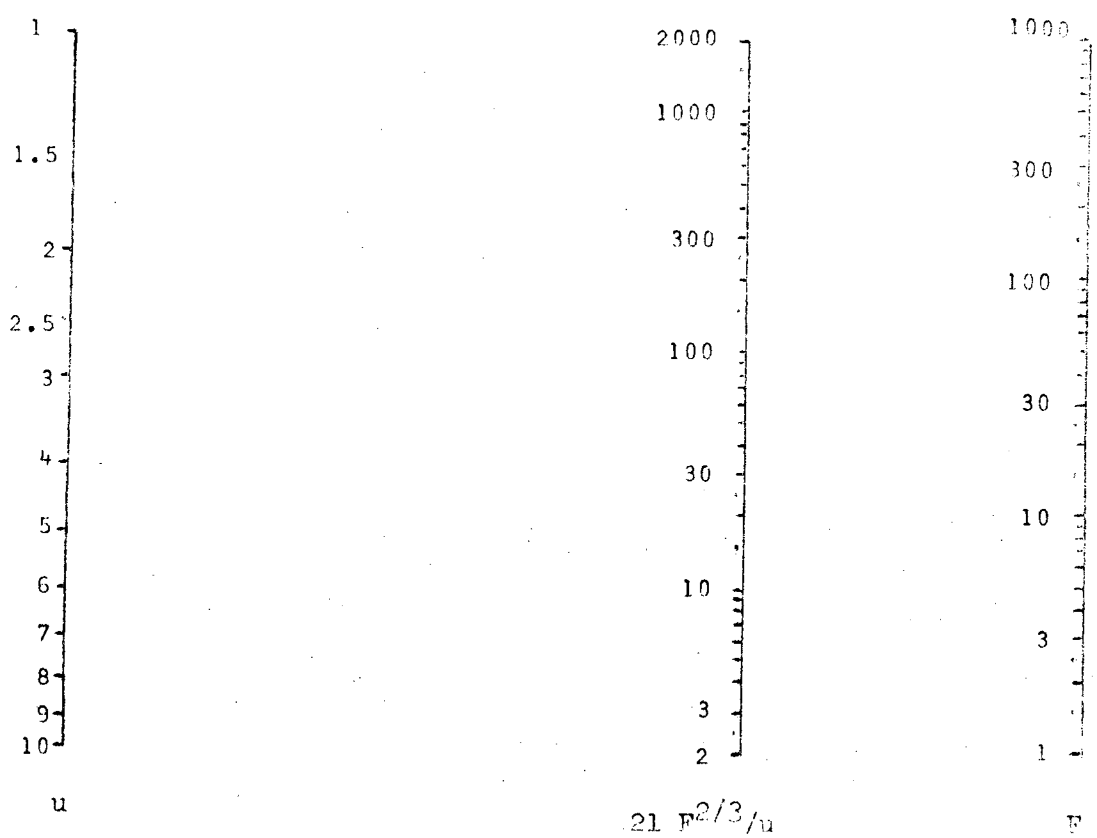
During the day, or at night when the wind speed u is greater than 3.5 m/sec, the effective source height of a buoyant plume is approximated by

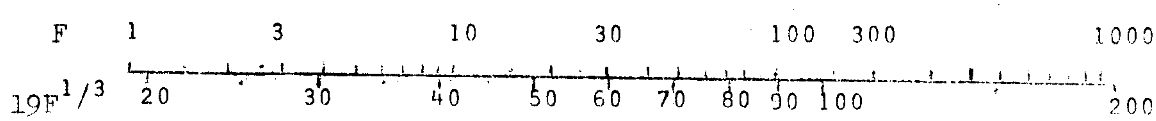
$$h = h'' + 21\ F^{2/3}/u \quad . \tag{5}$$

A nomogram is provided below for calculating $21\ F^{2/3}/u$. During the night when u is less than 3.5 m/sec, calculate the effective source height with

$$h = h'' + 19\ F^{1/3} \quad . \tag{6}$$

A scale is given below for calculating $19\ F^{1/3}$.





3.0 ESTIMATING GROUND CONCENTRATIONS

3.1 Simple Diffusion Models:

The main simplifications made in the diffusion models given here is that the plume cross-section at any point is taken to be rectangular and to contain a uniform concentration of effluent. As in most diffusion models, the variation of wind speed with height is neglected; the horizontal transport rate of the effluent is taken to be constant throughout the plume, equal to the mean wind speed, u. Thus, the volumetric flow rate of plume material through any plane intersecting the plume at right angles is u times the cross-sectional area. Since it is also assumed that there is no depletion of any components in the effluent, the concentration within the plume at any point downwind is just Q divided by the volumetric flow rate past that point, where Q is the mass flow rate of the substance in question.

Since the volumetric flow rate is in m^3/sec with the units recommended here, if Q is expressed in kgm/sec the resulting units of X, the concentration, are kgm/m^3. To convert this to gm/m^3, multiply by 10^3. To convert to μg/m^3, multiply by 10^9. To convert the concentration of a gas to ppm, multiply by 10^6 times $(24/m_o)$, where m_o is its molecular weight. An alternative method to get X in ppm is to express Q as 10^6 times (T/T_o) times the volume flow rate of the component gas in m^3/sec.

3.2 Diffusion Coefficients and Stability Classes:

A basic feature of diffusion in the atmosphere is that the cross-sectional area of plumes always grows with distance downwind. This feature will be described in the models here by means of the plume half-width, R_y, and the plume half-depth, R_z, which are given as functions of distance in Appendix D. The reader will note that two sets of values are given in this appendix; one for rural sites and one for urban sites. This is done because diffusion is considerably enhanced in urban areas, where atmospheric turbulence is increased by air flow over buildings and by greater thermal convection than over the countryside. The urban values for R_y and R_z should be used if the area within 10 stack heights or 10 building heights of the source is mostly built up.

R_y and R_z are also functions of the stability of the atmosphere. This is accounted for in a rough way by means of stability classes, ranging from very unstable (Class A) to very stable (Class F). The most appropriate stability class depends somewhat on cloudiness, but most strongly depends on the wind speed and whether it is day or night. The following table gives the best average stability class for different wind speeds.

Table 1 - Stability Classes

Wind speed, m/sec	1	2.5	4.5	7	10
Day	A	B	C	D	D
Night	F	E	D	D	D

The values for R_y and R_z given in Appendix D apply best to 30 minute averages. For other averaging times, correction factors for ground concentration are suggested in Section 3.5.

In cities and near prominent terrain there are special situations which require modification of the general diffusion models given below in Sections 3.3 and 3.4. For these cases, consult Chapters 6 and 7.

Since wind speed strongly influences the stack aerodynamic effect, the buoyancy effect, and the rate of diffusion, it is suggested that the procedures in this chapter be carried out for at least five different wind speeds: 1, 2.5, 4.5, 7, and 10 m/sec. If estimates of the frequency of occurrence are needed, consult Chapter 4 for information on wind speed frequencies.

It should be cautioned that the procedures developed in this chapter are based on <u>average</u> rates of diffusion in various conditions. However, the diffusing power of the atmosphere varies considerably even at a given wind speed and time of day; therefore, occasional 30-minute average concentrations <u>twice</u> those computed here should be anticipated.

3.3 Ground Concentrations from Ground Sources

If the procedure detailed in Chapter 2 predicts that, for the circumstances and wind speed given, the plume becomes a ground source, the following equation approximates the ground concentration downwind of the cavity region:

$$\chi = \frac{Q}{u(A + 2 R_y R_z)} , \qquad (7)$$

where A is the initial cross sectional plume area as specified in Chapter 2. The question of units for χ and Q were discussed in Section 3.1. To make a calculation for a specific point downwind, such as at the property line, consult Appendix D for values of R_y and R_z appropriate to the site (rural or urban), distance, and stability class. To allow for atmospheric diffusion between the source height and the ground, assume a minimum distance downwind equal to h_s.

For ground source, the highest ground concentrations generally occur at low wind speeds, especially at nighttime, when the growth of R_y and R_z is more limited. (For the frequency of winds less than 1 m/sec, consult Section 2.3.1). If the plume is not a ground source at very low wind speeds, as reckoned by Chapter 2, the highest ground concentration generally occurs at the lowest wind speed which does render the plume a ground source (if this is greater than 10 m/sec, it may be regarded as extremely infrequent).

3.4 Ground Concentrations from Elevated Sources:

If the procedure detailed in Chapter 2 predicts that, for the circumstances and wind speed given, the plume remains elevated, the following equation approximates the ground concentration downwind of the source:

when $R_z < h$, $\chi = 0$

when $R_z > h$,

$$\chi = \frac{Q}{2\, u\, R_y (h + R_z)} \quad , \qquad (8)$$

where h is the effective source height of the effluent as calculated in Chapter 2. If the effluent is buoyant ($\Delta < 0$), use Eq. (6) for h for nighttime, u <35 m/sec cases (stability classes E and F) and use Eq. (5) for h for all other cases (stability classes A, B, C, and D). Units for χ and Q were discussed in Section 3.1, and values for R_y and R_z appropriate to the site (rural or urban), distance downwind, and stability class are given in Appendix D.

Note that no ground concentration occurs until the bottom of the plume reaches the ground ($R_z = h$). The maximum ground concentration occurs at the distance that $R_z = h$, and is given by

$$\chi = \left(\frac{R_z}{R_y} \right) \frac{Q}{4\, u\, h^2} \quad , \qquad (9)$$

where R_z/R_y is the ratio of the plume depth to the plume width at the distance where $R_z = h$. **A graph of R_z/R_y versus R_z is given in Appendix D.** For small **effective source heights, R_z/R_y** ranges from 0.6 to 0.9 at urban sites. The range of this ratio is somewhat greater for larger value of h and at rural sites, but the most important variable in Eq. (9) by far is h^2. One can see that an increase in effective source height can reduce ground concentrations considerably.

If the plume is an elevated source at all wind speeds, in general the highest ground concentrations occur in "A" and "B" stability classes for small buoyancy and in "C" and "D" classes for large buoyancy. The maximum concentration can occur at a distance as near as 4h in "A" conditions, and occurs progressively at larger distances in more stable conditions At rural sites, if h is greater than 40 m, small or zero ground concentration results in "F" conditions since $R_z/R_y < 0.2$. If h > 100m, small or zero concentration also results in "E" conditions. Zero X can also occur at urban sites in E-F conditions if h is sufficiently large (see Chap. 6).

3.5 Effect of Averaging Time:

The values of R_y and R_z given in Appendix D are based on observed diffusion patterns after averaging the concentration at each grid point over approximately 30 minutes. For longer averaging periods, the plume boundaries will be more "smeared," and the average ground concentration is correspondingly less. This is due mostly to shifts in wind direction, although gradual changes in the mean wind speed will affect the diffusion pattern also. This effect is less pronounced at urban sites, since small shifts in wind direction less affects the concentration pattern from a wide plume than from a narrow plume.

Conversely, for averaging periods shorter than 30 minutes there will be "peak" periods of higher ground concentration, since the 30-minute average itself is the result of some "smearing." The "peak" short period concentration is likely to be particularly high when A and B stability conditions prevail, since plume "looping" is commonly observed in unstable conditions. For ground sources and for elevated sources in stable (E and F) conditions, the peak concentrations are not so much greater, since at least the vertical fluctuations of plumes are damped out in these cases, either by the presence of the ground or by the stable stratification. For an elevated plume, the "peak" ground concentration pattern shifts closer to the source than the 30-minute average ground concentration pattern, by roughly a factor of 2 in the case of a 1 minute peak.

Figure 3 shows the approximate ratios of peak or longer term ground concentrations to the 30-minute average ground concentration. To estimate the worst concentration to be expected over averaging times other than 30 minutes, multiply the values of X computed in Sections 3.3 or 3.4 by the appropriate ratio from Figure 3. As was cautioned at the end of Section 3.2, on infrequent occasions values of X might reach twice those computed here.

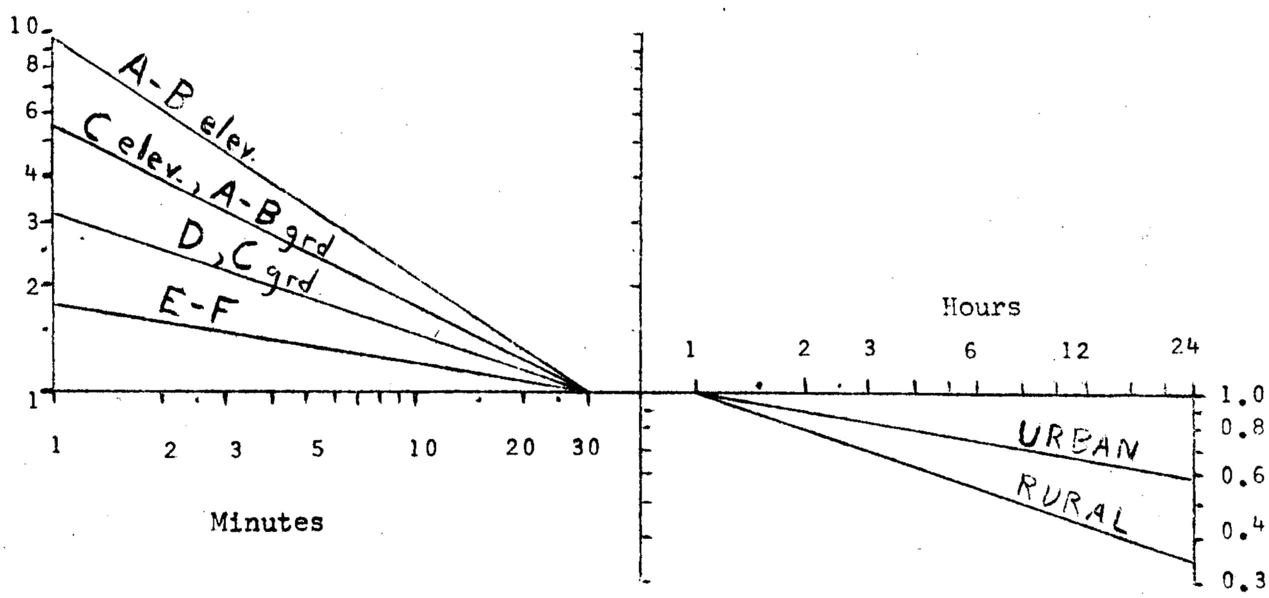


Figure 3 - Maximum χ (relative to 30 min.) vs. averaging time.

4.0 LONG TERM AVERAGE CONCENTRATIONS

The ground concentration averaged over a month or more naturally depends strongly on the wind direction frequency. Normally, it is not more than 5% of the maximum 30-minute average concentration; however, in valleys where "channeling" of the wind occurs it may reach higher values along the valley axis. It may also depend a lot on the wind speed frequency, especially if downwash occurs. Thus, the first step in estimating long term average concentrations is to obtain climatological information about the wind, either at the emission site or at the place with wind records likely to be most representative of the site. Normally, this place would be the nearest to the site having appropriate records; however, in rough topography or near large bodies of water, care should be made to get records from a place situated similarly to the site. If the emission site is in a valley, it would be best if the wind records come from a valley of similar orientation and depth, somewhere in the general area, rather than from the nearest hilltop. The wind information should be from within 50 miles of the site (100 miles if the region is sparsely populated.)

The primary collection point for wind records in the United States is the National Weather Records Center (Federal Office Building, Asheville, N. C. 28801). Ten-year summaries of the frequency of wind speeds, by direction, are available for major city airports for ten cents each. In addition, unpublished summaries can be obtained for many smaller cities and many military bases for the cost of reproduction (currently $5.50 each). Summaries can be tabulated for almost any other airport, according to how detailed a wind record is kept, but tabulation may cost several hundred dollars.

Wind speed frequencies in the United States are commonly grouped according to certain ranges of mph. To interpret these statistics in terms of the five wind speeds suggested for calculations here, use the following approximate correspondences:

1 m/sec	= 0 to 3 mph
2.5 m/sec	= 4 to 7 mph
4.5 m/sec	= 8 to 12 mph
7 m/sec	= 13 to 18 mph
10 m/sec	= 19 to 31 mph

Winds are labeled according to the direction they blow from, not towards. If one is concerned with the long term concentration produced SSE of a source, then he would want to find the frequency of NNW winds. It is customary to tabulate wind direction statistics for sixteen sectors of wind direction, each 22 1/2° wide (N, NNE, NE, ENE, E, etc.).

For a first estimate of the long term ground concentration, follow the procedures in Chapter 2 using the average wind speed; use the average wind speed for each sector of wind direction, if possible. If the plume turns out to be a ground source, the long term value of X in a 22 1/2° wind sector is given by

$$X = \frac{f}{100} \frac{2.5\,Q}{\overline{u}(A+x\,R_z)} \qquad (10)$$

where x is the distance downwind of the source, A is the initial cross sectional area as determined in Chapter 2, and f is the percentage frequency that the wind blows towards that sector over the period being considered (year, season, or month). If the plume turns out to be an elevated source, the appropriate formula is

$$X = \frac{f}{100} \frac{2.5\,Q}{u\,x(h+R_z)} \quad , \qquad (11)$$

with X = 0 when $R_z < h$; f is the same as above and h is the effective source height as determined in Chapter 2 (for buoyant sources, use Eq. (5) for h). One may use the values of R_z for the "C" stability class, namely, $R_z \simeq 0.09\,x$ at rural sites and $R_z = 0.25\,x$ at urban sites. However, one should anticipate that the actual pattern of X vs. x will be much more smeared out than the pattern given by this crude calculation, since it ignors variations in wind speed and stability. Thus, the maximum X will be less than calculated by this method, but near-in and far-out values will be greater than calculated.

A much improved estimate can be made if the frequency of each wind speed class is available. One may then go through the procedure in Chapter 2 and use Eq. (10) or (11), whichever is appropriate, for u = 1, 2.5, 4.5, 7, and 10 m/sec (using the correspondences suggested above). If only the mean wind speed is available, the frequency of various winds can be estimated from Figure 4 . One may divide the wind into more than five categories, if desired. The appropriate stability class should be used for the calculation of R_z at each wind speed, keeping in mind the relative "frequency" of the day and night categories. For an annual average, day and night are each weighted 50%, but for shorter averages this weighting will depend on the season and the latitude (consult a sunrise-sunset table in any almanac). For some sites separate wind speed statistics for day and night may be available; use of these will improve the calculation.

For buoyant, elevated sources, remember that Eq. (5) applies to stability categories A, B, C, and D and Eq. (6) applies to categories E and F. After the statistics have been sub-categorized as much as possible (by sector, wind speed, time of day, etc.), the contribution of each sub-category is calculated by Eq. (10) or (11), letting f be the frequency of that sub-category, and the results are summed for each sector. Be sure that the sum of f's for all sub-categories totals % 100.

In the case of urban sites, it is advisable to consider the possiblity of nighttime trapping in computing the nighttime contribution to χ. The effect is to limit the value of $(h + R_z)$ (see Chapter 6). The special effects due to nearby terrain features, discussed in Chapter 7, rarely affect the long-term average concentration significantly.

The above procedures are designed to estimate the average long-term ground concentration pattern. If it is desired to estimate the "worst ever" long-term concentration likely to occur is a given wind sector, it is best to go back to wind speed summaries for each year and find the period with the greatest frequency of wind in the given sector. If these summaries are not available, use the following, rather crude, guidelines: (1) in some years, the frequency of wind towards any one sector can be 1.5 times average annual value; (2) in some months, the frequency of wind towards any one sector can be two times the average value for that month; (3) monthly average frequencies of wind may be as great as 1.5 times the annual average in sectors of high frequency and two times the annual average in sectors of low frequency.

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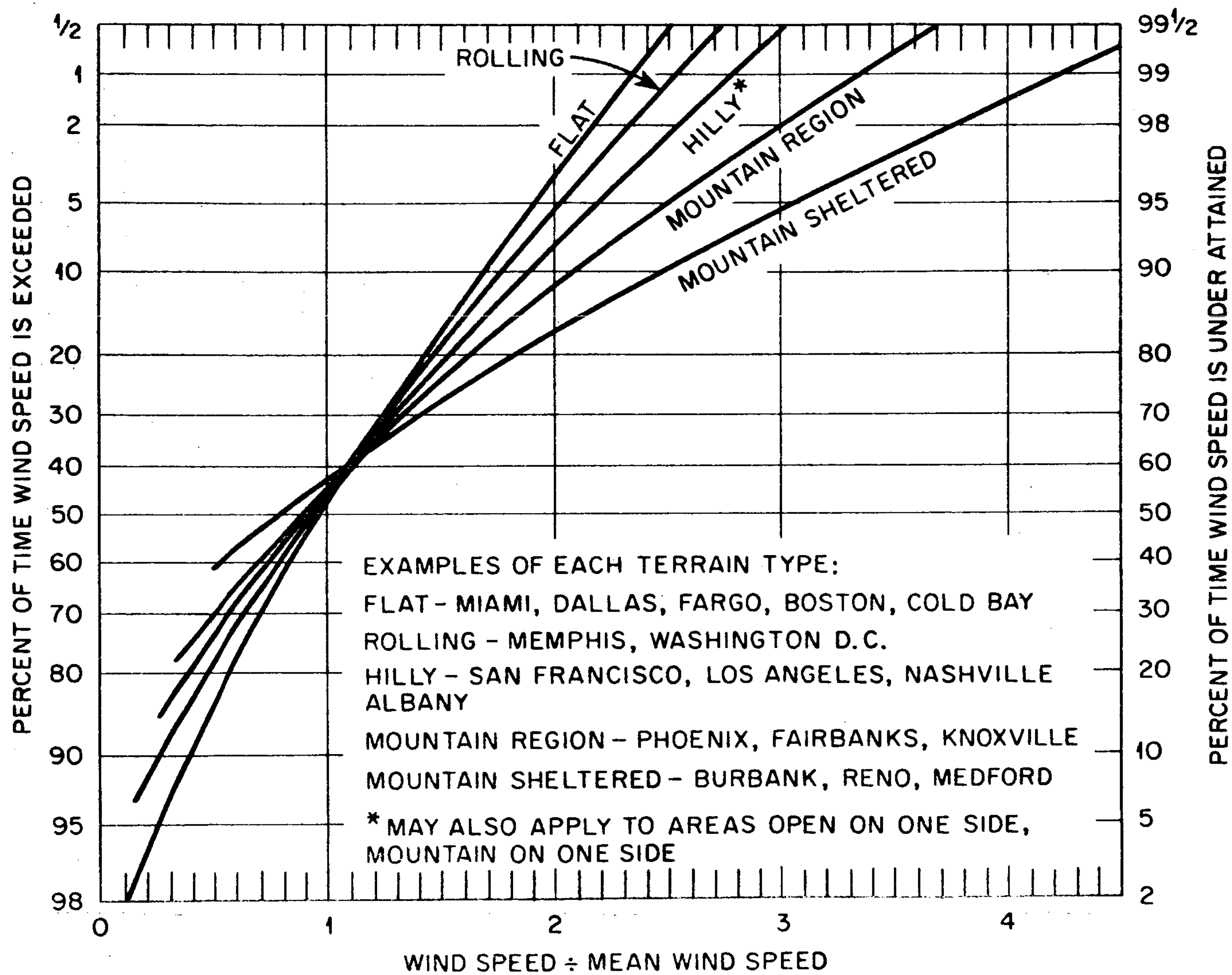

Figure 4 - Frequency of wind speeds (normalized by the local mean wind speed), according to terrain type.

5.0 LONG-TERM AVERAGE DEPOSITION OF PARTICULATES

This guide is primarily concerned with the concentration of gases and aerosols in the air close to the ground. In the case of dust, or particulates, one may also want to estimate the amount of deposition over a substantial period of time. The procedure used is similar to that used for determining long-term average concentrations, except that one must take into account the settling velocity, w_s. Direct measurements of w_s are best; for instance, if it were possible to sample some of the effluent and keep it agitated until it could be released in still surroundings, such as indoors, one could merely time the fall of the dust cloud to infer w_s. If this procedure is too difficult, one should determine the diameter (D) of the particles in microns (μ) and approximate w_s by the following formulas:

$$w_s = 3 \cdot 10^{-5} \rho D^2 \text{ if } D < 70 \mu$$

$$w_s = 2 \cdot 10^{-3} \rho D \text{ if } D > 70 \mu \quad ,$$

where w_s is in m/sec and the particulate density ρ is in gm/cm^3 (values of ρ range from 2 to 6 gm/cm^3 for most minerals).

In most cases, a range of particle sizes is present. In this case, one may use a value of w_s appropriate to the mean diameter, but should expect the actual pattern of deposition to be more "smeared out" as a function of distance from the source than calculated. Alternatively, one may want to divide the rate of particulate efflux Q into several different ranges of particulate sizes, each with different values of w_s, then superimpose the final results. This would be highly advisable if the particle density vs. D distribution has more than one mode.

For a ground source the deposition rate can be approximated by

$$\chi_D = \left(\frac{f}{100}\right) \frac{2.5\ w_s\ Q}{u(A = x\ R_z)} \qquad (12)$$

where f is the percentage frequency of wind into the particular sector being considered, as before. For an elevated source if u is greater than $2\ C\ w_s$, where C is given in a table at the beginning of Section 2.3.1, use

$$\chi_D = \left(\frac{f}{100}\right) \frac{2.5\ w_s\ Q}{u\ x(h + R_z)} \qquad (13)$$

when $R_z > h$ and $\chi_D = 0$ when $R_z < h$. For an elevated source if u is less than $2\ C\ w_s$, the maximum deposition rate is given by

$$\chi_D = \left(\frac{F}{100}\right) \frac{2.5\ Q}{x_s^2}\ , \qquad (14)$$

where $x_s = (u/w_s)h$. Deposition begins at a distance $x = 0.5\ x_s$, attains the above value in the range $0.75\ x_s \leq x \leq x_s$, and declines to near zero at $x = 2\ x_s$ (linear interpolation gives adequate estimates of χ_D for intermediate distances).

For a buoyant, elevated plume, if f is less than $0.3\ w_s^2\ u\ h''$, buoyant plume rise should not be taken into account, as the particles may fall out of the plume before it rises much; in this case, let $x_s = (u/w_s)h''$ (i.e., use h" instead of h).

If Q is expressed in gm/sec, the calculated deposition rate is in gm/m^2-sec. To get the total deposition over a 30-day period in gm/m^2, multiply χ_D by $30 \cdot 24 \cdot 60 \cdot 60 = 2.59 \cdot 10^6$. to get the deposition over a 365-day period in gm/m^2, multiply χ_D by $3.14 \cdot 10^7$. To get the long term average deposition rate, one uses the same procedures as in the preceeding section, except with the above formulas. For instance, the crudest estimate can be made by using the class "C" stability category for determining R_z and the mean wind speed at the site for u. Naturally, this method yield more compact deposition pattern and a higher maximum deposition rate than a more realistic analysis using several wind speeds, corresponding stability categories, and appropriate frequencies of occurrence. Variable factors such as static electricity and re-suspension affect w_s for some particulates, so one must not trust these simplified calculations too far.

6.0 SPECIAL CONSIDERATIONS IN CITIES

Diffusion is more rapid in urban surroundings than in rural areas because of the mechanical turbulence produced by wind flow over buildings and the convective turbulence generated by loss of building heat. If the area within 10-stack heights or building heights of the source is mostly built-up, consider the site to be urban. This means, first of all, that the urban values of R_y and R_z should be used in the formulations given in Chapter 3.

In addition, it is prudent to recognize that the nighttime diffusion of effluents from low sources differs markedly in the city from that in rural areas, especially in the "E" and "F" categories. The reason is that a shallow mixing layer developes over a city at night, due to the "heat island"effect, while the air over the countryside becomes relatively stable and unmixed throughout. Thus, effluents from low sources initially diffuse much faster in the city. This leads to higher maximum concentrations from elevated (but low) sources, because the effluent reaches the ground faster and with less lateral diffusion. However, at greater distances the urban plume becomes more diffuse, thus ground concentrations are lower. When the effluent reaches the top of the nighttime urban mixing layer, at height H, its vertical diffusion virtually ceases, but it continues to spread laterally. The concentrations from ground sources are less at urban sites than at rural sites at all distances downwind of the source. On the other hand, if the effective source height of an elevated source is sufficiently above H, nighttime diffusion is more like that at rural sites, because the stability and turbulence structure of the air above H is not modified nearly as much as the lower layer as it moves over the city.

Thus, it is important to take H into account in E and F conditions. An estimate of its median value is given by

$$\overline{H} = 1.0\text{m} \sqrt{10 \sqrt{P}} , \qquad (15)$$

when P is the metropolitan area population. The probability of a given value of H being exceeded is approximately $100\% \div (1+(H/\overline{H})^4)$. In the case of a highly elongated city, such as a valley city, P should be multiplied by the factor of elongation when the wind is along the major axis of the city, and should be divided by the same factor when the wind is across the city.

For a ground source, the calculation for E and F conditions is made exactly as in Chapter 3 except that R_z cannot exceed H ($R_z \leq H$). This is called a "trapping" model. Thus when the R_z given by Figure D.3 exceeds H, instead of Eq. (7) use

$$X = \frac{Q}{u(A + 2\, R_y H)} \qquad (16)$$

Similarly, for an elevated source, if $h \leq H$ assume that the plume is "trapped." The same diffusion formula (Eq. 8) is used except that $(h + R_z)$ never exceeds H. As before, $X = 0$ when $R_z < h$. In the case of a buoyant source, Eq. (6) is used to determine whether $h \leq H$. If this h turns out to be less than or equal to H, recalculate h using Eq. (5); if this second calculation of h yields $h > H$, set $h = H$.

If $h > (4/3)H$, then you may assume that the plume does not reach the ground until it has drifted out of the city, and treat it the same as a rural source. In other words, use the rural curves for R_y and R_z in E and F conditions.

In cases where h is just above H, the real situation is rather ambiguous since the bottom of the plume may get mixed down into the mixing layer, while the top of the plume remains aloft. One way to "hedge the bet" is to treat $3(h/H - 1)Q$ the same as a rural source of height h and to treat $[1 - 3(h/H - 1)]Q$ the same as a "trapped" urban source with $h = H$, then superimpose the two concentration patterns.

7.0 SPECIAL CONSIDERATIONS NEAR PROMINENT TERRAIN

Prominent terrain can have a great effect on diffusion, but there are so many possibilities and so few definitive data that only a few, rather oversimplified guidelines can be suggested here. Adverse effects on diffusion from an elevated source can be expected whenever the terrain rises higher than 1/4 the effective source height at a distance where $(h - h_t) < R_z < h$, where h_t is the height of the terrain above the source site elevation. In general, terrain has much less effect on diffusion from a ground source, so this will not be discussed.

If a terrain rise is downwind of the source, in neutral and unstable conditions (A-B-C-D) the plume tends to "ride up" the slope, while losing part of its effective stack height relative to the ground. In this case, the value of h computed in Chapter 2 should be reduced by h_t or by $h/2$, whichever is the smallest reduction. Then proceed to Chapter 3. However, in stable conditions (E-F), the plume tends to maintain a constant elevation, so the value of h computed in Chapter 2 should be reduced by h_t.

If the terrain, or for that matter, a structure, rises above the effective source height ($h_t > h$), there is the possibility that the plume will impinge it in E or F conditions, resulting in very high concentrations. This occurrance is relatively infrequent. If f is the frequency of the nighttime wind direction towards the 22 $1/2^{\circ}$ sector in question, the frequency of inpingement during E-F conditions can be estimated by $5 \cdot f(R_y/x)$, where R_y is the plume half-width at the distance downwind of the obstruction and x is that distance. For instance, if the frequency of "F" conditions is 10% of the time, the nighttime frequency of wind towards the sector of nearest abutment of a broad rise of terrain is 2% (wind favors the "grain" of the terrain, rarely going across it), and the abutment occurs at x = 2 km, the frequency of "F" condition impingement is <u>at most</u> (0.10)5. (0.02) (90m/2000m) = 0.045%. Actually, the frequency of low speed winds towards terrain rises is lower than that of higher winds. The concentration experienced during impingement is given by

$$\chi = \frac{Q}{4\,u\,R_y\,R_z} \quad . \qquad (17)$$

If there is a terrain rise upwind of the source, and the average slope of the rise above the source site exceeds 2%, there is the possibility of downwash induced by the air flowing down over the terrain drop. In the case of an abrupt drop, it is possible to get a "cavity" effect, i.e. a counter-rotating eddy, just as in the wake of a building. Unfortunately, these effects are difficult to predict. They are commonly simulated by means of wind tunnel modeling at present. Large tunnels, such as those at New York University and Colorado State University, are required, which involves considerable expense. An alternative to modeling is the release of neutral buoyancy balloons or smoke from the site at the effective stack height during down-terrain winds. This should be carried out over a good range of wind speeds and in both in clear and cloudy weather; nighttime runs are not as important, since air flow tends to be more horizontal then.

Many effluent sources are located in valleys, where water and rail transportation are more available. However, diffusion is poorest in valleys, due to the above effects during cross-valley flow and to nighttime trapping of the effluent in the valley if $h < h_t$. In the low wind speed, nighttime case (E-F conditions), there is usually a "drainage" wind of the order of 1 m/sec flowing down the valley. The plume stratifies at height h and travels with the drainage wind, diffusing very little in the vertical and spreading horizontally until it impinges on both valley walls. At the distance where $2 R_y$ equals the width of the valley at height h, W_h, the highest concentration the valley walls could experience would be $\chi = Q/(2 u R_z W_h)$. In the morning, "break-up fumigation" brings the effluent down to the valley floor when the stable layer is eroded from below by the heating of the ground. The average concentration experienced throughout the valley in this case is

$$\chi = \frac{Q}{u\, h\, W} \qquad , \qquad (18)$$

where Q is the nighttime effluent release rate, u is the nighttime drainage wind speed, h is the nighttime effective source height, and W is the average width of the valley up to height h.

APPENDIX A: SYMBOLS AND DEFINITIONS

Symbol	Definition	Units Used	Refer to Section
A	Initial cross-sectional area of a ground plume.	m^2	2.2, 2.3
A,B,C,D,E,F	Stability classes or "conditions" - An adaptation of the Pasquill stability categories.	—	3.2
c_p	Specific heat capacity (at constant pressure) of air = 0.24.	cal/gm-°C	2.3
c_{po}	Specific heat capacity of effluent.	cal/gm-°C	
D	Inside stack diameter.	m	2.1
D	Particle diameter.	μ	5
f	Percentage frequency of wind (or a certain range of wind) into a 22 1/2° sector of wind direction.	—	4, 5
F	Buoyancy flux parameter (see Eq. 3 and 4).	m^4/sec^3	2.3
g	Gravitational acceleration = 9.8.	m/sec^2	2.3
h	Effective source height (after stack aerodynamic, building, and buoyancy effects have been accounted for).	m	2.3
h'	Plume height after stack aerodynamic effect is accounted for.	m	2.1
h"	Plume height after building effect is accounted for.	m	2.2
h_b	Building height.	m	2.2
h_s	Source height above the ground.	m	2.1
h_t	Terrain height above the source site elevation.	m	7
H	Height of urban nighttime mixing layer (see Eq. 15).	m	6
K	Dimensionless concentration coefficient in cavity region.	—	2.2
ℓ_b	The lesser of h_b or w_b.	m	2.2
m_o	Mean molecular weight of the effluent.	—	2.3
M_o	Mass efflux of the effluent.	kgm/sec	2.3
P	Metropolitan area population.	—	6
Q	Source strength of a component of the effluent; gas particulates.	kgm/sec gm/sec	3.1 5

APPENDIX A (continued)

Symbol	Definition	Units Used	Refer to Section
Q_H	Dry heat emission carried by the effluent.	cal/sec	2.3
R_y	Plume half-width.	m	3.2
R_z	Plume half-depth.	m	3.2
s	Distance from source along plume axis.	m	2.2
T	Ambient absolute temperature $\simeq$ 288.	°K	2.3
ΔT	Difference between effluent and ambient temperatures.	°K	2.3
u	Wind speed at source height or at an open location.	m/sec	2.1,4
v_s	Average efflux velocity (volume flow rate ÷ area).	m/sec	2.1
w_b	Building width perpendicular to the wind direction.	m	2.2
w_s	Settling velocity of particulates.	m/sec	5
W	Average width of a valley from the floor up to height h.	m	7
W_h	Width of a valley at height h.	m	7
x	Distance downwind of the source.	m	3.2
x_s	$= (u/w_s)h$, or if $F < 0.5\ w_s^2\ u\ h''$, $= (u/w_s)h''$.	m	5
Δ	= (effluent density - air density) ÷ air density	—	2.3
Δ_T	Temperature difference contribution to Δ.	—	2.3
Δ_m	Molecular weight difference contribution to Δ.	—	2.3
Δ_w	Liquid water contribution to Δ (after cooling due to evaporation).	—	2.3
χ	Concentration of a component of the effluent.	kgm/m^3	3.1
χ_d	Deposition rate of particulates.	gm/m^2-sec	5

APPENDIX B: CONVERSION FACTORS

$1\ m = 3.28\ ft$ | $1\ ft = 0.305\ m$

$10^3 m = 0.621\ mi$ | $1\ mi = 1.61 \cdot 10^3 m$

$1\ sec = min/60 = hr/3600 = day/86{,}400 = 30\ days/2.59 \cdot 10^6 = yr/3.14 \cdot 10^7$

$1\ kgm = 10^3\ gm = 10^6\ mgm = 10^9\ \mu gm$

$1\ kgm = 2.2\ lb$ | $1\ lb = 0.454\ kgm$

$1\ ^\circ K = 1.8 ^\circ R$ | $1 ^\circ R = 0.555\ ^\circ K$

$^\circ K = ^\circ C + 273$ | $^\circ R = ^\circ F + 460$

1 cal = 1 **gram-calorie** = 10^{-3} kilogram**-calorie**

$1\ cal = 0.00397\ BTU$ | $1\ BTU = 252\ cal$

$1\ m/sec = 3.28\ ft/sec$ | $1\ ft/sec = 0.305\ m/sec$

$1\ m/sec = 2.24\ mph$ | $1\ mph = 0.447\ m/sec$

$1\ kgm/sec = 3.96\ ton/hr$ | $1\ ton/hr = 0.252\ kgm/sec$

$1\ kgm/m^3 = 10^6 (24/m_o) ppm$ | $1\ ppm = 10^{-6} (m_o/24) kgm/m^3 = (m_o/24) mgm/m^3$

$1\ gm/sec = 7.93\ lb/hr$ | $1\ lb/hr = 0.126\ gm/sec$

$1\ gm/m^2 = 2.85\ ton/mi^2$ | $1\ ton/mi^2 = 0.35\ gm/m^2$

$1\ cal/sec = 4.185\ watt$ | $1\ watt = 0.239\ cal/sec$

$1\ cal/gm\text{-}^\circ C = 1.00\ BTU/lb\text{-}^\circ F$ | $1\ BTU/lb\text{-}^\circ F = 1.00\ cal/gm\text{-}^\circ C$,

$1\ watt = 1\ joule/sec = 1\ kgm\text{-}m^2/sec^3$

APPENDIX C: SUMMARY OF EQUATIONS

Chapter 2 - Elevated or Ground Source?

Stack aerodynamic effect: $h' = h_s + 2D(v_s/u - 1.5)$. (1)

Building effect: applies only if stack is on or near building or is within $3\,\ell_b$ downwind and $h' < h_b = 1.5\,\ell_b$, where ℓ_b = lesser of h_b or w_b; if not, $h'' = h'$.

If $h' < h_b + 0.5\,\ell_b$, high concentrations may occur in building "cavity;" see Section 2.2(1).

If $h' > h_b$, compute $h'' = 2h' - (h_b + 1.5\,\ell_b)$ (2)

If $h' < h_b$, compute $h'' = h' - 1.5\,\ell_b$

If $h'' < \ell_b/2$, treat plume as ground source with $A = \ell_b^2$, skip "Buoyancy effect."

Buoyancy effect: (to calculate Δ and F; see Section 2.3)

If $\Delta > 0$ and $u > 0.22\,C\sqrt{g\,\Delta D}$, plume is elevated source with $h = h''$ (table of C values given in Section 2.3.1).

If $\Delta > 0$ and $u < 0.22\,C\sqrt{g\,\Delta D}$, plume becomes a ground source at $x = 4.5\,h_s\,u/\sqrt{g\,\Delta D}$ with $A = 0.2\,h_s^2$. "Minimum effective wind speed" equals $|F/h_s|^{1/3}$.

(If source is rural and $100\,|F|^{1/4} < 0.8\,h_s$; see Section 2.3.1 for details).

If $\Delta < 0$, plume is an elevated source,

$h = h'' + 21\,F^{2/3}/u$ in A, B, C, and D categories (5)

$h = h'' + 19\,F^{1/3}$ in E and F categries (6)

Chapter 3 - Estimating Ground Concentration

Ground source: $$\chi = \frac{Q}{u(A + 2\ R_y\ R_z)} \qquad (7)$$

Elevated source: $\chi = 0$ when $R_z < h$

$$\chi = \frac{Q}{2\ u\ R_y (h + R_z)} \quad \text{when } R_z > h \qquad (8)$$

$$\chi = \frac{R_z}{R_y} \frac{Q}{4\ u\ h^2} \quad \text{at } R_z = h \ (\max.\ \chi). \qquad (9)$$

Chapter 4 - Long Term Average Concentrations

Ground source: $$\chi = \frac{f}{100} \frac{2.5\ Q}{u(A + x\ R_z)} \qquad (10)$$

Elevated source: $\chi = 0$ when $R_z < h$

$$\chi = \frac{f}{100} \frac{2.5\ Q}{u\ x\ (h + R_z)} \quad \text{when } R_z > h\ . \qquad (11)$$

Chapter 5 - Long Term Average Deposition of Particulates

Ground source or elevated source with $u > 2\ C\ w_s$:

$\chi_D = w_s\ \chi$, where χ is long term average concentration.

Elevated source with $u < 2\ C\ w_s$:

$x_s = (u/w_s)h$, unless $F < 0.3\ w_s^2\ u\ h''$; then

$x_s = (u/w_s)h''$. Max. χ_D occurs when $0.75\ x_s \leq x \leq x_s$

and given by

$$\chi_D = \frac{f}{100} \frac{2.5\ Q}{x_s^2} \qquad (14)$$

APPENDIX D: DIFFUSION COEFFICIENTS

A, B, C, D, E, and F are the stability classes (see Section 3.2). Following are analytical expressions for the plume half-depth, R_z, and the plume half-width, R_y, as functions of the downwind distance, x. Figures D.1 to D.4 show these functions, and Figure D.5 gives the ratio of R_z to R_y versus x.

Rural	Sites	
A	$R_z = 0.25\,x$	$R_y = 0.28\,x/\sqrt{1 + 0.0001\,x}$
B	$R_z = 0.15\,x$	$R_y = 0.20\,x/\sqrt{1 + 0.0001\,x}$
C	$R_z = 0.10\,x/\sqrt{1 + 0.0002\,x}$	$R_y = 0.14\,x/\sqrt{1 + 0.0001\,x}$
D	$R_z = 0.07\,x/\sqrt{1 + 0.0015\,x}$	$R_y = 0.10\,x/\sqrt{1 + 0.0001\,x}$
E	$R_z = 0.04\,x/\ (1 + 0.0003\,x)$	$R_y = 0.07\,x/\sqrt{1 + 0.0001\,x}$
F	$R_z = 0.02\,x/\ (1 + 0.0003\,x)$	$R_y = 0.05\,x/\sqrt{1 + 0.0001\,x}$

Urban	Sites	
A - B	$R_z = 0.30\,x\ \sqrt{1 + 0.001\,x}$	$R_y = 0.40\,x/\sqrt{1 + 0.0004\,x}$
C	$R_z = 0.25\,x$	$R_y = 0.28\,x/\sqrt{1 + 0.0004\,x}$
D	$R_z = 0.18\,x/\sqrt{1 + 0.0003\,x}$	$R_y = 0.20\,x/\sqrt{1 + 0.0004\,x}$
E - F	*$R_z = 0.10\,x/\sqrt{1 + 0.0015\,x}$	$R_y = 0.14\,x/\sqrt{1 + 0.0004\,x}$

*For a ground source or an elevated source trapped beneath the urban nighttime mixing layer, (R_z + h) never exceeds H (see Chapter 6 for details).

APPENDIX D (continued)

The following approximations for R_z/R_y are adequate (± 20%) for computing the maximum ground concentration from an elevated source with an effective height h:

	Stability	R_z/R_y	Suitable only if h is less than
Rural	A	0.9	300 m
	B	0.8	300 m
	C	0.7	300 m
	D	0.6	40 m
	E	0.5	40 m
	F	0.3	30 m
Urban	A-B	0.9	300 m
	C	0.9	300 m
	D	0.9	300 m
	**E-F	0.6	100 m

**Max. χ proportional to R_z/R_y only if h is less than H/2.

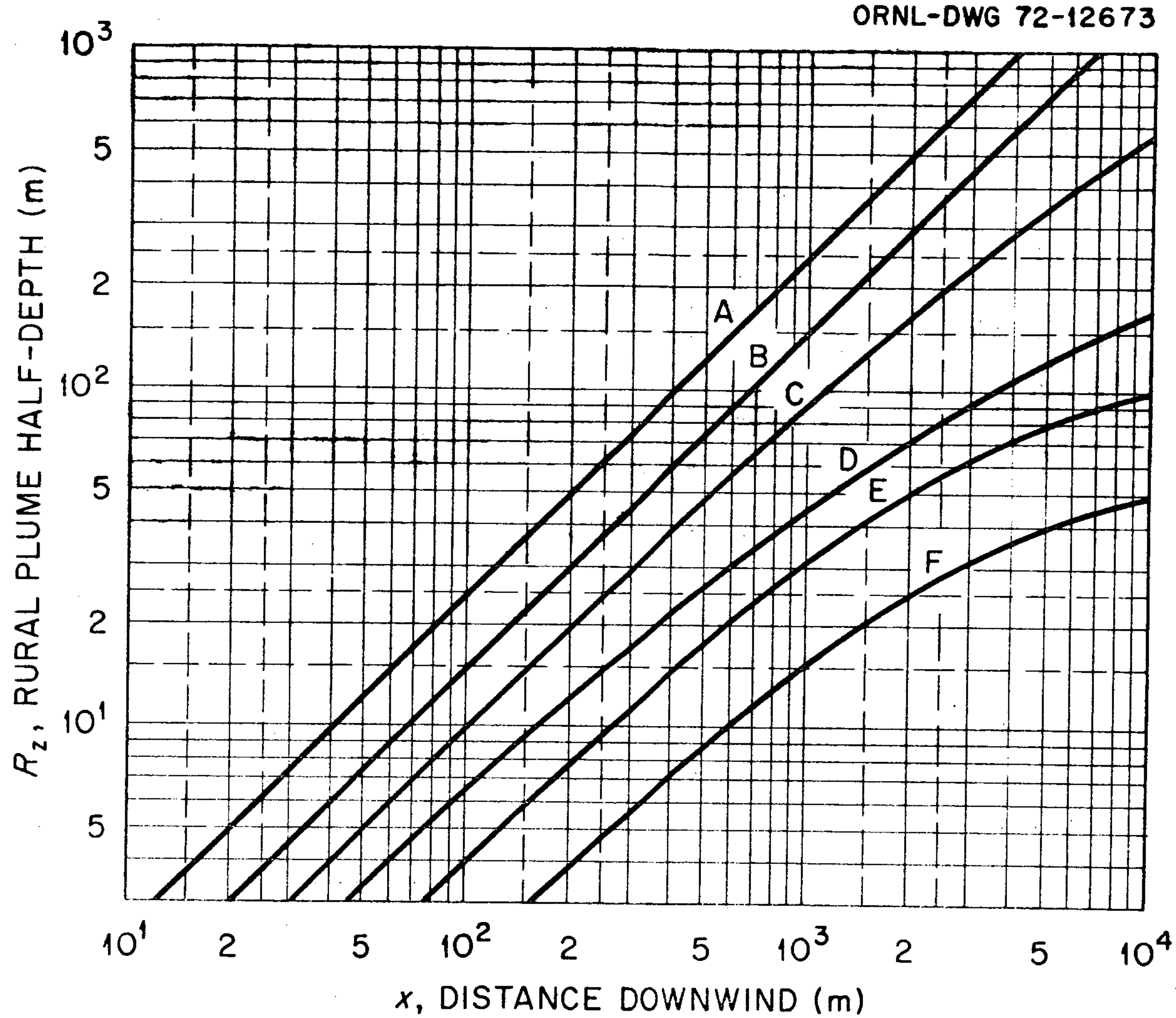

Figure D.1 - Rural plume half-depth, R_z, vs. distance downwind.

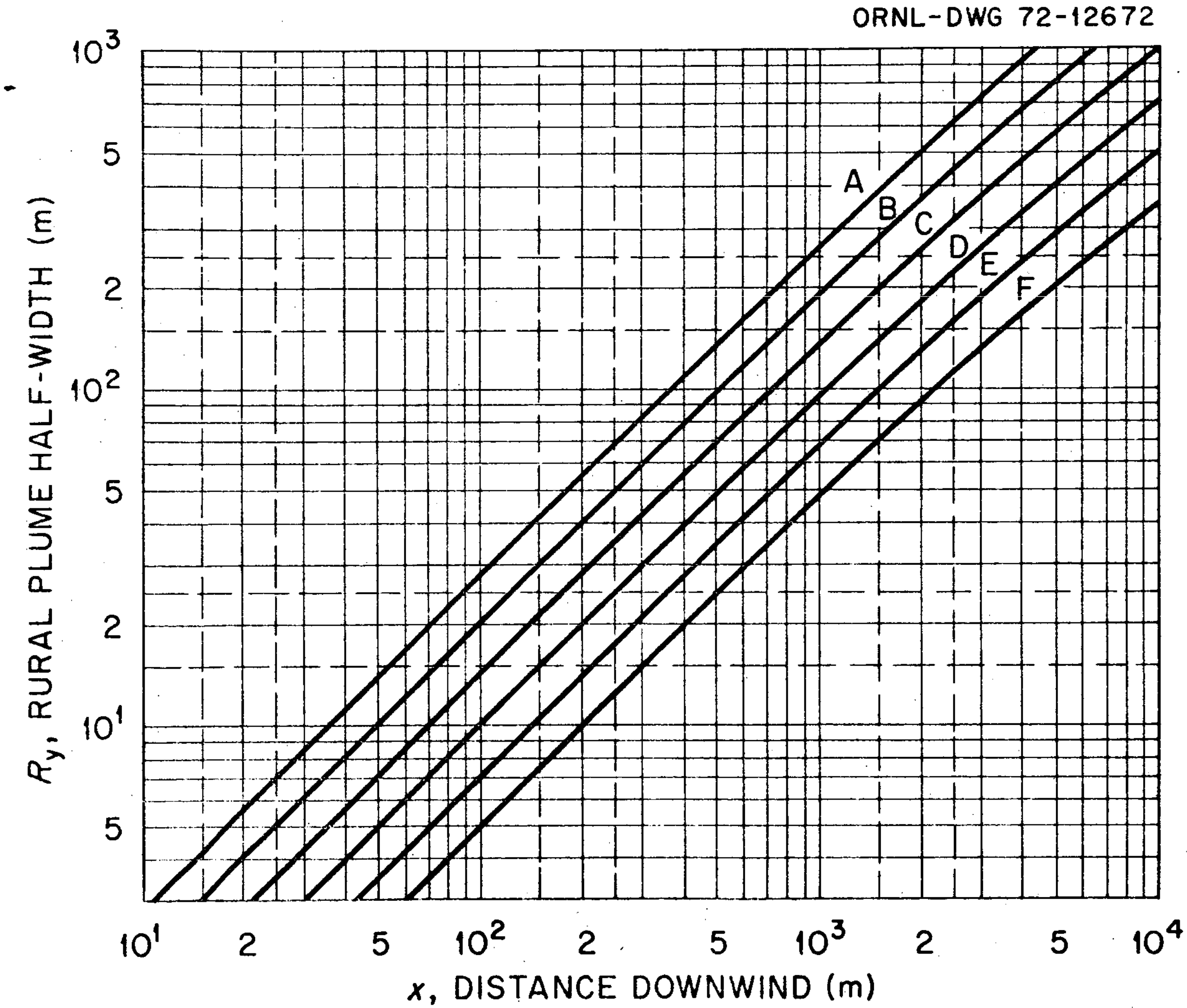

Figure D.2 – Rural plume half-width, R_y, vs. distance downwind.

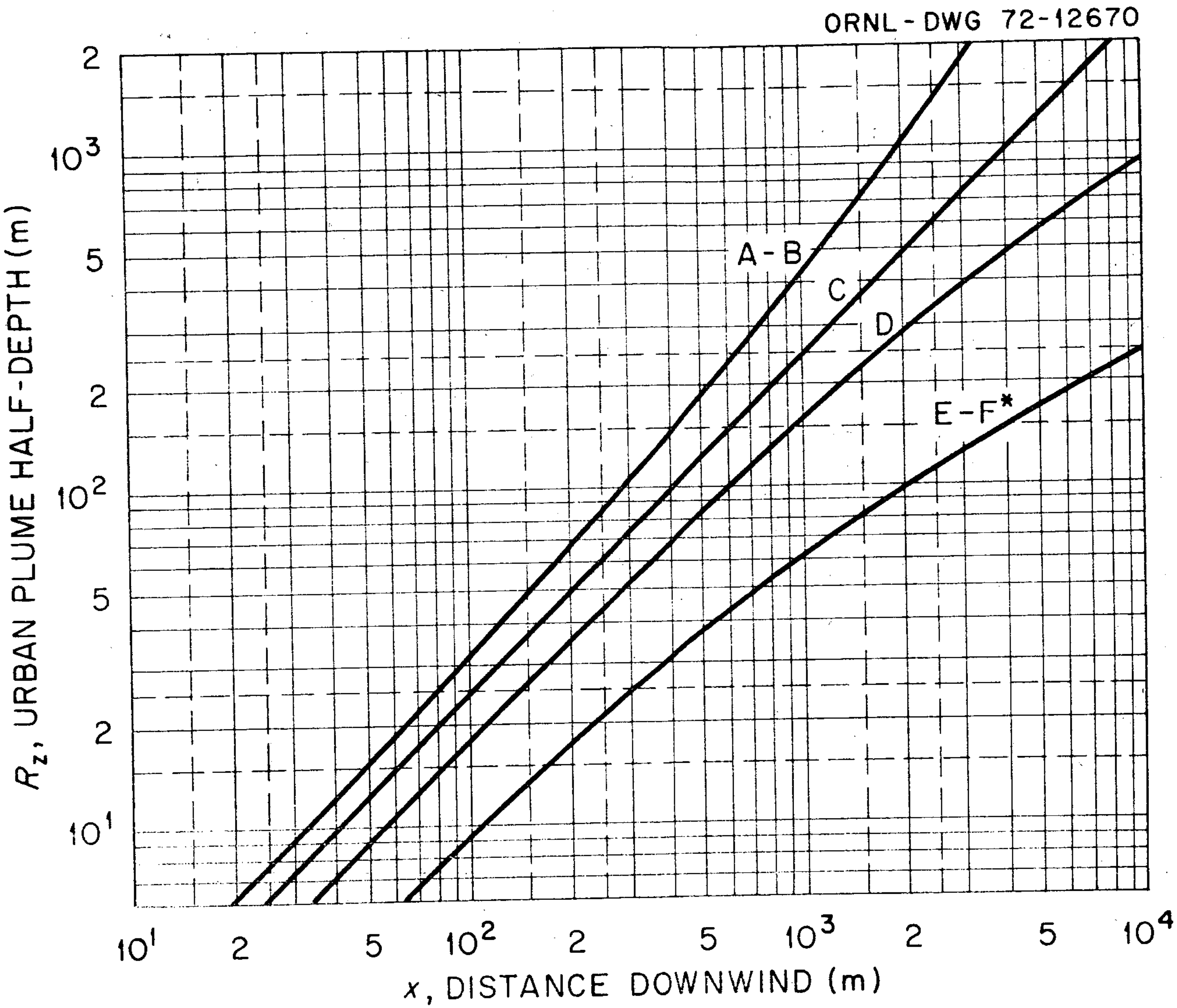

Figure D.3 - Urban plume half-depth, R_z, vs. distance downwind.

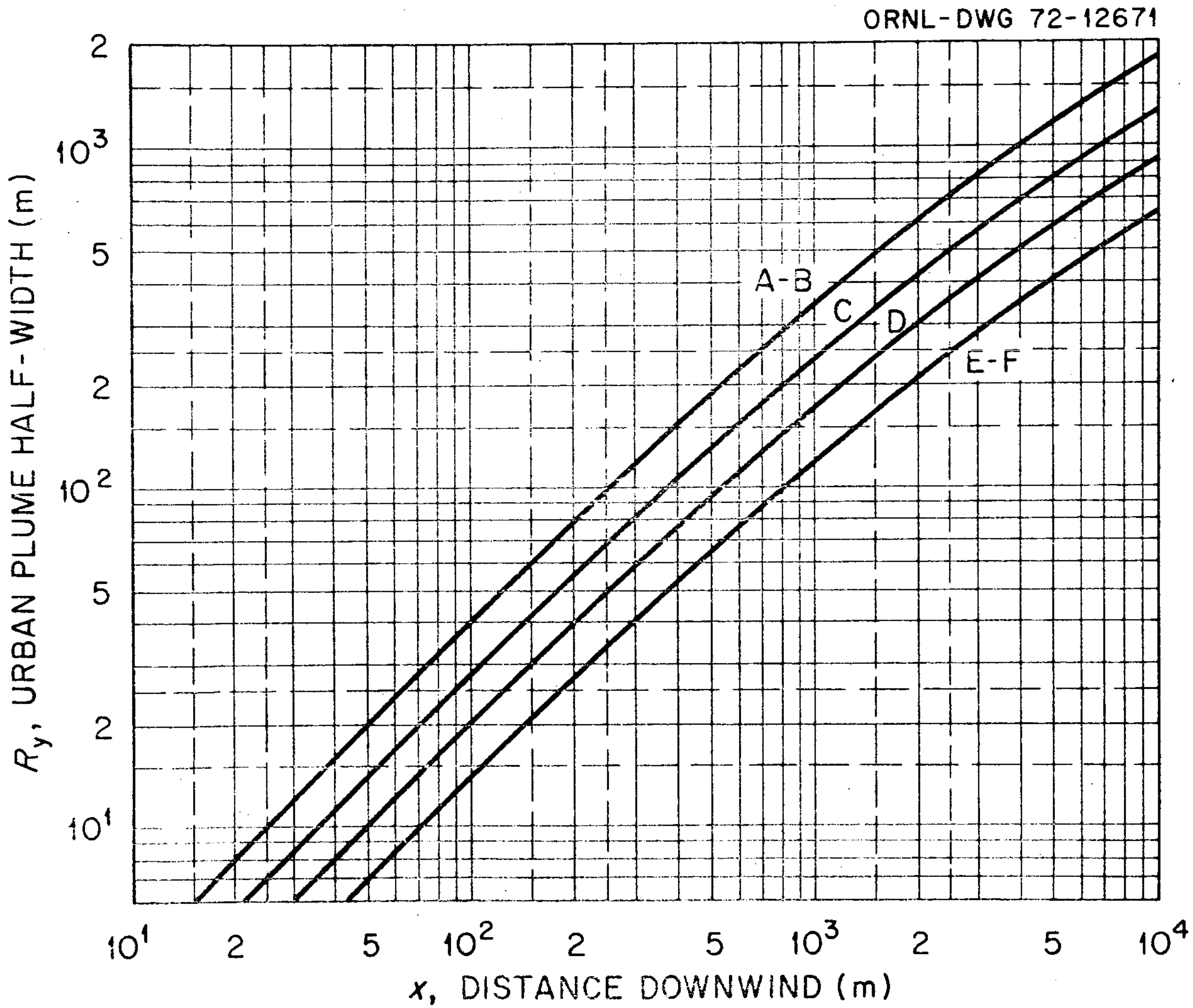

Figure D.4 - Urban plume half-width, R_y, vs. distance downwind.

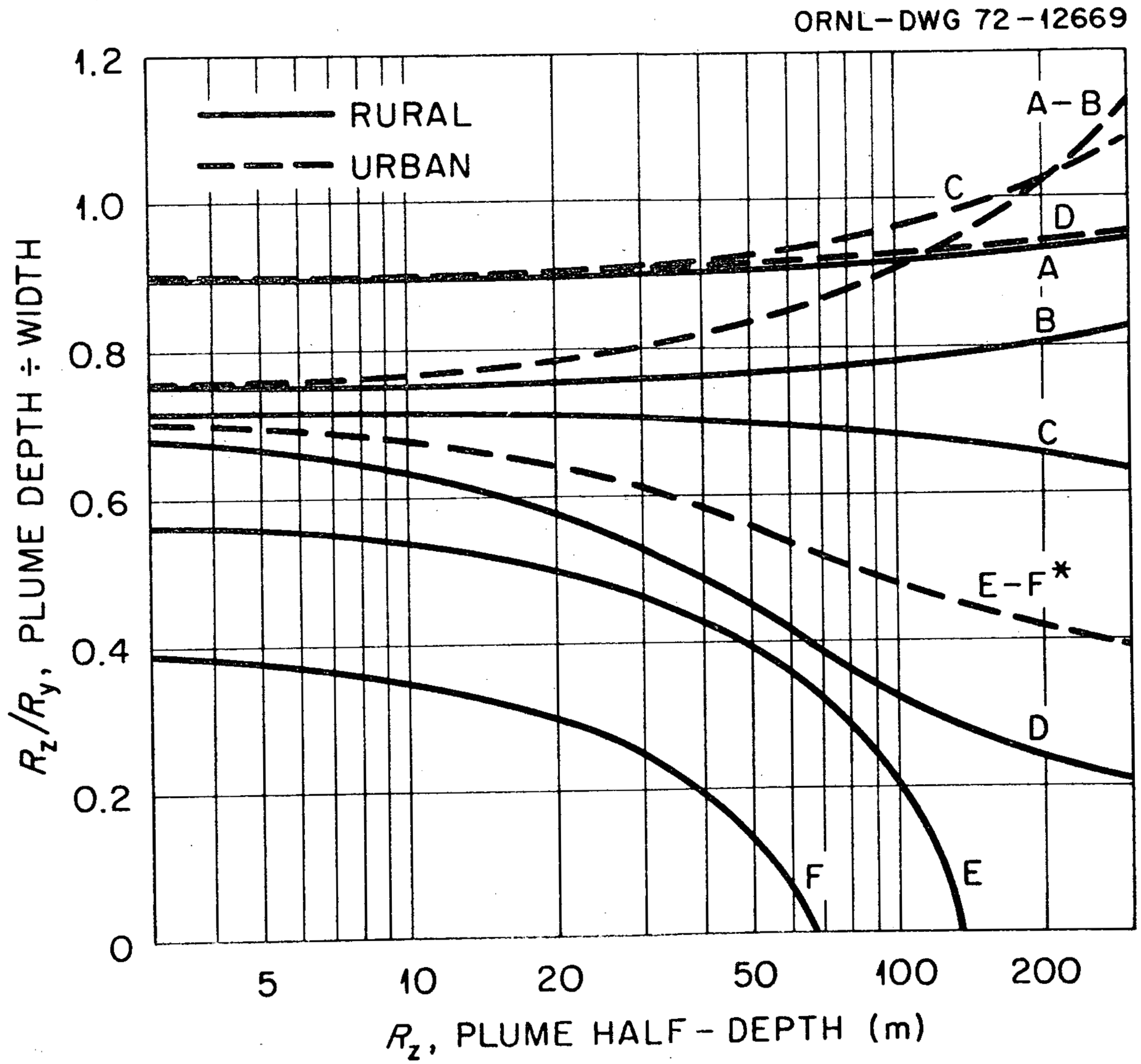

Figure D.5 - Ratio of plume depth to plume width, R_z/R_y, vs. plume half-depth.

APPENDIX E: BASES OF RECOMMENDATIONS

Stack Aerodynamic Effect (Sec. 2.1):

The formula $h' - h_s = 2(v_s/u - 1.5)D$ is based partly on wind tunnel observations of Sherlock and Stalker (1941) which showed that downwash (negative rise) occurs when v_s/u is less than about 1.5 and that the plume downwashes about one stack diameter at $v_s/u = 1$. For high values of v_s/u, it is a conservative form of equation (5.2) recommended in Briggs (1969) for momentum rise; $2(v_s/u)D$ approximates the plume rise at the point where it is equal 1.7 times the downwind distance, so essentially represents the very close-in plume rise. Buoyancy is neglected in this stage, since it does not cause a doubling of the plume rise until a distance $x \simeq 10\ u\ v_s/(-g\ \Delta)$

Building Effect (Sec. 2.2):

The method suggested here for accounting for the building effect is an interpolation of several rules-of-thumb respecting air flow around buildings. It is generally accepted that a building has very little effect on the airflow at 2-1/2 building heights above the ground and above. On the other hand, the aerodynamic cavity downwind of a sharp-edged building developes to roughly 1-1/2 building heights. It developes higher over a very wide (i.e. squat) building, but the plume also has more distance in which to rise out of the cavity in this case. This method does allow some close-in plume rise to be considered with respect to escaping the cavity; however, it should be conservative since it does not allow for the lower wind speed near the building, which promotes greater rise. The cavity height may be less than 1-1/2 building heights in the case of pitched or rounded roofs.

For a squat building, this method assumes that if $h' < 1.5\ h_b$, the plume behaves as if it were a ground source of initial area $A = h_b^2$. This gives concentrations in approximate agreement with those measured by Meroney and Yang (1970) near the end of the cavity. The values of χ within the cavity adjacent to the building were estimated from measurements around cubes and rectangles by Halitsky (1968). Equation (2) is a linear interpolation formula giving $h'' = h'$ when $h' = 2.5\ h_b$ and $h'' = 0.5\ h_b$ when $h' = 1.5\ h_b$, thus giving a χ of the same order as that given for a ground source ($h' < 1.5\ h_b$, $A = h_b^2$).

For tall buildings, w_b replaces h_b as the characteristic cavity width and height above h_b. It is assumed that a roof level plume is not pulled all the way down to the ground within the cavity if $h_b > 2\ w_b$; hence, h'' is no more than $1.5\ w_b$ below h'.

Meroney and Yang (1970) found that atmospheric stability had only a slight effect on concentrations immediately downwind of a building, so this effect is neglected here.

Buoyancy Effect (Sec. 2.3):

The calculation of the relative density difference, Δ, is straightforward. It is a simple superpostion of temperature, molecular weight, and latent heat contributions. It is assumed that the effluent will mix with many times its volume of air, so that Δ will become very small (except perhaps very close to the source); Δ times g times the total mass flux of the plume (which is mostly air) represents the total flux of buoyant force carried by the plume. This also explains why the ratio of specific heats appear in the Δ_T term. For Δ_w, it is assumed that all liquid water in the plume evaporates close to the source; for small emissions, observations of "steam" plumes indicate that this is almost always the case.

Dense Plumes (Sec. 2.3.1):

The recommendations in this section are based on an analysis of wind tunnel observations by Bodurtha (1961). It was assumed that the source diameter D was much smaller than h_s, so that only the total fluxes coming from the source were important in determining the distance at which the plume falls to the ground, x_d. Then x_d depends only on h_s, u, and the fluxes of momentum and buoyancy ejected from the stack. Dimensional analysis then indicates that x_d/h_s is a function of $u/\sqrt{g\Delta D}$ and $w_s\ D/(u\ h_s)$. When values of x_d/h_s were plotted against these dimensionless ratios, no clear trend with $w_s\ D/(u\ h_s)$ was seen. There were a few anomalously low values of x_d/h_s at low values of this ratio, but the stack Reynold's number was also very low in these cases, and could have been responsible (poorly developed turbulence would result in a more compact plume, which would fall faster). A strong trend with $u/\sqrt{g\Delta D}$ was seen, and this was approximated by

$$x_d/h_s = 4.5\ u/\sqrt{g\Delta D}$$

The effect of the negative density is ignored if x_d is greater than the distance at which the maximum concentration would occur anyway (i.e., at $R_z = h$). The values of C given in 2.3.1 approximate x/R_z at small distances

The initial cross-sectional area $A = 0.2\ h_s^2$ was taken from Bodurtha's estimates of "dilution," the square of the ratio of plume diameter at contact with the ground to stack diameter. The low efflux velocity (i.e. low Reynold's number) runs were omitted. These did show considerably less dilution, consistent with the more rapid fall observed in these cases.

The fall distance limit for stable conditions, $100\ |F|^{1/4}$, is based on equation 4.25 of Plume Rise (Briggs, 1969) applied to an isothermal temperature gradient. Usually, when $u < 3.5$ m/sec at night the stratification is stronger than this and the plume fall is less. The upward initial momentum of the plume is not taken into account, but its effect is to make the final plume height still higher.

The "effective minimum wind speed" is based on the idea that the initial plume dilution when it contacts the ground, $u(0.2\ h_s^2)$, should be at least that of a negatively buoyant plume falling a distance h_s in completely calm surroundings. Data from a modeling experiment by Rouse, Yih, and Humphreys (1952) suggest that this is $0.2\ |F|^{1/3}\ h_s^{5/3}$, hence the effective minimum wind speed equal to $|F/h_s|^{1/3}$.

The frequency of winds less than 1 m/sec is taken from Figure 4. The estimate of frequencies of winds less than 1 m/sec assumes no correlation between the components of horizontal wind speed and uniform probability distribution within each component in this range.

Buoyant Plumes (Sec. 2.3.2):

For the definition of the buoyancy flux, F, see Briggs (1969) or (1970). Equation (5) is a compromise between equations (22) and (26) of Briggs (1970), which give a plume rise $\Delta h = 21\ F^{3/4}/u$ when F < 55 and $\Delta h = 39\ F^{3/5}/u$ when F< 55. This simplified formula, $\Delta h = 21\ F^{2/3}/u$, also gives a very good fit to plume rise data listed in Table 5.1 of Briggs (1969).

Equation (6) is based on equation (5.7) of Briggs (1969) (same as Eq. 18) of Briggs 1970). It is applied assuming that wind speed times the potential temperature gradient equals 10(m/sec)(°C/100m). It should be pointed out that, close to the ground, large nighttime wind speeds are associated with small potential temperature gradients and vice versa, so that the resultant plume rise is relatively unaffected by variations in the meteorology, particularly since it depends only on the 1/3 power of the above variables.

Simple Diffusion Models (Sec. 3.1):

It is standard practice to approximate the distribution of material with off-axis distance in a plume with a Gaussian shape. The main simplification adopted here is a rectangular plume with uniform concentration within its boundaries (at a given distance) and zero concentration without. As a best compromise, it was decided to set the plume half-width and depth, R_y and R_z, each equal to $\sqrt{\pi/2} = 1.25$ times the lateral and vertical standard deviations describing the Gaussian shape, σ_y and σ_z. Thus the edge of the "rectangular approximation" is set where the off-axis concentration (laterally or vertically) is $\exp(-\pi/4) = 0.44$ times the axial concentration. With this value, the rectangular and Gaussian models give the same axial concentrations for a ground source or for an elevated source at great distances ($R_z >> h$), both for short periods and for long term averages. For an elevated source, the maximum short period concentration and long term concentration given by the rectangular model are 1.07 and 1.03 times those given by the Gaussian model, respectively. The values of σ_z at which the maxima occur are 1.13 and 0.80 times those given by the Gaussian model, respectively.

Diffusion Coefficients and Stability Classes (Sec. 3.2):

The stability classes used here are adaptations of the six Pasquill stability classes which are in wide use. However, these are more crude in that variability in insolation and cloudiness has been left out. "Moderate" insolation in the day and about 50% cloudiness at night are assumed, and only the wind speed and whether it is day or night are used to determine these categories. Thus, in a given 30 minute period, under very cloudy or very clear skies the present stability classification scheme is less than the Pasquill scheme by about one-half a stability class. Even with a more exact scheme, the rate of diffusion observed in a given period is often what one would expect in the next class over. As a result of this uncertainity, the distance at which the maximum χ from an elevated source occurs might be over or underpredicted by a factor of 2 or 3. However, the error in the predicted maximum χ is not so serious, since it depends on the ratio R_z/R_y, and this generally does not change drastically from one stability class to the next.

The values of R_y and R_z given in Appendix D are analytical approximations to existing, published curves for σ_y and σ_z versus x. The curves for rural sites predominantly follow the curves given by Pasquill as published in Meteorology and Atomic Energy (1968), being very good approximations in the range 100m < x <10,000 m. The only exceptions are the "A" and "B" curves for R_z, which approximate the Pasquill values only when σ_z < 100 m. Beyond this point, the functions recommended approximate the curves given by the ASME guide (1968) labeled "very unstable" and "unstable," which lie considerably below the Pasquill "A" and "B" curves. The ASME curves are based on diffusion observations from a 100 m high source, while the Pasquill are based on ground source data, so it seems likely that the former are more relevant when σ_z > 100 m.

The curves for urban sites are based on the analysis of a diffusion experiment in St. Louis by McElroy and Pooler (1968). These data indicate much more rapid diffusion than at rural sites in comparable stability conditions. The functions for R_z given here attempt to approximate the reported values very closely over the range of measurement (from x = 600 m to 17 km). The functions for R_y given here agree with the reported values on the average, but more crudely approximate them within some stability classes than in others. Note that for the B, C, D, and E classes, the urban values given for R_y start out being twice the respective rural values, but asymptotically approach the rural values at great distances.

Ground Concentrations from Ground Sources (Sec 3.3):

The geometric assumptions leading to equation (7) have already been stated, except that a linear addition of the initial plume area and the area due to atmospheric diffusion alone is assumed, after Gifford (Culkowski, 1967).

Ground Concentrations from Elevated Sources (Sec. 3.4):

The simple geometric assumptions leading to equations (8) and (9) have already been stated.

Effect of Averaging Time (Sec. 3.5):

Information on this effect over short periods is incomplete, so the suggested correction factors shown in Figure 3 are provisional, i.e., better than no correction, but not as good as they could be. For convenience, they all are shown as power laws of the averaging time. The ratio is held at unity in the 30 to 60 minute range, as the diffusion models given in this chapter are based on this range of averaging times; there is reason to expect less variation within this range, as it is near a minimum in the meteorological energy spectrum.

The peak concentration for averaging times shorter than 30 minutes is due mostly to variations caused by turbulent eddies within the planetary boundary layer. Except for stable conditions, these cause vertical as well as horizontal fluctuations, which is why larger power laws are indicated for elevated sources. The -2/3, -1/2, and -1/3 power laws are approximations to those recommended for elevated sources by the ASME Guide (1968) for very unstable, unstable, and neutral conditions. For ground sources, observations of Ramsdell et al. (1970) and Cramer et al. (1959) in the daytime fit power laws ranging from -0.21 to -0.67 for averaging times ranging from 3 seconds up to 5 minutes, but generally range between -1/3 and -1/2 for intermediate averaging times. Figure 3 arbitrarily assigns the larger power to the A-B classes and the smaller power to C-D, as the data contain insufficient stability information. The Cramer et al. nighttime observation are fit adequately by a -1/6 power law, so this is assigned to E and F conditions. It should apply about as well to low level elevated sources, since there is little vertical meander in these stability conditions.

The concentration drop-off for averaging times longer than one hour is due mostly to shifts in the mean wind direction due to changes on the synoptic scale. Less drop-off is indicated for the urban source because of the greater initial diffusion. The -1/6 power law is a good fit to the curves of Wipperman and of Meade, both reported by Slade (1968). The -1/3 power law give a factor of 3 reduction in concentration over 24 hours, as recommended by the ASME Standard APS-1 (second edition). A factor of

4 to 5 reduction is reported by Clarke et al. (1970), but this is for large, elevated sources, where the change of plume rise over a 24-hour period would further reduce the average concentration at any one point.

Long Term Average Concentration (Sec. 4.0):

The basic method given in this chapter is an elaboration of standard calculation techniques, which assume uniform long term average concentration at a given distance within each wind direction sector. The factor of 2.5 which appears in equation (10) and (11) is just the inverse of $2\pi/16$, which assumes 16 equal sectors. For simplicity, in equation (10) it is assumed that a receptor at $x = 0$ experiences the full building downwash concentration over 2.5 sectors of wind direction. Figure 4 was derived simply by plotting the wind speed frequencies for the cities listed in the various terrain groups. The curves appeared to be very well ordered by the terrain type.

Long-Term Average Deposition of Particulates (Sec. 5.0):

The basic procedures here are similar to those of Chapter 4, except for the inclusion of settling velocity. The formulas given for w_s are good approximation to Fig. 5.4 of Meteorology and Atomic Energy (1968), based on the fall of spheres. The formula for $D < 70\ \mu$ is just an expression of Stoke's law. Equations (12) and (13) simply assume that $\chi_D = w_s\ \chi$. Equation (14) assumes that, in the case of fast falling particulates, the maximum deposition rate occurs at a distance $x_s = (u/w_s)h$. The shape and magnitude of the deposition approximate cross wind integrated rates measured by Stewart (1968) and Hage (1961). The criterion for choosing equation (13) or (14) selects the formula which gives the greatest maximum.

The particles are assumed to fall out before buoyant plume rise is complete if the vertical velocity of the rising plume is less than w_s at the point that the rise is (1/2) h". The "2/3 law" of plume rise is used in this calculation, such as is given by Briggs (1972).

Special Considerations in Cities (Sec. 6.0):

The basic model for the effect of the urban nighttime mixing layer is adequately explained in the text. The estimate of H was obtained from data summarized by Ludwig et al. (1958), by assuming that the temperature difference between the city and the surrounding countryside (the "heat island") is approximated by H times the potential temperature gradient near the ground outside the city. This assumes a nearly adiabatic lapse rate within the mixing layer. Using this assumption and heat conservation, the heat flux integrated across a city should be proportional to H^2. The heat emission per capita does not vary much from city to city; the integrated heat flux is proportional to $P^{1/2}$ (population distributed in 2 dimensions) and $H \propto P^{1/4}$. This prediction gave a good fit to the data. The scatter defined by the probability distribution given in the text is partly due to variations in stability and wind speed, which affect H also.

The assumption that plume escapes the nighttime mixing layer entirely if h > (3/2)H is based on the observation (Briggs, 1972) that the bottom of a visible, rising plume is about half way between the top of the stack and the plume centerline. If the stack top is somewhere near H/2 and the plume rises to (3/2)H, then almost all the plume should imbed in the stable air above H.

A very similar model (capping from above) applies in the case of inshore fumigation, which sometimes occurs at coastal installations when the wind blows from a cool body of water towards warmer land. This is called a "lake breeze" or "sea breeze." Such air coming off the water is usually stable, so an elevated plume levels off and stratifies within it. The land heats up the air in contact with it and a mixing layer developes, eventually reaching the stratified plume and mixing it downward. A model for this case has not been included here because the wind speeds are moderately high, so the resultant ground concentrations are usually no worse than in other conditions for small sources (this is not true for large sources, however).

Special Considerations Near Prominent Terrain (Sec. 7.0):

Recommendation that h by reduced by up to a factor of 2 when higher terrain is encountered by the plume in A-B-C-D conditions is based on inspection of streamlines computed by Stümke (1964) for flow up various kinds of terrain steps. A potential flow model was used; this usually simulates the approach streamlines well for the neutral case. In unstable conditions, the tendency to "ride up" over terrain steps is likely to be slightly enhanced.

The impingement frequency calculation for E-F conditions simply assumes that the flow is horizontal, and only one streamline in a given horizontal plane impinges on the obstacle. If the plume expands to include that streamline, then it impinges also.

The possibility of terrain downwash if upwind $h_t/x > 0.02$ is mentioned in light of the experience at the Conemaugh power plant in southwest Pennsylvania. On a few occasions the plume was observed to descend to the ground almost immediately. This occurred when it was cloudy (i.e. probably neutral) and the wind was from the southeast. The only unusual feature in this direction is a ridge about 200 m higher than the plant and about 10,000 m away (Schiermeier, 1972).

The valley fumigation model is essentially described in the text.

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