Chapter 5

Processes Other Than Natural Turbulence Affecting Effluent Concentrations

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5-1 INTRODUCTION

A number of processes other than natural atmospheric turbulent diffusion can be significant in the fate of radioactive material emitted into the atmosphere. First is the effect of momentum and buoyancy due to the mode of emission. Thus, for example, the forced emission of a hot effluent from a stack will cause the plume to rise, depending on both the plume and the ambient-air characteristics. A second process is the surface deposition of airborne material composed of either particulate or gaseous matter with resulting depletion of the airborne cloud and quasi-permanent residence of material upon ground surfaces. In the case of radioactivity, surface deposition creates a fixed source of radiation exposure with its cumulative effect as opposed to the rather transitory effect of the airborne cloud. The mechanisms causing deposition are numerous and often not well understood. These include gravitational settling (fallout), precipitation scavenging (washout, snowout, and rainout), surface impaction, electrostatic attraction, adsorption, and chemical interaction. A further complica-

tion is the possibility of resuspension and redeposition of material. A third process is the modification of the natural flow by solid boundary constraints ranging from a building or complex of buildings to the topographic constraint of hills and ridges. The law of conservation of fluid mass states that the fluid must flow around or over the obstruction and that there will be subsequent changes of speed, pressure, and streamline configuration.

The variety of topics included in this chapter creates some overlap in the notation used in the various sections. Rather than arbitrarily changing some of this notation to ensure compatibility within the sections of this chapter and thus ensuring incompatibility with literature on the same topics, we have included a list of the symbols used in each major section at the beginning of the section.

5-2 MOMENTUM AND BUOYANCY EFFECTS (Gary A. Briggs)

Material released into the atmosphere is generally contained in a volume of gas having a velocity and buoyancy relative to the air; its behavior will differ from that of a passive volume of gas according to the magnitude of these parameters and the prevailing meteorological conditions. Although accidental releases are difficult to define in these terms, it is possible, on both theoretical and empirical grounds, to specify with some accuracy the behavior of the gases released as a continuous plume and as an instantaneous cloud.

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List of Symbols

Symbols used frequently in Sec. 5-2 on momentum and buoyancy effects are listed here. (The dimensions mass, length, time, and temperature are abbreviated as M, L, T, and D, respectively. Equation or table number indicates the first appearance of the symbol.)

c_p, c_{ps}	Specific heat at constant pressure of ambient and stack air ($L^2 T^{-2} D^{-1}$), Eq. 5.11
d	Inside stack diameter (L), Eq. 5.1
F	Buoyancy flux = $g(\Delta T/T_s) w r^2$ ($L^4 T^{-3}$), Eq. 5.11
F_i	Instantaneous buoyancy = $g Q_i / c_p \rho T$ ($L^4 T^{-2}$), Eq. 5.22
F_m	Proportional to momentum flux = $(T M_s / T_s M) w^2 r^2$ ($L^4 T^{-2}$), Eq. 5.10
g	Gravitational acceleration ($L T^{-2}$), Eq. 5.6
h	Effective stack height = $h_s + \Delta h$ (L), Eq. 5.32
h_s	Actual stack height (L), Table 5.1
Δh	Plume rise (L), Eq. 5.1
K	Stümke regression coefficient = $\left(\frac{1}{N} \sum \frac{\Delta h \text{ calculated}}{\Delta h \text{ observed}} \right)^{-1}$, Eq. 5.14
L	Length parameter = $F / \bar{u}^3$ (L), Eq. 5.5
M, M_s	Average molecular weight of ambient and stack air, respectively, Eq. 5.10
Q_H	Rate of heat emission of a continuous source ($M L^2 T^{-3}$), Eq. 5.2
Q_i	Heat emission from an instantaneous source ($M L^2 T^{-2}$), Eq. 5.22
r	Inside stack radius (L), Eq. 5.6
s	Stability parameter = $\frac{g}{T} (\partial \Theta / \partial z) (T^{-2})$, Eq. 5.9
t	Time after emission from the stack (T), appears in various equations
T, T_s	Absolute temperature of ambient and stack air, respectively (D), Eq. 5.1
ΔT	Stack effluent temperature minus ambient air temperature (D), Eq. 5.1
$\bar{u}$	Average value of the wind component in the direction of the mean horizontal wind vector ($L T^{-1}$), Eq. 5.1
$\bar{u}_c$	A critical windspeed ($L T^{-1}$), Eq. 5.29
w	Stack-gas efflux velocity ($L T^{-1}$), Eq. 5.1
ρ	Air density ($M L^{-3}$), Eq. 5.22

$\frac{\partial \Theta}{\partial z}$ Potential temperature gradient ($D L^{-1}$), Eq. 5.9

5-2.1 Behavior of Continuous Plumes

5-2.1.1 Qualitative Behavior. While a smoke plume quickly attains the wind speed in the horizontal plane, its rise is determined by its vertical momentum and buoyancy due to heat and molecular-weight difference. Rise of the plume is impeded by entrainment with air, which at first is due to turbulence generated by the relative motion of the plume. As this dies out, atmospheric turbulence dominates the mixing. In stratified air the buoyancy of the stack gases and entrained air is altered by the change of the relative density of the ambient air with height. In stable air this change acts as a restoring force on the plume, but in unstable air the plume may rise to unlimited heights. Plume behavior may be influenced by aerodynamic effects due to chimney phenomena, surrounding buildings, and terrain. The relation between the temperature profile and the appearance of plumes is shown in Fig. 2.40 (Chap. 2, Sec. 2-7.2), and a discussion of plume types appears in the accompanying text.

5-2.1.2 Height-of-rise Formulas. At least twenty formulas for calculating plume rise have been published since 1950.* None is universally accepted, primarily because of the lack of comprehensive data. This lack is due largely to observational difficulties, especially the difficulty of detecting the plume at large distances downwind. The fact that many plumes are still rising after becoming invisible through dilution has led to apparent contradictions in results when the final visible height was taken to be the ultimate rise. Some of the differences between transitional rise and ultimate rise are discussed by Scorer (1962). Published data are often based on an inadequate determination of lapse rate up to

*See Batchelor (1954), Bosanquet (1957), Bosanquet, Carey, and Halton (1950), Briggs (1965), Bryant and Cowdrey (1955), Csanady (1961), Danovich and Zeyger (1963), Davidson (1954), Hill, Thomas, and Abersold (1945), Lucas, Moore, and Spurr (1963), Morton (1959, 1959a), Morton, Taylor, and Turner (1956), Priestley (1956), Priestley and Ball (1955), Rupp et al. (1948), Schmidt (1957, 1963, 1965), Scorer (1958, 1959, 1959a), Scorer and Barrett (1962), Stümke (1961), Sutton (1950), Thomas (1954), and U. S. Weather Bureau (1953).

plume level and an insufficient number of runs for averaging in unstable conditions.

Four of the most commonly used formulas are presented in the following paragraphs. The Davidson-Bryant (1954) and Holland (U. S. Weather Bureau, 1953) formulas are completely empirical, and the Bosanquet (1957) and dimensional-analysis formulas (Batchelor, 1954, Briggs, 1965, and Scorer, 1958, 1959, 1959a) are semiempirical. Each author has his own criterion for final rise, but usually we are concerned with height of rise at the point where maximum ground concentration occurs.

1. The Davidson-Bryant Formula. Davidson (1954) suggested the formula

$$\Delta h = d \left(\frac{w}{\bar{u}} \right)^{1.4} \left(1 + \frac{\Delta T}{T_s} \right) \quad (5.1)$$

stating that the factor $(w/\bar{u})^{1.4}$ is in fair agreement with Bryant's (1949) wind-tunnel data on plume rise due to momentum. To account for rise due to buoyancy, Davidson proposed using the multiplying factor $(1 + \Delta T/T_s)$. He indicates that this formula may be applied to "stacks of moderate or great height" but does not define these terms.

2. The Holland Formula. Rupp, Beall, Bornwasser, and Johnson (1948) give the height of rise of an effluent without buoyancy as $1.5 d (w/\bar{u})$, which is based on wind-tunnel experiments with ammonium chloride as a tracer. Holland (U. S. Weather Bureau, 1953) added a buoyancy term to this to get closer agreement with photographs of plume trajectories of three power stations, whose parameters are shown in Table 5.1. The Holland, or Oak Ridge, formula is

$$\Delta h = 1.5 d \frac{w}{\bar{u}} + 4.0 \times 10^{-5} \frac{Q_H}{\bar{u}} \quad (5.2)$$

where Q_H is in calories per second and all other units are in the MKS system. To take stability into account, Holland suggests that the predicted rise be increased by 10 to 20% in unstable conditions and be decreased by an equal percentage in stable conditions.

Davidson presents no field data in his original paper. Although Holland does present such data, observations apparently were carried no further than 600 ft downwind (Hawkins and Nonhebel,

Table 5.1—RANGE OF STACK AND METEOROLOGICAL PARAMETERS USED IN DERIVING HOLLAND FORMULA

	X-10 pile	X-10 steam plant	Watts Bar steam plant
h_s , ft	200	180	160
d , ft	5.8	9	14
w , mile/hr	45	5	34
T_s , °F	180	400	350
Q_H , cal/sec	8.3×10^5	7.1×10^5	6.6×10^6
$\bar{u}$, mile/hr	1 to 21	1 to 15	1 to 15
Number of observations	11	33	93
$\bar{u}\Delta h$, (mile/hr) ft			
Mean	620	452	2632
Standard deviation	410	324	2950

1955) and show much scatter. Both formulas have been criticized because they are empirical and their reliability is questionable when the ranges of variables are much outside those used in their formulation. Holland's formula has been further criticized because it includes a dimensional constant which is not based on the physical constants of air and thus must really be an averaged function of one or more variables.

3. The Bosanquet Formula. Bosanquet, Carey, and Halton (1950) published a technique for calculating plume rise which has been widely used. Nonhebel (1957) reported that the Beaver Committee in England (Beaver, 1954) applied this formula to stack data and found it gave too high a thermal rise for large plants. Bosanquet was asked to reexamine his original calculations, and he published a revised technique (Bosanquet, 1957), which is described in the following paragraphs in somewhat altered form.

Bosanquet first considers a "cold" plume, i.e., one with a density the same as that of the ambient air. When $w/\bar{u} > 0.48$,

$$\Delta h = 3.14 d \frac{w}{\bar{u}} \left\{ 1.31 - \frac{0.615}{[(w/\bar{u})^2 + 0.57]^{1/2}} \right\} \quad (5.3)$$

When $w/\bar{u} < 0.48$,

$$\Delta h = 2.83 d \left(\frac{w}{\bar{u}} \right)^{1.5} \quad (5.4)$$

If the stack gases are similar to air in specific heat and molecular weight but are buoyant owing to heating, Bosanquet's formulation becomes

$$\Delta h = 29.6 L \left\{ F_1(X) + F_2(X_0) - \frac{0.615 X_0^{1/2}}{[(w/\bar{u})^2 + 0.57]^{1/2}} \right\} \quad (5.5)$$

$$L = \frac{\Delta T g w r^2}{T_s \bar{u}^3} = \frac{F}{\bar{u}^3} \quad (5.6)$$

$$X_0 = 0.180 \frac{T_s}{T} \left(\frac{\bar{u}^2 T}{dg \Delta T} \right)^2 \quad (5.7)$$

$$X = X_0 + 0.034 \frac{x}{L} = 0.034 \frac{\bar{u} t'}{L} \quad (5.8)$$

In the above equations L is the length parameter based on buoyancy flux and on wind speed, x is the distance downwind of the source, and the quantity within the parentheses in the definition of X_0 is proportional to the ratio of aerodynamic to buoyant accelerations at the chimney. Implicit in the equations is a turbulent diffusion coefficient assumed equal to 0.13. This formulation gives the rise trajectory rather than final rise; so it should be applied to the distance downwind of greater interest. Bosanquet presents tables of $F_1(X)$ and $F_2(X_0)$, which are condensed here in Table 5.2.

atmosphere $t' = 200$ sec might be appropriate for computing X .

4. Dimensional-analysis Formulas. When the relevant physical parameters and their units are specified, it is often possible to predict the outcome of a physical situation purely on dimensional grounds; Batchelor (1954) and Scorer (1958, 1959, 1959a) did this for plume rise. Briggs (1965) extended their work, and his work forms the basis of the presentation here. Since dimensional analysis cannot predict constants in the equations, these constants must be determined empirically. Analysis is simplified by replacing the chimney with a virtual point source with a height that can usually be approximated by the chimney's height. The point source is then entirely specified by some measure of its momentum flux and its buoyancy flux. The volume flux at the stack is $w(\pi r^2)$. Since only the density of the smoke relative to air affects rise, we can use momentum flux divided by π and ρ as the momentum parameter, i.e.,

$$F_m = \frac{T M_s}{T_s M} w^2 r^2 \quad (5.10)$$

Buoyancy flux can be defined as the rate that buoyant force due to the effluent is added to a

Table 5.2—VALUES OF $F_1(X)$ AND $F_2(X_0)$ IN BOSANQUET'S PLUME-RISE FORMULAS*†

X or X_0	$F_1(X)$	$F_2(X_0)$	X or X_0	$F_1(X)$	$F_2(X_0)$	X or X_0	$F_1(X)$	$F_2(X_0)$
0.1	0.170	-0.044	1	0.767	0.155	10	2.33	1.99
0.15	0.225	-0.046	1.5	0.965	0.296	15	2.70	2.73
0.2	0.274	-0.043	2	1.13	0.43	20	2.95	3.41
0.3	0.360	-0.030	3	1.39	0.69	30	3.33	4.56
0.4	0.434	-0.010	4	1.59	0.91	40	3.61	5.54
0.6	0.562	-0.041	6	1.90	1.32	60	4.00	7.24
0.8	0.671	-0.096	8	2.14	1.67	80	4.28	8.68

*From Bosanquet, The Rise of a Hot Waste Gas Plume, *J. Inst. Fuel*, 30: 326 (1957).

†Outside the range of the tables the following approximations are valid: when $X \geq 10^2$, $F_1(X) = \ln X - 0.12$; when $X_0 \geq 10^2$, $F_2(X_0) = 1.31 X_0^{1/2} - 0.5 \ln X_0 - 1$.

In a stable atmosphere the plume reaches a limiting height in a time proportional to $s^{-1/2}$, s being a measurement of stability defined by

$$s = \frac{g}{T} \frac{\partial \Theta}{\partial z} \quad (5.9)$$

where $\partial \Theta / \partial z = (\partial T / \partial z) + 9.8$ °C/km, the potential temperature gradient. When $\partial \Theta / \partial z > 3.5$ °C/km, Bosanquet suggests that for final rise $t' = 2.16 s^{-1/2}$ be used and that for a weakly stable

large volume of air divided by $\pi \rho$. It is given by

$$F = \frac{T}{T_s} g w r^2 \left[\left(1 - \frac{M_s}{M} \right) + \left(\frac{T_s}{T} - 1 \right) \left(\frac{c_{ps} M_s}{c_p M} \right) \right] \quad (5.11)$$

When the stack gases have nearly the same specific heat and molecular weight as air, the expression simplifies to

$$F = \frac{\Delta T}{T_s} g w r^2 \quad (5.12)$$

which can be further approximated by

$$F = 3.8 \times 10^{-5} Q_H \quad (5.13)$$

where F is in meters⁴ per second³ and Q_H in calories per second. When the wind is strong enough to bend the plume, the above quantities are diluted along the plume's length in proportion to $\bar{u}$, and the relevant parameters become $F_m/\bar{u}$ and $F/\bar{u}$. In the stable case the height is limited by the stability parameter, s , determined from the average potential temperature lapse rate through the layer in which the plume rises. In a neutral atmosphere rise is limited chiefly by $\bar{u}$ and depends to a lesser extent on the roughness of the ground and height. In all cases the trajectory before the final height is approached is not much dependent on stability; this will be called transitional rise.

With these assumptions we can derive the dimensional relations shown in Table 5.3. Where observations are available, the appropriate constants are estimated and included in the table. The constant for the neutral windy momentum-dominated plume is taken from the results of Rupp, Beall, Bornwasser, and Johnson (1948). In the buoyancy-dominated cases, the constant for the calm stable case is a compromise between the results of Morton, Taylor, and Turner (1956) and those of Crawford and Leonard (1962) [this is a correction of the value stated by Briggs (1965)]. The other constants are estimated from Figs. 5.1 and 5.2. Estimation of the constant for the windy neutral situation is particularly difficult since none of the plumes in Fig. 5.2 level off. The "constant" is also dependent on surface roughness and stack height; a conservative value would be about 400. The most pertinent atmo-

spheric situation is the one whose formula gives the lowest value of rise; the momentum and buoyancy rises may be considered to add approximately linearly. Most hot plumes are buoyancy dominated.

5-2.1.3 Comparison with Observations. Data adequate to fully test the validity of the preceding and other proposed formulas do not exist. Nevertheless a number of investigations have been made in which available data were tested. The earliest studies comparing plume rise formulas with observations were made by Katz (1952), who compared the formula of Sutton (1950) with that of Bosanquet, Carey, and Halton (1950), and by Best (1957), who compared these two formulas and the one by Holland.

More recently, comparisons between observed and calculated plume rises were made by Moses and Strom (1961) using data taken at the Argonne National Laboratory in the United States, by Rauch (1962) using data taken at Duisburg and at Gernsheim in Germany, and by Stümke (1961, 1963) using data taken at Argonne, at Duisburg and Gernsheim, and at Harwell in England. Much of this work has been summarized by Moses, Strom, and Carson (1964). Additional comparisons will be made here, including a regression equation proposed by Stümke and the previous dimensional-analysis predictions.

Stümke defined a constant regression coefficient K by the formula

$$\frac{1}{K} = \frac{1}{N} \sum \frac{\Delta h_{calc}}{\Delta h_{obs}} \quad (5.14)$$

where N is the number of observations. Thus, if K is calculated for a particular formula and set of observations, multiplying the calculated rises by K assures that their average ratio to observed values will be 1.0. A number of investi-

Table 5.3—DIMENSIONAL ANALYSIS PLUME-RISE PREDICTIONS

Wind	Type of rise	Momentum-dominated plume	Buoyancy-dominated plume
Calm	Transitional	$\Delta h = \text{constant } F_m^{1/4} t^{1/2}$	$\Delta h = \text{constant } F^{1/4} t^{3/4}$
	Stable	$\Delta h = \text{constant } F_m^{1/4} s^{-1/4}$	$\Delta h = 5.1 F^{1/4} s^{-3/4}$
	Neutral	$\Delta h = \text{constant } F_m^{1/4} t^{1/2}$	$\Delta h = \text{constant } F^{1/4} t^{3/4}$
Windy	Transitional	$\Delta h = \text{constant } (F_m/\bar{u})^{1/2} t^{1/2}$	$\Delta h = 2.0 F^{1/2} \bar{u}^{-1} s^{3/2}$
	Stable	$\Delta h = \text{constant } (F_m/\bar{u})^{1/2} s^{-1/2}$	$\Delta h = 2.6 (F/\bar{u})^{1/2} s^{-1/2}$
	Neutral	$\Delta h = 3.0 F_m^{1/2} \bar{u}^{-1}$	$\Delta h \approx 10^3 F \bar{u}^{-3}$

Fig. 5.1—Observed plume rises for buoyant sources during stable windy conditions compared to $\Delta h = 2.6(F/u)^{1/3} s^{-1/3}$ (solid line; see Table 5.3) in nondimensional form. (From Briggs, 1965).

gators have made use of Stümke's correction factor.

Moses and Strom used least-squares techniques to compare the formulas of Davidson-Bryant, Holland, and Bosanquet, as well as those of Sutton, Scorer, and Bosanquet, Carey, and Halton. The plume-rise data used by Moses and Strom were obtained at the Argonne experimental meteorological stack using photogrammetric techniques. These measurements extended only to 60 m. The buoyancy in these experiments was very low, and it is likely, although not certain, that the plume rises were near their maximum since the angles between the smoke center line and the horizontal were 5° or less in 27 of the 31 cases studied. The weakness of the source may have made the plume more susceptible to variances due to atmospheric eddies. A statistical summary of three of the formulas considered is shown in Table 5.4. Also included are the plume rises obtained by applying Stümke's correction factor K . These data show that both the Holland and the Davidson-Bryant formulas yield values that are too low and that the Bosanquet formula yields values that are too high.

Rauch, using the same data used by Stümke from the Gernsheim and Duisburg stacks plus measurements taken later (for a total of 428 individual runs), compared Holland's formula with a K factor of 3.09 and a formula suggested by Lucas, Moore, and Spurr (1963) which states

$$\Delta h = 530 \left[\frac{(Q_H)^{1/4}}{u} \right] \quad (5.15)$$

where units are in the MKS system and Q_H is the power in megawatts generated by the unit. Rauch concludes that for these two stacks the Lucas formula is superior to that of Holland. It does not take into account rise due to momentum, but for most hot plumes this factor is negligible compared to buoyant rise. The Lucas formula is an empirical fit to Priestley's theory (1956), in which the first phase predicts transitional rise approaching $\Delta h = 2.0 F^{1/4} u^{-1} x^{3/4}$ (MKS units) and differs from the dimensional prediction of Table 5.3 by a factor of only $(x/F)^{1/2} (m/sec)^{1/2}$. The Lucas formula is equivalent to the above applied at a fixed distance of 800 m; actual measurements of balloons released into the plume (as tracers) were at distances of 1100 to 1800 m.

The most extensive tests of observed and calculated plume rise have been made by Stümke. In the first of his two papers, he used measurements by Stewart, Gale, and Crooks (1958) from a stack at Harwell, England, and by Rauch (1962) from stacks at Gernsheim and Duisburg, Germany, as well as the four sets of data presented in the paper by Bosanquet, Carey, and Halton. Stümke compared eight different formulas with these measurements, i.e., those of Bosanquet, Carey, and Halton, Davidson-Bryant, Holland, Scorer, Morton, two formulas of his own, and the Hill, Thomas, and Abersold formula (1945), which states that a $1^\circ F$ temperature increase represents 2.5 ft of plume rise.

Stümke concluded that the Holland formula with a K factor of 2.92 gave the best representation of plume rise since the relative standard

Fig. 5.2—Observed transitional plume rises for buoyant sources during windy conditions compared to $\Delta h = 2.0 F^{1/2} \bar{u}^{-1} x^{3/2}$ (dashed line; see Table 5.3) in nondimensionalized form. (From Briggs, 1965.) Data on the sources of the trace lines are as follows:

Trace number	Source	Q_H , cal/sec	F , ft^4/sec^3	$\bar{u}$, ft/sec
1	Bosanquet	1.53×10^6	6,900	14
2	Bosanquet	1.53×10^6	6,900	33
3	Bosanquet	1.53×10^6	6,900	26.5
4	Bosanquet	1.53×10^6	6,900	19
5	Bosanquet	7.24×10^4	326	10
6	Bosanquet	7.24×10^4	326	13
7	Bosanquet	1.58×10^6	7,130	20.4
8	Harwell	1.10×10^6	4,830	21
9	Harwell	1.10×10^6	4,830	32
10	Harwell	1.10×10^6	4,830	46
11	Van Vleck & Boone	7.2×10^6	31,600	7 to 9
12	Van Vleck & Boone	7.2×10^6	31,600	16 to 19
13	Csanady	2.73×10^6	12,000	15 to 23
Circles	Ball	0.96×10^4	42.1	3 to 13

deviation of the ratio of calculated to observed height was the smallest. Also the correlation coefficient between observed and calculated values was largest. The results have been extended using Stümke's data to include the Bosanquet 1957 formula and are summarized in Table 5.5.

In his second paper Stümke used the data of Moses and Strom, of Stewart, Gale, and Crooks, and of Rauch (although Rauch's data appear to have been reevaluated) and derived a generalized formula of which the Holland and the Lucas, Moore, and Spurr formulas are special cases. Optimizing his adjustable parameters for best

fit with data he gets

$$\Delta h = 1.5 \frac{w}{u} d + 65.0 \frac{d^{3/2}}{u} \left(\frac{\Delta T}{T_s} \right)^{1/4} \quad (5.16)$$

where the units are in the MKS system.

Table 5.6 shows sample calculations, chosen for a wide variety of source strengths, for a comparison of the new Stümke formula and the dimensional-analysis formula for transitional rise ($\Delta h = 2 F^{1/2} u^{-1} x^{3/2}$) with the older formulas. Data of Bosanquet, Carey, and Halton (1950), of Rauch (1962) at Duisberg, and of Gartrell et al. (1964) at the Colbert plant in Alabama are pre-

Table 5.4—STATISTICAL SUMMARY OF CALCULATED AND OBSERVED PLUME HEIGHTS AT 60 M FROM EXPERIMENTAL SMOKESTACK AT ARGONNE NATIONAL LABORATORY*

		Calculated		
	Observed	Davidson— Bryant formula	Holland formula	Bosanquet formula
Without Stümke's K correction factor:				
Mean plume rise, m	6.1	3.5	2.6	7.3
Standard deviation, m	3.5	3.6	1.5	6.1
Root-mean-square observed height minus calculated height, m		4.2	4.7	5.2
Correlation coefficient (calc. vs. obs.)		0.52	0.46	0.52
With Stümke's K correction factor:				
Mean plume rise, m	6.1	5.7	4.8	5.5
Standard deviation, m	3.5	5.9	2.8	4.6
Root-mean-square observed height minus calculated height, m		4.9	4.3	4.0
Correlation coefficient (calc. vs. obs.)		0.52	0.46	0.52
Stümke's correction factor		1.63	1.86	0.753

*Moses, Strom, and Carson, 1964.

Table 5.5—STATISTICAL SUMMARY OF STÜMKE'S 1961 ANALYSIS BASED ON GERNSHEIM, DUISBURG, AND HARWELL DATA*†

	Observed	Calculated		
		Davidson— Bryant formula	Holland formula	Bosanquet formula
Average plume-rise height, m	65.4	66.7	65.4	66.1
Standard deviation, m	17.7	44.1	34.0	56.8
Stümke correction factor		6.69	2.92	0.75
Root-mean-square of observed height minus calculated height, m		37.4	26.5	51.7
Correlation coefficient		0.62	0.64	0.43

*Moses, Strom, and Carson, 1964.

†The Stümke K correction factor was applied.

Table 5.6—SAMPLE PLUME-RISE CALCULATIONS

(a) Observed Plume and Meteorological Data for the Case of Transitional Rise

Source*	$Q_H, 10^6 \text{ cal/sec}$	$\bar{u}, \text{ ft/sec}$	T, °C	d, ft	w, ft/sec	x, ft	$\Delta h_{\text{obs}}, \text{ ft}$
Bosanquet (2)	0.072	10	25	4.1	28	300	67
Bosanquet (1a)	1.5	14	180	8.2	31	600	186
Bosanquet (1b)	1.5	33	180	8.2	31	800	84
Duisburg	2.7	24	114	11.5	38	1640	223
Colbert	7.2	30	126	16.5	47	10,560	1000

(b) Ratios of Calculated Δh to Observed Δh , Stümke Regression Coefficients (K), and the Product of the Data Standard Deviation and K

Source	Davidson-Bryant formula	Holland formula	Bosanquet formula	Stümke formula	Dimensional-analysis formula
Bosanquet (2)	0.28	0.30	0.82	1.04	0.92
Bosanquet (1a)	0.19	0.40	0.80	0.98	1.03
Bosanquet (1b)	0.12	0.37	0.37	0.92	1.17
Duisburg	0.13	0.34	0.59	0.91	1.16
Colbert	0.04	0.14	0.20	0.23	1.03
K	6.58	3.23	1.80	1.23	0.94
Standard deviation multiplied by K, %	53	29	43	36	9

*See legend of Fig. 5.2 for Bosanquet data.

sented. At Colbert the height of maximum SO_2 concentration for the two highest wind-speed runs are used.

Best results, with the lowest normalized standard deviation, were obtained from the dimensional-analysis formula for buoyant transitional rise (see also Fig. 5.2). This indicates that momentum rise for these plumes was probably unimportant and suggests that all the plumes were still rising, even the Colbert plume at 2 miles downwind. In fact, there are at present no data for neutral conditions in which the plume clearly levels off to a final height. In light of theoretical considerations, it is questionable whether there even exists an ultimate height of rise in these conditions. What are needed are observations of rise in neutral conditions at the point of maximum average ground concentration of effluent. Of the formulas for final rise, both the Stümke formula and the Holland formula times a factor of 3 seem to give good agreement for the moderate-sized sources but grossly underestimate rise in the case of the large Colbert plant.

To test the power law predicted by dimensional analysis for a stable windy buoyant source, Briggs (1965) plotted nondimensional-

ized height and stability parameter (Fig. 5.1). The data for inversion conditions at Colbert fit the law very well, especially at higher wind speeds. The most stable runs of Moses and Strom (1961) do not fit as well, but their source was three orders of magnitude weaker. The Colbert data show very definite leveling with the plume maintaining a constant height from $\frac{1}{2}$ mile to as far as 9 miles downwind.

Figure 5.2 amply demonstrates the validity of the dimensional-analysis law $\Delta h = 2.0 F^{\frac{1}{2}} \bar{u}^{-1} x^{\frac{3}{2}}$ since seven widely different sources seem to give reasonable agreement with the predicted rise. Observed rise and distance downwind are nondimensionalized in terms of $L = F/\bar{u}^3$. The stack-plume trajectories plotted are from Bosanquet, Carey, and Halton (1950), Csanady (1961), and Stewart, Gale, and Crooks (1958) at Harwell. Also plotted are rise data from lard-pail oil burners (Ball, 1958) and from exhaust clouds of horizontally fired rocket motors (Van Vleck and Boone, 1964). Because winds were measured much below the plume levels for the Harwell and the rocket-exhaust data, these wind speeds were adjusted by estimating roughness and assuming the logarithmic wind profile generally found in neutral conditions.

It was hoped that Fig. 5.2 would show evidence of a final height, but none of the observations went far enough downwind that a definite leveling was evident. However, a probably conservative estimate of final rise in neutral conditions is

$$\Delta h > 400 \frac{F}{\bar{u}^3} \quad (5.17)$$

since traces from six of the seven sources approach or exceed this level.

In summary the Davidson-Bryant formula gives rises nearly 7 times too small for moderately large plants (Q_H about 10^6 cal/sec). Because this factor of underestimation varies from about 2 for a very small source to about 20 for a large source, with large standard deviations, this formula is not recommended. Both the Holland formula multiplied by a Stümke correction factor of 3 and Stümke's own formula give reasonable results for reported rises from moderate-sized plants but greatly underestimate rise for a large plant. The Bosanquet formula works well at short distances downwind but greatly underestimates rise at large distances downwind. The dimensional-analysis formulas for buoyant sources give consistently good results for all source sizes and distances downwind and take into account atmospheric stability. The formula for final rise in neutral conditions is necessarily conservative since there are few observations at large distances downwind, but it is not so severely conservative as the other formulas. Recommended then is whichever of the following formulas gives the minimum rise in a given situation:

Transitional:

$$\Delta h = 2.0 F^{1/3} \bar{u}^{-1} x^{2/3} \quad (5.18)$$

Final, neutral:

$$\Delta h = 400 \frac{F}{\bar{u}^3} + 3r \frac{w}{\bar{u}} \quad (5.19)$$

Final, stable with wind:

$$\Delta h = 2.6 \left(\frac{F}{\bar{u}s} \right)^{1/2} \quad (5.20)$$

Final, stable and calm:

$$\Delta h = 5.1 F^{1/4} s^{-1/4} \quad (5.21)$$

5.2.2 Behavior of Instantaneous Clouds

5.2.2.1 Qualitative Behavior. The rise of an instantaneous cloud, such as that originating from an explosion, is similar to the rise of a plume except that the cloud diffuses in three dimensions rather than just two. The cloud rises owing to its buoyancy and original vertical momentum, being carried along by the wind in the horizontal. Entrainment occurs at first because of the cloud's relative motion in the air and later because of the air's own turbulence. In stratified air the buoyancy of the cloud is altered by the relative density of the entrained air. In stable air a limiting height is reached when the buoyancy decays to zero; in unstable air the cloud will rise indefinitely.

5.2.2.2 Height-of-rise Formulas. The rise of a cloud from an instantaneous point source in a stable fluid is treated theoretically by Morton, Taylor, and Turner (1956) in agreement with Batchelor's dimensional analysis (1954). The point source is specified by the total buoyant force imparted to a large volume of entrained air divided by the density of air, given by

$$F_i = \frac{g Q_i}{c_p \rho T} \quad (5.22)$$

This gives for a stable atmosphere

$$\Delta h \propto F_i^{1/4} s^{-1/4} \quad (5.23)$$

For a neutral atmosphere, neglecting roughness effects, dimensionally we would have

$$\Delta h \propto F_i^{1/2} \bar{u}^{-1} \quad (5.24)$$

but this formula has not yet been tested.

5.2.2.3 Comparison with Observations. Morton, Taylor, and Turner (1956) performed experiments in a stably stratified salt solution and found a 0.98 correlation factor between observed rises and a formula whose point-source atmospheric equivalent would be

$$\Delta h = 2.66 \left(\frac{Q_i}{c_p \rho \partial \Theta / \partial z} \right)^{1/4} = 2.66 \frac{F_i^{1/4}}{s^{1/4}} \quad (5.25)$$

In Fig. 5.3 this formula is compared with the rise of clouds from nuclear detonations in Phase II of Operation Hardtack, where detonations ranged from 0.6 tons to 6 kt TNT equiv-

how to take best advantage of this to alleviate pollution at the ground. There are also undesirable aerodynamic effects that must be avoided, such as downwash at the chimney and large eddies due to surrounding buildings and terrain.

One obvious way to increase rise would seem to be to increase efflux velocity. Since the rise

Fig. 5.3—Observed cloud rises from nuclear detonations vs. $\Delta h = 2.66 F_i^{1/4} / s^{1/4}$ (solid line).

alent (Telegadas and Nagler, 1960). The rises average about 30% higher than the above formula predicts, but this is not unexpected since the fireball at first rises as a bubble without mixing owing to the great density difference between it and the surrounding air; energy losses other than that of heating the air have not been accounted for. The potential temperature difference between the bottom and top of the rise layer was measured from the top to the ground inversion, when present, to allow for the bubble effect.

5-2.3 Effects on Ground-level Concentration

5-2.3.1 Practical Considerations. The general effect of efflux velocity and buoyancy is to raise the effective height of emission of gases, thereby reducing their ground-level concentration. Air-pollution meteorologists would like to know

due to efflux velocity is only of the order 1.5 d ($w/\bar{u}$), however, the rise gained is generally much less than the total stack height and is therefore uneconomical. The TVA installed a nozzle on the stack of a 150-Mw unit increasing the efflux velocity from 45 to 90 ft/sec and found no significant increase in rise over adjacent unmodified units during pollution conditions (Thomas, Carpenter, and Gartrell, 1963). For a buoyant plume in stable conditions, it is even possible to get less rise with increased efflux velocity since this increase causes more vigorous entrainment at the chimney level (Morton, 1959).

A more effective way to increase rise is to make the heat efflux, Q_H , larger. When a single unit is involved, this method, too, is usually uneconomical since a higher stack would be cheaper than the long-run cost of added heat. When more than one pollutant-producing unit is available, however, combining the effluents into

one common stack results in a double advantage: first, for the same cost a single stack can be made taller than several individual stacks and, second, the buoyancies are additive so that the overall plume rise increases.

At two large London power stations, an attempt to reduce sulfur dioxide contamination was made by removing 90% of the gas through a washing process (Hawkins and Nonhebel, 1955). Unfortunately the process also reduced the temperature of the gas and saturated it with water vapor, causing the plume to lose its buoyancy and spread to the ground more quickly. Iso-pleths of SO_2 at the ground showed that the maximum concentration of the washed plume was comparable to that of the unwashed plume. One advantage gained by washing, however, was that the areas bounded by isopleths of relatively high concentration were substantially reduced.

When the wind is high, effluent may be drawn into the low-pressure area created on the leeward side of the chimney, a condition known as downwash. Wind-tunnel experiments by Sherlock and Stalker (1941) suggest that downwash is not serious as long as $w > \bar{u}$. Thus efflux velocity should exceed the wind speed at which the worst pollution is expected. One power-station stack in Bankside, England, is divided internally into four sections so that a partial load uses only part of the chimney and a sufficient efflux velocity is maintained. When efflux velocity is low, another way to eliminate downwash is to install around the chimney top a horizontal disk about one chimney diameter in width; such a disk is in use at St. Auban sur Durance, France (Scorer, 1959).

5.2.3.2 Prediction of Concentration. Once the possibility of extraneous aerodynamic effects has been eliminated, the usual method of predicting ground concentration is to calculate the total plume rise and to use this in the diffusion equations. This procedure is not simple to execute since a variety of meteorological situations must be accounted for and the best diffusion model and plume-rise formula must be chosen.

The meteorological complications are reduced if we consider only the average conditions (this treatment is given by Scorer and Barrett, 1962) and the worst situations, i.e., the windy neutral case and the low-wind fumigation case. In industrial areas the fumigation case is likely to be the worst since pollution from each source spreads and superimposes itself on that of its

neighbors. These two situations were treated for maximum ground concentration from a buoyant source by Briggs (1965). A summary follows.

In the neutral case, assuming a Gaussian distribution and constant σ_z/σ_y for the pollutant, we find at the distance of maximum concentration

$$\bar{x}_{\max.} = \frac{\sigma_z}{\sigma_y} \frac{2Q'}{\pi h^2 e \bar{u}} \quad (5.26)$$

where the notation is that of Chaps. 3 and 4 (see Chap. 3, Eq. 3.146). If we assume that $\sigma_z/\sigma_y \approx 0.5$ in the neutral case and, further, assume a conservative rise given by $400F/\bar{u}^3$, a critical wind speed at which the highest concentration occurs is found by differentiation:

$$\bar{u}_c = 12.6(F/h_s)^{1/3} \quad (5.27)$$

This results in a maximum ground concentration of approximately

$$\bar{x}_{\max.} = a \frac{Q'}{F^{1/3} h_s^{5/3}} \quad (5.28)$$

where $a = 0.0065$.

The corresponding equations for a nonbuoyant source whose plume rise is $1.5 d (w/\bar{u})$ are

$$\bar{u}_c = 3 w \frac{r}{h_s} \quad (5.29)$$

$$\bar{x}_{\max.} = 0.01 \frac{Q'}{w r h_s} \quad (5.30)$$

For a large plant $\bar{u}_c$ may be 40 mph or more; so the maximum concentration predicted in Eq. 5.28 is rarely reached. Equations 5.27 through 5.30 best apply to about a half-hour average; peak concentrations for shorter averages may be higher owing to sustained eddies in the atmosphere. This is seen in the first three cases of Table 5.7 which shows some observed maximum ground concentrations expressed in terms of the dimensionless coefficient a in Eq. 5.28 for a buoyant source. Data are shown for ^{41}Ar at reactors in Oak Ridge, Tenn. (U. S. Weather Bureau, 1953), and in Harwell, England (Stewart, Gale, and Crooks, 1958), as well as for SO_2 at TVA plants. Since the TVA data involve multiple sources, observed concentrations were reduced by the factor plotted in Fig. 7 of Thomas,

Table 5.7—OBSERVED MAXIMUM GROUND CONCENTRATIONS IN NEUTRAL CONDITIONS

Plant	Type of average	Wind speed, m/sec	Height of wind-speed measurement, m	$\bar{u}_c$, m/sec	a
Oak Ridge	Peak 15-min average	6	47	10	0.019
	Average 15-min average	6	47	10	0.012
Harwell	Peak	12	35	11	0.012
	Peak 40-min average	5	1	11	0.006
TVA plant A	Peak 30-min average	8 to 12	55	17	0.006
TVA plant B	Peak 30-min average	9	67	18	0.007
TVA plant C	Peak 30-min average	12	98	20	0.005

Carpenter, and Gartrell (1963) showing maximum observed ground concentration vs. number of units operating.

In calm, stable conditions a buoyant plume rises to a limited height and stratifies, spreading horizontally over an increasing area. Fumigation occurs in the morning when convection due to ground heating builds up to the level of the stratified smoke and mixes it evenly down to the ground. Although highest ground concentrations usually occur during fumigation, as far as this author knows there is no quantitative model in the literature which predicts concentration at fumigation when there is no wind. Briggs suggested a simple model for a single source by assuming that during the inversion the smoke spreads horizontally at a constant rate of area increase and that this rate of spread is a function only of the buoyancy flux, F , and the stability parameter, s . Dimensionally, the area of spread must then be

$$b^{-1} F^{1/2} s^{-1/4} \Delta t \quad (5.31)$$

where Δt is the time over which the smoke accumulates in the stratified layer and s is determined from the nighttime lapse rate through the layer of plume rise. The constant of proportionality, b , is estimated from data discussed in the next paragraph to be of the order 0.05. During calm, stable conditions we use the appropriate plume-rise formula to predict stratification at the height

$$h = h_s + 5.1 F^{1/4} s^{-3/8} \quad (5.32)$$

If, at fumigation, the pollutant becomes evenly mixed down to the ground throughout the area of spread and edge effects are negligible, the con-

centration is given by

$$\bar{x}_{\max.} = b \frac{Q'}{F^{1/2} s^{-1/4} (h_s + 5.1 F^{1/4} s^{-3/8})} \quad (5.33)$$

Adequate data to test this formula do not exist, but the TVA observations were used to estimate b by assuming that a ground concentration of 0.1 ppm or more, occurring when the wind is not greater than 5 mph, is a case of fumigation. Since the temperature gradient at the plume level is not known, it was estimated from earlier TVA studies to be about $2.7^\circ \text{F}/1000 \text{ ft}$. Fortunately this factor is not very critical, e.g., if it were as much as $10^\circ \text{F}/1000 \text{ ft}$, b would be 30% smaller. Unfortunately the number of stacks, N , is greater than one at all three plants; so, for a conservative estimate of b , it was assumed that increasing N only increases the area of spread and does not affect the magnitude of concentration. This would be the case if the plumes merely displaced each other in spreading. The resultant estimates of b are shown in Table 5.8. Although this fumigation model looks promising, the assumption of a constant rate of horizontal spread is questionable and should be tested further.

In a valley of average width, W , and average drainage wind, $\bar{u}$, at night, we can use a simple channel model to predict fumigation downwind of buoyant sources that do not escape the valley. Assuming that the plume stratifies at the level given by the stable windy plume-rise formula and that it mixes evenly below this level at fumigation, we have

$$\bar{x}_{\max.} = \frac{Q'}{\bar{u} W [h_s + 2.6 (\bar{u}s/F)^{-1/2}]} \quad (5.34)$$

Table 5.8 — MAXIMUM GROUND CONCENTRATION OF SO₂ DURING FUMIGATION AT TVA PLANTS (30-MIN AVERAGES)

	Plant A	Plant B	Plant C
F, ft ⁴ /sec ³	23,000	31,000	67,000
h _s , ft	250	300	500
Q, tons/day	84	135	334
N (number of stacks)	8	4	2
Period of data	3/56 to 10/56	3/55 to 4/58	12/58 to 1/61
Number of fumigations	1	9	12
X _{max} , ppm	0.4	0.6	0.6
Calc. h, ft	1350	1500	1900
b	0.05	0.06	0.05

5.3 DEPOSITION OF PARTICLES AND GASES (Isaac Van der Hoven)

List of Symbols

Symbols used frequently in Sec. 5-3 on the deposition of particles and gases are listed here. (The dimensions mass, length, time, and temperature are abbreviated as M, L, T, and D, respectively. The equation number indicates the first appearance of the symbol.)

C _D	Drag coefficient (dimensionless), Eq. 5.35
C _y , C _z	Sutton's virtual diffusion coefficients (L ^{n/2}), Eq. 5.38
g	Gravitational acceleration (LT ⁻²), Eq. 5.35
h	Height of source above ground (L), Eq. 5.38
n	Sutton's parameter associated with stability (dimensionless), Eq. 5.38
Q', Q ₀	Initial source strength (MT ⁻¹), Eq. 5.38
Q' _x	Depleted source strength at a distance, x, from the source (MT ⁻¹), Eq. 5.42
r	Particle radius (L), Eq. 5.35
ū	Average value of the wind component in the direction of the mean horizontal vector wind (LT ⁻¹), Eq. 5.38
v _d	Deposition velocity (LT ⁻¹), Eq. 5.41
v _g	Fall velocity (LT ⁻¹), Eq. 5.35
λ	Mean free path of air molecules (L), Eq. 5.37

μ	Atmospheric dynamic viscosity (ML ⁻¹ T ⁻¹), Eq. 5.36
ρ	Particle density (ML ⁻³), Eq. 5.35
ρ _a	Atmospheric density (ML ⁻³), Eq. 5.35
σ _y , σ _z	Standard deviation of the distribution of material in a plume in the y and z directions (L), Eq. 5.44
$\bar{X}$	Average concentration (ML ⁻³), Eq. 5.38
ω	Amount of aerosol removed per unit time per unit area (ML ⁻² T ⁻¹), Eq. 5.39

5.3.1 Gravitational Settling

The earth's gravitational field plays an important role in the deposition of particulate matter on the earth's surface. The rate of descent of the particle depends upon a balance between the aerodynamic drag force and the gravitational force exerted by the earth. For a smooth spherical particle, neglecting the effect of slip flow, this balance may be expressed as

$$\rho_a v_g^2 C_D = \frac{8}{3} r g \rho \quad (5.35)$$

where the notation is as given in the list of symbols. Equation 5.35 cannot be solved directly for the fall velocity because the drag coefficient is an empirical function of the Reynolds number, Re, and therefore also of velocity. McDonald (1960) has conveniently plotted this empirical relation for Re ≥ 1.0 from which values of fall velocity vs. particle size can be computed. For the Reynolds number range between 10⁻⁴ and 10, the relation C_D = 24/Re may be used, and, since Re = 2ρ_av_gr/μ, Eq. 5.35 reduces to the familiar Stokes equation

$$v_g = \frac{2 r^2 g \rho}{9 \mu} \quad (5.36)$$

The effect of the slip flow upon the fall velocity is a function of the ratio of the mean free path of the air molecules to the particle size. It can be expressed by multiplying the fall velocity by a slip correction factor (Davis, 1945)

$$1 + \frac{\lambda}{r} \left[1.26 + 0.4 \exp \left(-\frac{1.1r}{\lambda} \right) \right] \quad (5.37)$$

where λ is primarily a function of altitude.

The effect of shape upon fall velocities is, on the average, to reduce the velocity by about $\frac{2}{3}$ from that of a smooth sphere. Smooth ellipsoidal particles theoretically will vary in fall velocities by factors ranging from 0.5 to 1.04.

At fall velocities less than about 1 cm/sec, the effect of sedimentation is negligible, and vertical movement of the particle is largely controlled by the larger vertical turbulent and mean air motions. Figure 5.4 (after Hage, 1964) shows the fall velocity of smooth spheres with a density of 5 g/cm³ as a function of the altitude and particle diameter, with inertia terms and slip flow corrections taken into account where significant. It can be seen that the predominant

Fig. 5.4—Fall velocity of smooth spheres with a density of 5 g/cm³ as a function of altitude and particle diameter (microns). (From Hage, 1964.)

factor affecting fall velocity is the particle size. Similar fall-velocity computations for a particle with a density of 2.5 g/cm³ are given by McDonald (1960a).

In the range where the sedimentation rate is significant, the vertical transport of an initially airborne particle (fall velocity greater than about 1 cm/sec) depends upon horizontal as well as vertical transport and diffusion. For fall velocities ranging from about 1 to 100 cm/sec, the diffusion of a cloud of particles under homogeneous horizontal transport (no wind shear with height) can be described by assuming that the particles are diffused according to a statistical diffusion model, such as that of Sutton (1953), and at the same time that they will settle with appropriate fall velocities. For the case of an elevated plume, the effect is essentially that of

the downward tilt of the plume center line, which can be expressed by replacing the constant height of the plume center line in the Sutton equation by a variable expression such that

$$\bar{\chi}(x,y,0) = \frac{2Q'}{\pi C_y C_z \bar{u} x^{2-n}} \exp \left\{ -x^{n-2} \left[\frac{y^2}{C_y^2} + \frac{(h - x v_g / \bar{u})^2}{C_z^2} \right] \right\} \quad (5.38)$$

With the assumption that the particles are removed (deposited) when they reach the ground—air interface, the deposition pattern can be described by the expression

$$\omega = v_g \bar{\chi}(x,y,0) \quad (5.39)$$

where ω is the amount removed per unit time per unit area and $\bar{\chi}$ is the volumetric concentration pattern of the air at the surface.

Van der Hoven (1963) used this tilted plume model to describe the observed deposition pattern of radioactive effluents and included a cloud depletion factor (Csanady, 1955) of

$$1 - \frac{1}{(1-n/2)(h_0 \bar{u} / x v_g - 1) + 2} \quad (5.40)$$

where n is one of Sutton's diffusion parameters. In practice the tilted plume model is only applicable in a well-mixed atmospheric layer, such as is typical of daytime adiabatic conditions within the lowest thousand meters.

The effect of horizontal wind-direction shear in the vertical becomes important as a diffusion mechanism if there is an initial distribution of particle sizes with height. With an initial cloud dimension of about 1000 m and particle fall velocities greater than 1 m/sec, the effect of turbulent diffusion on the ground deposition pattern can be neglected. The problem then becomes that of calculating particle trajectories using the appropriate fall velocity of each particle and the resultant wind vector of the atmospheric layer through which the particle falls. This technique as described by Kellogg, Rapp, and Greenfield (1957) has been applied primarily to the particle cloud resulting from surface nuclear-device detonations to calculate the fall-out pattern for the first few hours after detonation.

5.3.2 Dry Deposition

5.3.2.1 Deposition Velocity. The observed fact that the deposition rate of small particles onto the ground can be greater than can be explained by the appropriate gravitational fall velocity has focused attention on nongravitational and non-precipitation mechanisms, such as surface impaction, electrostatic attraction, adsorption, and chemical interaction. In analyzing the deposition of spores, Gregory (1945) concluded that the deposition rate was proportional to the immediate ground-level air concentration. Chamberlain (1953) defined the ratio of the deposition rate to the immediate ground-level air concentration as the deposition velocity, which, analogous to Eq. 5.39, can be stated as

$$\omega = v_d \bar{\chi}(x, y, 0) \quad (5.41)$$

The interesting feature of such a formulation is that by using it as an experimental tool to compute v_d through the field or laboratory measurement of ω and $\bar{\chi}$, we can apply it to gases and vapors as well as to small particles. It in no way explains the physics of the deposition mechanism, but nevertheless it is a convenient way to express the whole complex and little-understood dry-deposition phenomenon.

5.3.2.2 Cloud Depletion. To account for the depletion of an airborne cloud because of dry deposition, Chamberlain (1953) modified Sutton's equation so that the original source term, Q'_0 , was replaced by an effective depleted-source term, Q'_x . Thus, for a continuous source at ground level, the depletion factor was expressed by Chamberlain as

$$\frac{Q'_x}{Q'_0} = \exp \left(-\frac{4v_d x^{n/2}}{n\bar{u}\pi^{1/2} C_z} \right) \quad (5.42)$$

Using Eq. 5.41 and the modified Sutton equation, we can express the deposition rate per unit time per unit area for a source at ground level as

$$\omega = \frac{2Q'_0 v_d}{\pi\bar{u} C_y C_z x^{2-n}} \exp \left(-\frac{4v_d x^{n/2}}{n\bar{u}\pi^{1/2} C_z} \right) \times \exp \left(-\frac{y^2}{C_y^2 x^{2-n}} \right) \quad (5.43)$$

Chamberlain further expressed the depletion factor for the case of an elevated source. Cul-

kowski (1958) has presented graphical solutions to these equations.

The generalized Gaussian diffusion formula (in the notation used in Chap. 3) can also be modified for cloud depletion. The depletion correction for a continuous elevated source can be derived as follows:

$$\begin{aligned} \omega(x, y) &= v_d \bar{\chi}(x, y, 0) \\ &= \frac{v_d Q'_x}{\pi\sigma_y\sigma_z\bar{u}} \exp \left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2} \right) \right] \end{aligned} \quad (5.44)$$

where $\omega(x, y)$ is the surface deposition at (x, y) and Q'_x is the residual source at x meters downwind. The depletion of the source per unit distance is given by

$$\begin{aligned} \frac{\partial Q'_x}{\partial x} &= - \int_{-\infty}^{\infty} \omega(x, y) dy \\ &= - \left(\frac{2}{\pi} \right)^{1/2} \frac{v_d Q'_x}{\bar{u}\sigma_z} \exp \left(-\frac{h^2}{2\sigma_z^2} \right) \end{aligned} \quad (5.45)$$

which can be rearranged as

$$\int_0^x \frac{dQ'_x}{Q'_x} = - \left(\frac{2}{\pi} \right)^{1/2} \frac{v_d}{\bar{u}} \int_0^x \frac{dx}{\sigma_z \exp(h^2/2\sigma_z^2)} \quad (5.46)$$

If $Q'_x = Q'_0$ at $x = 0$, then

$$\ln \frac{Q'_x}{Q'_0} = - \left(\frac{2}{\pi} \right)^{1/2} \frac{v_d}{\bar{u}} \int_0^x \frac{dx}{\sigma_z \exp(h^2/2\sigma_z^2)} \quad (5.47)$$

and therefore

$$\frac{Q'_x}{Q'_0} = \left[\exp \int_0^x \frac{dx}{\sigma_z \exp(h^2/2\sigma_z^2)} \right]^{-(2/\pi)^{1/2} v_d/\bar{u}} \quad (5.48)$$

Since σ_z is not generally available as an analytical function of x in the generalized Gaussian form, the integral expression in Eq. 5.48 was evaluated numerically using the experimentally derived values of $\sigma_z(x)$ given by Hilsmeier and Gifford (1962). Figure 5.5 shows the depletion fraction, (Q'_x/Q'_0) , as a function of distance from the source, diffusion category (in terms of Pasquill types or the corresponding values of σ_θ as given in Chap. 4, Sec. 4-4.4), height of release, a deposition velocity of 1 cm/sec, and a mean wind speed of 1 m/sec. To obtain depletion fractions for other deposition velocities and wind speeds, we may use the expression

Fig. 5.5 — Source-depletion fraction, Q'_x/Q_0 , for a wind speed, $\bar{u}$, of 1.0 m/sec, a deposition velocity, v_d , of 10^{-2} m/sec, for source heights from 0 to 100 m above the ground and for various stability categories.

$$\left(\frac{Q'_x}{Q'_0}\right)_2 = \left(\frac{Q'_x}{Q'_0}\right)_1 \bar{u}_1 v_{d2} / \bar{u}_2 v_{d1} \quad (5.49)$$

where the subscript 1 refers to values found in Fig. 5.5 and the subscript 2 refers to the desired values. Thus, for example, to find the depletion fraction at a distance of 10^4 m for a source 50 m high, a $\bar{u}_2$ of 1 m/sec, a v_{d2} of 0.1 cm/sec, and a type F diffusion category, first find, in Fig. 5.5, the value of $(Q'_x/Q'_0)_1$ for $h = 50$ m, $x = 10^4$ m, $\bar{u} = 1$ m/sec, and $v_d = 1$ cm/sec: $(Q'_x/Q'_0)_1 = 0.50$. Now substitute this value in Eq. 5.49,

$$\left(\frac{Q'_x}{Q'_0}\right)_2 = (0.50)^{0.1} = 0.93$$

The Chamberlain and the generalized Gaussian depletion models assume that the shape of the concentration profile in the vertical is unaltered by deposition. In an approach suggested by Calder (1961), K theory diffusion equations (see Chap. 3, Sec. 3-2.1.2) were used to describe the effect of deposition on a plume. In models of this type, the reduction of concentration caused by removing material from the cloud is not distributed evenly through the depth of the cloud but depends upon the profile of vertical mixing. Therefore the shape of the vertical profile of concentration will change as the computation proceeds. Smith (1962a) schematically illustrates the effect for a case where $h = 0$, $v_g = 0$, $v_d > 0$, and the exchange coefficient is constant with height. The net result is a more rapid depletion of the bottom portion of the plume; so downwind from the source the height of the maximum concentration is above the surface and increases in the downwind direction. Definitive field measurements to evaluate the statistical depletion model and the K-theory depletion model are not yet available. Computations show that the statistical models (Eqs. 5.42 and 5.48) give higher depletion factors than the K-theory models under stable conditions.

5-3.2.3 Deposition Measurements. Among the important measurements of the deposition of radioactive vapors and aerosols are the pioneering efforts of Chamberlain (1960) at Harwell. He was concerned with the fission products formed in reactors or by nuclear detonations. The isotope ^{131}I was one of the more important fission products studied. Although liberated as a

vapor, ^{131}I is thought also to be adsorbed on condensation nuclei which are too small to have an appreciable gravitational settling velocity but which, nevertheless, deposit on surfaces under electrostatic, chemical, and other physical forces. Chamberlain's ^{131}I -vapor-release experiments were conducted both in the wind tunnel and in the free atmosphere and included simultaneous air concentration and deposition measurements on natural and simulated leaves and grass and on filter paper.

Recently, a series called Controlled Environmental Radioiodine Tests (Hawley, Sill, Voelz, and Islitzer, 1964) was conducted at the National Reactor Testing Station in Idaho to trace the radioiodine through the air-vegetation-cow-milk-human chain. The field results of both the Harwell and Idaho tests are summarized in Table 5.9a, which gives the existing meteorological conditions and the computed (from Eq. 5.41) deposition velocities for various collection surfaces. Similar results on the deposition of ^{131}I were obtained by Convair (1959, 1960) from the Fission-products Field Release Test I held in Idaho (NRTS) and Test II held in Utah (Dugway). Results are summarized in Table 5.9b. Chamberlain (1959) further computed an ^{131}I deposition velocity averaging 0.4 cm/sec on grass for the Windscale accident; Islitzer (1962) computed 0.2 cm/sec on sagebrush for the SL-1 accident, which occurred in the winter.

From these results one would conclude that the dry-deposition velocity of ^{131}I ranges over an order of magnitude and is dependent, to a large extent, upon the characteristics of the vegetation and ground surface. It is not clear if or how wind speed, thermal stability, or atmospheric turbulence affects the velocities. It is also possible that downwind distance has an effect because of a physical change in the iodine, for example, from a vapor to an aerosol. At present, without really having any information on the physical processes involved in the dry deposition of ^{131}I upon natural surfaces, a value of 2.0 cm/sec for grass or water surfaces appears appropriate as an average maximum, and somewhat smaller values ranging down to 0.5 cm/sec, for soil and snow surfaces.

The Convair (1959, 1960) studies essentially involved the release and downwind measurement of various radioactive isotopes from irradiated metallic reactor fuel elements, including isotopes of iodine, cesium, ruthenium,

Table 5.9a—SUMMARY OF ¹³¹I DEPOSITION FIELD EXPERIMENT RESULTS*

	Harwell tests							Idaho tests		
	1	2	3	4	5	6	7	I	II	Snow
Deposition velocity, cm/sec										
Grass	1.9	2.6	1.8	3.7	1.7	1.8	1.1	0.6	1.0	
Soil								0.8	0.4	
Snow										0.2
Carbon								0.6	0.7	0.9
Clover leaves			1.3	0.9	0.5		0.3			
Paper leaves			2.0	1.5	1.0		0.6			
Filter paper	0.6	0.7	0.9	0.6	0.3					
Sticky paper								0.2	0.4	0.6
Wind speed, m/sec	5.2	4.3	5.2	4.1	1.6	2.3	3.9	7.1	9.3	6.0
Friction velocity, cm/sec	48	35	48	38	15	20	26	61	69	50
Roughness length, cm	2.8	1.5	1.2	2.4	2.4	5.0	1.0	3.1	1.5	2.1
Downwind distance, m	15	20	20	20	20	100	100	300	375	340
Grass cover, g/m ²	500	200	260	420	420	610	420	153	246	Snow cover
Stability	Lapse	Neutral	Lapse	Lapse	Neutral	Lapse	Neutral	Lapse	Lapse	Stable

*Chamberlain, 1960, and Hawley, Sill, Voelz, and Islitzer, 1964.

Table 5.9b—SUMMARY OF CONVAIR ¹³¹I FIELD RELEASE TESTS*

	E	F	H	1	2	3	4	5	8	10	11
Deposition velocity, cm/sec											
Grass				2.1†						1.2‡	
Soil	0.5	1.4	0.5								
Sticky paper	1.1	0.7	1.5	0.4	0.3	0.1	0.2	0.2	0.3	0.2	0.6
Water	1.8†	2.3†	1.4†								
Wind speed, m/sec	6.8	5.3	4.0	5.0	4.2	3.2	2.4	4.4	2.7	2.6	4.4
Downwind distance, m	1,600	1,600	1,600	32,000	1,000	1,000	1,000	4,000	1,000	4,000	16,000
Stability	Lapse	Lapse	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable

*Convair, 1959, 1960.

†Downwind distance of 2000 m.

‡Downwind distance of 1000 m or less.

zirconium, cerium, niobium, and tellurium for which deposition-velocity calculations were made. Meteorological conditions included both adiabatic and stable lapse rates, and measurements of ground deposition and air concentrations were made to distances of 3200 m. Some sticky-paper measurements were made out to 3.2×10^4 m. All particles were less than 10μ in diameter. Table 5.10 summarizes the deposition-velocity calculations. Note that these values are averages and that there is considerable scatter in the data which cannot be explained by the meteorological parameters that were measured. For example, the average deposition velocity of 0.2 cm/sec for ¹³⁷Cs on a

grass surface was computed from 21 values ranging from 0.04 to 0.4 cm/sec.

Table 5.10—SUMMARY OF CONVAIR RADIONUCLIDE FIELD RELEASE TEST DEPOSITION VELOCITIES

	Deposition velocities, cm/sec			
	Water	Soil	Grass	Sticky paper
¹³⁷ Cs	0.9 (5)*	0.04 (15)	0.2 (21)	0.2 (117)
¹⁰³ Ru	2.3 (9)	0.4 (16)	0.6 (20)	0.4 (98)
⁹⁵ Zr, ⁹⁵ Nb	5.7 (6)	2.9 (6)		1.4 (10)
¹⁴¹ Ce				0.7
¹²⁷ Te, ¹²⁹ Te				0.7 (8)

*Number in parentheses indicates the number of determinations.

Another technique used in calculating deposition velocities is material-balance measurements such as performed by Islitzer and Dumbauld (1963) in their fluorescent-particle studies. The technique involves the determination of the mass flux of material through a vertical plane perpendicular to the mean wind direction. The downwind decrease of this flux is attributed to a material loss through deposition. Using uranin particles with a median diameter of 1μ and a fall velocity of less than 10^{-2} cm/sec, Islitzer and Dumbauld computed deposition velocities of 0.2, 2.4, and 7.1 cm/sec for inversion, neutral, and lapse conditions, respectively, for the arid terrain in Idaho. From data presented by Simpson (1961), these authors also computed a value of 0.5 cm/sec for four stable cases with zinc sulfide submicron particles over similar terrain at Hanford, Wash. These and other deposition data are quoted in a summary article by Gifford and Pack (1962).

Two conclusions seem apparent from the available field data on the deposition of vapors and submicron particles, i.e., that chemically active materials such as ^{131}I deposit more readily than inactive materials such as ^{137}Cs or nonradioactive fluorescent particles and that vegetation surfaces such as grasses and bushes provide removal rates that are greater than bare surfaces. At present, however, what effects atmospheric transport and diffusion parameters have upon deposition or what effect more complex surfaces, such as buildings and forests, have upon deposition rates is not clear.

5-4 THE CALCULATION OF PRECIPITATION SCAVENGING (Rudolf J. Engelmann)

5-4.1 Introduction

The scavenging process has three major divisions: (1) delivery or transport of the material to the scavenging site, (2) in-cloud scavenging by the cloud elements and precipitation, here called rainout and snowout, and (3) below-cloud scavenging by the precipitation, here called washout. Material from low-elevation sources will be transported with the low-elevation winds and diffused upward by low-level turbulence. Once in the vicinity of clouds

it may be carried into those clouds by organized vertical motions. When the material is from high elevations (the stratosphere), the general circulation of the earth's atmosphere and the exchange mechanism at the tropopause have control of the delivery.

There are several good starting points for the study of scavenging. Junge (1963) and Facy (1962) have looked at in-cloud scavenging but with differing conclusions. Fletcher (1962) and Mason (1957) have published texts on precipitation and cloud physics with comprehensive bibliographies. Chamberlain (1953) appears to have attempted the first broad application of scavenging equations, and his approach is still used. Fuchs (1964) has presented an extensive volume on the mechanics of aerosols. Reiter (1964) and Danielsen (1964) serve as introductions to the controversy on stratosphere-troposphere exchange. There is increasing interest in the scavenging problem, and the reader should be alert for the very probable future measurements of rain spectra, washout coefficients, scavenging efficiencies, and other parameters discussed later in the section.

List of Symbols

Symbols used frequently in Sec. 5-4 on precipitation scavenging are listed here. (The dimensions mass, length, time, and temperature are abbreviated as M, L, T, and D, respectively. The equation or section number indicates the first appearance of the symbol.)

A	Cross-sectional area of drop of diameter D (L^2), Eq. 5.54
a	Particle radius (L), Eq. 5.52
D	Drop diameter (the collector) (L), Eq. 5.52
d	Particle diameter (the collected) (L), Eq. 5.56
E	Scavenging efficiency (dimensionless), Eq. 5.53
F	Flux density of drops (drops/area-time-diameter interval), Eq. 5.54
K	Impaction parameter or Stokes number (dimensionless), Eq. 5.52
k_1	Concentration of contaminant in cloud water (M/L^3), Eq. 5.60
L/ρ	Fraction of cloud space filled with liquid water (dimensionless), Eq. 5.60

M	Mass of aerosol particle of diameter d (M), Eq. 5.56
N	Concentration of drops in air (drops/volume-diameter interval), Eq. 5.55
Q, Q'	Plume source strength (M, M/T), Eq. 5.62
Re	Reynolds number of waterdrop (dimensionless), Eq. 5.58
Sh	Nusselt diffusion number or Sherwood number (dimensionless), Eq. 5.57
T	Age of cloud (T), Eq. 5.61
t	Time (T), Eq. 5.50
U	Obstacle (raindrop) speed (L/T), Eq. 5.52
$\bar{u}$	Average value of the wind component in the direction of the mean horizontal vector wind (L/T), Eq. 5.64
Y	Diffusivity of a vapor in air (L ² /T), Eq. 5.57
α	Radioactivity per mass of particle (curies/g), Eq. 5.56
ϵ	Rainout efficiency, $1-(\chi/\chi_0)$ (dimensionless), Eq. 5.60
Λ	Washout coefficient (T ⁻¹), Eq. 5.51
μ	Dynamic viscosity of air (M/LT), Eq. 5.52
ν	Kinematic viscosity of air (L ² /T), Eq. 5.58
ρ	Density (M/L ³), Eq. 5.52
σ_θ	Standard deviation of horizontal-wind-direction distribution (radians), Sec. 5-4.11
σ_y	Standard deviation of plume concentration in the crosswind direction (L), Eq. 5.62
χ	Concentration of contaminant in air (M/L ³), Eq. 5.50
χ_0	Concentration at start of scavenging (M/L ³), Eq. 5.50
Ψ	Rainout coefficient (T ⁻¹), Eq. 5.50
ω	Deposition rate by washout or total deposition in accordance with dimensions of Q' or Q (M/L ² T or M/L ²), Eq. 5.62

5-4.2 Specification of the Problem

Quite obviously the intensity and location of the clouds and precipitation will determine the potential for scavenging and can usually be stated explicitly. However, fine details of the clouds and precipitation, such as entrainment, electrical charge, and snow-crystal shape, are

also important but generally impossible to specify.

The nature of the material to be scavenged is fully as important as the nature of the precipitation and should be specified as to size, if particulate, and to solubility, if gaseous. Density is important for at least the larger particles. Characteristics of electrical charge and wettability can be quite important, and these effects are yet under debate and investigation. With increasing time and distance from the source, all these characteristics are modified by agglomeration and by attachment and adsorption onto natural aerosols. The material should then assume the nature of this host.

Now the natural aerosol is not a well-defined parameter either, varying with elevation, geography, and meteorology. In his extensive treatment of natural aerosols, Junge (1963) presents model size distributions that may be used in the absence of local measurements (Fig. 5.6). Although little is known about the density of natural aerosols, Junge concludes, from chemical composition, that most have densities of 1.0 to 2.0 g/cm³.

The scavenging process consists of repeated exposures of particles and gases to cloud or precipitation elements with some chance of collection on the element for each exposure. The scavenging is, consequently, an exponential decay process obeying the equations

$$\chi = \chi_0 \exp(-\Psi t) \quad (5.50)$$

$$\chi = \chi_0 \exp(-\Lambda t) \quad (5.51)$$

where Ψ and Λ are called the rainout and washout coefficients, respectively. Because these coefficients are dependent upon many aerosol and scavenger characteristics, it is easier and generally as accurate to begin the solution of a problem by adjustment or modification of previously measured or predicted coefficients than with the more basic variables.

Note that Eqs. 5.50 and 5.51 and other equations in this section apply to instantaneous and space-averaged concentration fields but cannot apply to time-averaged concentrations since time is here used as an independent variable.

5-4.3 The Theory of Washout by Rain

When an obstacle (such as a raindrop) falls, it sweeps out a volume of air. This volume of air

Fig. 5.6—Model size distributions for atmospheric aerosols. Curve 1 represents values over a continent, curve 2, over an ocean (the part of this curve below 1μ is estimated), and curve 3, sea-spray component of the maritime aerosol. The hatched area between curves 2 and 3 represents the nonsea-spray component over the ocean. The straight lines indicate the shift of the continental log radius-number distributions due to particle growth by humidity for mixed particles of about 20% soluble material. (From C. E. Junge, *Air Chemistry and Radioactivity*, p. 124, Academic Press Inc., New York, 1963.)

must separate to allow the obstacle to pass, and particles therein will tend to follow the air. Owing to their inertia and electrical attraction and to molecular diffusion, however, some fraction of these particles will cross the streamlines of the air and intersect the obstacle. This fraction is the target or collision efficiency.

Contact with the obstacle does not ensure collection. Some particles may bounce off or be reentrained by the air. Of those particles making contact, the fraction remaining with the

obstacle is the coalescence or retention efficiency.

The product of the target efficiency and the retention efficiency is the collection efficiency, E , of the obstacle for the particles considered. If 50 of the 100 particles in the path of a raindrop contact it, but only 20 are washed out, then the target efficiency is 0.5, the retention efficiency is 0.4, and the collection efficiency is 0.2.

The target efficiency is often presented as a function of the impaction parameter, which is derived from the equation of motion of a particle with drag resistance. The impaction, or inertial, parameter is

$$K = \frac{4 a^2 \rho U}{9 \mu D} \quad (5.52)$$

where a is the particle radius, ρ is the particle density, μ is the dynamic viscosity of the air, and U/D is the ratio of obstacle speed to diameter. In the case of rain, U and D are related and μ is nearly constant, therefore, approximately,

$$E = f(a^2 \rho, D) \quad (5.53)$$

Langmuir and Blodgett (1945) have calculated the target efficiencies for spherical collectors in potential and viscous flow fields, and Langmuir (1948) has provided an interpolation formula between the two flow types. In the past it has been generally assumed that this interpolation formula was applicable for raindrops; however, later measurements and theoretical predictions (e.g., Pearcey and Hill, 1957) cast doubt upon this.

Langmuir and Blodgett's target efficiencies were calculated for point-sized particles and did not allow for collection of a finite-sized particle whose center missed the drop but whose edge made contact. It may be that, if even the edge of some kinds of particles touch the drop, coalescence or collection may result. If so, the Langmuir efficiencies will be low. They may be approximately corrected by assuming a larger raindrop cross section of $(D+2a)^2/D^2$; this factor is to be multiplied by the Langmuir point-particle efficiency.

The Langmuir target efficiencies of raindrops at a pressure of 785 mb collecting particles of unit density appear in Table 5.11. Conversion

for particles of another density or at another altitude is made by equating $a^2\rho$ or K for the two particles in compliance with Eqs. 5.52 and 5.53.

Das (1950) and Fonda and Herne (Herne, 1960) have considered the finite size of the particles in later calculations of target efficiencies. The interception effect is noticeable for small raindrops and large particles. After adding to the calculations made by Fonda and Herne, Mason (1957) applied the Langmuir interpolation for-

Table 5.11—COLLISION (TARGET) EFFICIENCY, E , FOR DROPS OF DIAMETER D FALLING THROUGH A CLOUD OF SMALLER DROPS OF RADIUS a *

D, mm	a, μ							
	2	3	4	6	8	10	15	20
0.03					0.092	0.269	0.500	0.643
0.05				0.050	0.277	0.411	0.613	0.724
0.08				0.205	0.394	0.510	0.690	0.782
0.14			0.035	0.340	0.500	0.608	0.750	0.834
0.2			0.133	0.418	0.564	0.660	0.793	0.862
0.3		0.010	0.245	0.498	0.631	0.713	0.829	0.887
0.4		0.085	0.326	0.564	0.684	0.756	0.859	0.908
0.6		0.213	0.425	0.643	0.749	0.810	0.892	0.929
0.8	0.040	0.303	0.500	0.698	0.793	0.849	0.919	0.950
1.2	0.121	0.355	0.530	0.731	0.827	0.876	0.939	0.963
2.0	0.140	0.358	0.535	0.738	0.834	0.886	0.944	0.966
2.8	0.168	0.360	0.534	0.735	0.840	0.890	0.950	0.970
3.6	0.117	0.288	0.456	0.680	0.800	0.865	0.935	0.965
4.8	0.075	0.220	0.372	0.606	0.743	0.823	0.920	0.950
6.0	0.050	0.170	0.306	0.546	0.690	0.785	0.900	0.940

*From I. Langmuir, *The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperatures Above Freezing*, *J. Meteorol.*, 5(5): 182 (1948).

mula. The resulting target efficiencies for unit-density particles at 900 mb appear in Table 5.12. Approximate conversion to other densities can still be made by equating $a^2\rho$ for the two particles and multiplying the appropriate tabular efficiency by $(D + 2a_2)^2/(D + 2a_1)^2$ to allow for the change in interception area of the particle. It may be argued that, because of the uncertainties introduced by unknown retention efficiencies and by Langmuir's interpolation formula, there is little purpose in choosing Mason's efficiencies over Langmuir's or in considering corrections to these efficiencies for interception areas.

The effect on retention efficiencies of variations in the wettabilities of particles is a very unsettled question. McDonald (1963) and Owe Berg (1963) have published articles on the subject. Not only the effects of partial wettabilities but the actual wettability of natural airborne particles as well are in need of further definition.

Even the coalescence of colliding water droplets is not assured. In the absence of wettability information, however, the assumption believed most likely to give correct results is that of perfect retention or coalescence. This is equivalent to equating target and collection efficiencies.

When airflow patterns other than viscous and potential are considered to exist about falling drops, calculated efficiencies can become very

Table 5.12—COLLISION (TARGET) EFFICIENCIES FOR DROPS OF DIAMETER D COLLIDING WITH DROPLETS OF RADIUS a AT 0°C AND 900 mb*

D, mm	a, μ							
	2	3	4	6	8	10	15	20
0.03	0.03	0.05					0	
0.05	0.01	0.02	0.05	0.23				
0.08	0.004	0.01	0.04	0.29	0.55			
0.14	0.02	0.03	0.11	0.40	0.65	0.83	1.12	
0.2	0.03	0.07	0.18	0.47	0.67	0.83	1.08	1.26
0.3	0.07	0.14	0.28	0.55	0.72	0.84	1.04	1.16
0.4	0.10	0.21	0.35	0.61	0.76	0.86	1.01	1.11
0.6	0.15	0.31	0.45	0.68	0.80	0.89	1.00	1.06
0.8	0.17	0.37	0.51	0.72	0.84	0.91	1.00	1.06
1.2	0.17	0.40	0.54	0.74	0.85	0.91	0.99	1.02
2.0	0.15	0.37	0.52	0.74	0.83	0.90	0.97	1.00
2.8	0.11	0.34	0.49	0.71	0.83	0.89	0.96	0.96
3.6	0.08	0.29	0.45	0.68	0.80	0.86	0.98	0.95
4.8	0.04	0.22	0.39	0.62	0.75	0.83	0.93	0.97
6.0	0.02	0.16	0.33	0.55	0.71	0.81	0.91	0.95

*From B. J. Mason, *The Physics of Clouds*, p. 424, Oxford University Press, Inc., New York, 1957.

different. Efficiencies greater than 1.0 are predicted and observed for spheres with wakes (Pearcey and Hill, 1957). Whereas Langmuir's interpolation formula predicts a rather flat maximum in E at a drop diameter of 1.2 mm, Kinzer and Cobb (1958) and Engelmann (1963) have observed a peak in E for drops of about 0.4 mm diameter (Fig. 5.7).

When E is known as a function of drop size, the washout coefficient for a particular aerosol size and density can be computed from

$$\Lambda = \int_0^\infty FEA \, dD \quad (5.54)$$

where A is the cross-sectional area of drops of diameter D and F is their flux density (drops/area-time-diameter interval). The flux density divided by the terminal velocity, U , yields the space density, $N(D)$, which is the form most frequently used in presenting measured rain spectra. Equation 5.54 may, therefore, be written as

$$\Lambda = \int_0^{\infty} \text{NUEA } dD \quad (5.55)$$

Russian authors call the product UEA the "co-efficient of capture" of the drop of size D for the particle considered. Table 5.13 gives the terminal velocity of waterdrops near sea level

Table 5.13—TERMINAL VELOCITY OF FALL FOR DISTILLED-WATER DROPLETS IN STAGNANT AIR AT 20°C, 760 mm, AND 50% RELATIVE HUMIDITY*

Equivalent drop diameter, mm	Terminal velocity, cm/sec	Equivalent drop diameter, mm	Terminal velocity, cm/sec
0.1	27	3.2	826
0.2	72	3.4	844
0.3	117	3.6	860
0.4	162	3.8	872
0.5	206	4.0	883
0.6	247	4.2	892
0.7	287	4.4	898
0.8	327	4.6	903
0.9	367	4.8	907
1.0	403	5.0	909
1.2	464	5.2	912
1.4	517	5.4	914
1.6	565	5.6	916
1.8	609	5.8	917
2.0	649		
2.2	690		
2.4	727		
2.6	757		
2.8	782		
3.0	806		

*From R. Gunn and G. D. Kinzer, *The Terminal Velocity of Fall for Water Droplets in Stagnant Air*, *J. Meteorol.*, 6(4): 246 (1949).

as measured by Gunn and Kinzer (1949). Because waterdrops with a diameter greater than 1.2 mm are flattened, the diameter of a sphere of the same volume is listed as the equivalent diameter.

The washout coefficient for the entire aerosol is calculated by integrating Eq. 5.54 over particle size. If the aerosol characteristic of interest is size dependent, this relation can be inserted into the integral. For instance, for radioactivity uniformly distributed throughout the mass of aerosol,

$$\Lambda = \alpha \int_0^{\infty} \int_0^{\infty} \text{FEAM } dD dd \quad (5.56)$$

where α is the activity per mass and M is the mass of the aerosol particle of diameter d .

Fig. 5.7—Scavenging efficiencies vs. drop diameter and $a^2\rho$ ($\mu^2 \text{ g/cm}^3$), where a and ρ are the radius and density of the particles. The zinc sulfide experimental curves (solid lines) are labeled with $a^2\rho$ and the diameter in microns. The prediction by Langmuir (1948), when interpolating between viscous and potential flows, and the measurements of Kinzer and Cobb (1958) are entered as dashed lines. Two data points of Walton and Woolcock (1960) are entered as solid squares. (From Engelmann, 1965.)

5-4.4 Rain Spectra

Numerous measurements of rain spectra have been made, and several empirical equations have been fitted to them. Although rain spectra usually have peak frequencies between diameters of 0.5 and 1.0 mm, most empirical equations cannot fit peak frequencies. The distributions of Marshall and Palmer (1948) and Best (1950) have been most widely used, but these give excessive numbers of small droplets.

Levin (1954) has shown that several empirical space-density formulas are approximated by portions of a logarithmic-normal distribution. This distribution can fit a peak and can be argued to have a theoretical basis. It approximates, for example, rains sampled by Kelkar (1959) in India and a shower sampled by Engelmann in the semiarid climate of Sunnyside, Wash. (after somewhat arbitrary allowance for evaporation of the falling drops). The latter spectrum, uncorrected for evaporation, is shown

in Fig. 5.8 together with selected Kelkar spectra. Sims, Mueller, and Stout (1965) found that spectra from several locations were best fit with logarithmic-normal functions, but the function parameters did not seem to be ordered with rainfall rate.

Fig. 5.8—Selected rain spectra on logarithmic-normal probability paper. The large circles represent a spectrum from a semiarid region of Washington. The remaining curves were measured by Kelkar (1959) in India.

Users of measured rain spectra should consider the effects of evaporation as the rain falls between cloud and ground. Evaporation reduces the sizes of all drops and the number of the small ones. Splash droplets from the ground and equipment around rain samplers and breakup of drops on the entrance edge of rain samplers will increase the apparent number of small droplets. The errors introduced in spectra by these and other effects can be very large and frequently are not adequately discussed when the spectra are published.

5-4.5 Calculated Particle Washout Coefficients for Rain

Chamberlain (1953) used Langmuir's efficiencies and Best's (1950) fitted spectra to calculate washout coefficients for various rainfall rates and particle (cloud droplet) sizes. These coefficients are given in Fig. 5.9 as a function of $a^2\rho$.

Similar calculations have been made by May (1958) using the somewhat higher efficiencies of Mason, but these give coefficients only about

10% greater than Chamberlain's. May measured washout coefficients in natural rain using spores ($a^2\rho = 320 \mu^2\text{g}/\text{cm}^3$) and found Chamberlain's predictions "substantially correct."

A different result is obtained using the efficiencies of Kinzer and Cobb with the Washington State and Indian spectra as shown in Fig. 5.10. The two lines were fitted by eye to the co-

Fig. 5.9—Washout coefficients for unit density particles vs. rainfall rate and $a^2\rho$. These calculations are based on Best's (1950) spectra and Langmuir's (1948) target efficiencies. (From A. C. Chamberlain, *Aspects of Travel and Deposition of Aerosol and Vapor Clouds*, British Report AERE-HP/R-1261, Fig. 1, Sept. 17, (1953).)

Fig. 5.10—Washout coefficients for $a^2\rho = 42$ only, calculated from spectra measured in Washington and India, using theoretical efficiencies from Mason (1957) and measured efficiencies of Kinzer and Cobb (1958).

efficiencies calculated for $a^2\rho = 42 \mu^2 \text{ g/cm}^3$. A slightly convex line could be used. Only the plotted points for Kinzer and Cobb efficiencies are shown to prevent confusion; less scatter exists with the calculation using Mason's efficiencies.

Even though the Kinzer and Cobb efficiencies are greater than Mason's for the more numerous small drops, the calculated washout coefficients are lower. This is due to the greater contribution to the cross-sectional scavenging area made by the larger drops, where Mason's efficiencies are larger than Kinzer and Cobb's. The slopes of the lines show that the washout coefficient for large particles varies with about the 0.75 or 0.8 power of the rainfall rate. There is, however, a large amount of scatter within a single shower and between storms.

The coefficients calculated from the Langmuir or Mason efficiencies may be regarded as slight overestimates in the absence of significant electrical charges on the rain. Both the measurement of lower coefficients (actually collection efficiencies) by Kinzer and Cobb and by Engelmann and the possibility of retention efficiencies less than one support this view.

For particles less than about 1μ in diameter, the calculations based only upon inertial effects in idealized flow patterns show negligible washout. They cannot be considered at all reliable, however, owing to the presence of electrical charges, which increase washout (e.g., see Bytner and Gisina, 1963). Solutions for selected particle and drop charges have been made by several workers (summarized by Fuchs, 1964), but there is insufficient information for safely extrapolating these predictions to other charge values. In addition, there is insufficient information on the normal charges existent in rain and clouds.

There are also no measurements on natural washout of these smaller particles although some current research plans do include them; e.g., Engelmann, Perkins, Hagen, and Haller (1966), and Georgii and Weber (1964). It is apparent that the problems of small-particle measurement, low collection efficiencies, and non-uniform raindrop charge will cause difficulty in the performance of these experiments.

5-4.6 Scavenging of Particles by Snow

There are no published scavenging coefficients, theoretical or measured, for snow. The

large numbers of frozen cloud droplets occasionally attached to snowflakes establish that snow is an effective scavenger for at least large particulates. This effectiveness will vary with type of crystal, its shape, fall speed, and electrical charge.

For the same rate of precipitation, we expect a greater scavenging of smaller particles by the slower feathery snowflake, with its larger area and probable electrostatic charge, than by its equivalent waterdrop. Large numbers of Aitken particles (diameter $< 0.02 \mu$) have been observed on snowflakes.

Hinzpeter's (1958) data show a lower specific radioactivity for snow water (about 0.4 to 0.6 as great as rainwater), at the same daily precipitation rates. The snow and rain were sampled at different times of the year, however, and the air activity has greater variation than this. Georgii and Weber (1964) found snow water to contain ammonia, nitrate, sulfate, and other ions at 1.7 to 2.9 times their concentration in rainwater. Reasoning that both precipitation types were originally snow within the cloud, they conclude that snow is a better scavenger than rain for these particles. Comparable results were found on radionuclides by Perkins and Engelmann (1966).

However, Facy (1962) suggests that the snowflake is less able to retain its scavenged materials and gases and will even reject material in its path during evaporation. Hinzpeter's data (1958) show increasing radioactivity in air following snow but decreasing radioactivity following rain. He interprets this as the release of adsorbed material when the flakes melt and evaporate on the ground.

In the absence of quantitative measurement in snow, the provision of specific scavenging coefficients for particulates is highly speculative. A few washout coefficients in rain and snow for submicron particles of silver iodide, scandium, and cesium salts have been published (Pacific Northwest Laboratory, 1967).

5-4.7 Scavenging of Gases by Waterdrops

Scavenging of gases is predicted on the basis of molecular diffusion to the drop or droplet in accordance with the vapor pressures and solubilities of the free and collected gases (Junge, 1963, Chamberlain, 1960, and Griffiths, 1963).

For fully soluble gases,

$$\Psi \text{ or } \Lambda = \int_0^\infty \pi Y \text{Sh} DN \, dD \quad (5.57)$$

where Y is the coefficient of molecular diffusion (or diffusivity) and Sh is the Sherwood (or Nusselt diffusion) number. The Sherwood number for spheres is approximately

$$\text{Sh} = 2.0 + 0.6 \text{Re}^{1/2} \left(\frac{\nu}{Y} \right)^{1/3} \quad (5.58)$$

where Re is the Reynolds number and ν is the kinematic viscosity of air. Because Eq. 5.57 is nearly linear in Y , scavenging coefficients for soluble gases are nearly proportional to their diffusion coefficients in a rain of given flux density. Theoretically trace quantities of insoluble gases may be treated as soluble in the scavenging process.

Figure 5.11 gives predicted coefficients for those gases* which are very soluble in water.

Fig. 5.11—Washout coefficients divided by diffusivity for soluble gases as predicted from various rain spectra.

The upper line in the figure is based upon the fitted spectra of Best, which overestimate the number of small drops. The lower three curves were calculated from the spectra reported by Sims, Mueller, and Stout (1965) for Majuro in the Marshall Islands, Island Beach, N. J., and Corvallis, Oreg. These were measured with a raindrop camera and may underestimate the number of small drops when the rain is light.

*Very small particles that are unaffected by electrical charges and impaction can be regarded as gases, and their washout can be estimated from Fig. 5.11.

The dashed curve was calculated from the Washington State and Indian spectra, which were taken using water-sensitive paper.

The dashed curve is recommended for precipitation rates up to at least 20 mm/hr. At higher rainfall rates use of the raindrop camera spectra in calculations yields greater scavenging. How much of the increase is due to splash and is therefore erroneous is unknown. Differences in rain spectra affect the washout coefficients for gases more than for particles.

Recent laboratory work (Booker, 1965, Friedman, Machta, and Soller, 1962) confirms theoretical predictions of the exchange of deuterated and tritiated water vapor with monodisperse waterdrops in saturated air.

Three measurements of the washout of bromine gas by Engelmann, Perkins, Hagen, and Haller (1966) also verify the theoretical predictions in rain. The only three measurements available for iodine gas, however, yielded washout coefficients one and two orders of magnitude lower than those predicted in Fig. 5.11 and showed no relation to precipitation rate.

Engelmann et al. propose that the reaction rate with water, rather than the total solubility, determines washout rates. Figure 5.11 should then be used only for gases with reaction rates comparable to that of bromine after adjustment for the diffusion coefficient.

5-4.8 Washout Coefficients for Gases in Snow

The washout of bromine and inorganic iodine was also measured in snow. The six measurements of each show a great deal of scatter, and it is not possible to conclude from these data how the coefficients are related to precipitation rate or crystal type. The values for bromine and inorganic iodine were on the order of $3 \cdot 10^{-8}$ and $5 \times 10^{-8} \text{ sec}^{-1}$, respectively, in powder snow of 0.2 mm/hr.

The lower coefficients in snow compared to rain support the importance of reaction rates. It appears that, although the large surface area and small terminal velocity of snow crystals may increase the scavenging of gases, these factors are not able to balance the lower adsorption rates on ice surfaces.

Washout coefficients for other gases with similar reaction rates should compare to those

of bromine and iodine as the ratio of their diffusivities in air.

5-4.9 Washout Coefficients for Process-plant Iodine

A much higher washout rate was observed when process-plant inorganic radiiodine was used as a tracer (Engelmann, Perkins, Hagen, and Haller, 1966). Figure 5.12 shows three data points for columnar snow crystals, two for wet

Fig. 5.12—Washout coefficients for inorganic iodine in process-plant stack gases in rain and snow. (From Engelmann, Perkins, Hagen, and Haller, 1966.)

agglomerates of spatial dendrites, and two for rain. The data points for rain are nearly 10 times higher than the theoretical predictions for soluble gases from Fig. 5.11.

In explanation of the high washout, it was noted that there was sufficient water vapor in the plant stack exhausts to produce a cloud of water droplets on a rainy day. If all the radioiodine (or other gas) in the stack exhausts were swept up by the cloud droplets during formation, subsequent washout of the iodine would be at the rate appropriate to cloud drops. Theoretical rain-scavenging rates of uncharged 20- and 40- μ -diameter cloud drops are shown in Fig. 5.12. Lines of slope 1.0 have been drawn through the data for snow for the assumption that increases in snowfall rate are due to increases in the number of crystals falling.

Similar washout rates may be expected for reactive gases in other stack exhausts with high

water content. Again, reaction rates may influence the takeup during the condensation. In these tests washout coefficients for organic forms of iodine were about 1% as large as for the inorganic forms.

5-4.10 Rainout (In-cloud Scavenging)

Collection due to inertia becomes insignificant with small droplets in viscous flow and with very small particles. It is then necessary to use electrical effects, nucleation, diffusiophoresis, Brownian motion, and velocity gradients to explain rainout. These effects are also small, and calculations of rainout, such as those by Greenfield (1957), Junge (1963), and Chamberlain (1960), show long residence times for aerosols in nonfalling clouds. This is especially true in the aerosol range of 0.1- to 0.4- μ diameter, for which there seems to be no adequate scavenging mechanism.

Cloud elements do fall, however, and it may be that the inertia of a fine particle is sufficient to carry it into the boundary layer of the falling cloud element, where weak forces have opportunity to complete the collection. Facy (1962) considers the value of E in clouds to be at least 1.0. This yields high values for the rainout coefficient in the equations

$$\Psi = \int_0^\infty FEA \, dD \quad (5.59)$$

$$\chi = \chi_0 \exp(-\Psi t) \quad (5.50)$$

Byutner and Gisina (1963) have calculated rainout coefficients in clouds composed of 100 drops per cubic centimeter, 10 μ in diameter. They assumed charges of 5×10^{-7} esu on the cloud droplets and 4.8×10^{-10} esu on ash particles and calculated separate coefficients for the several effects operating. The coefficients cannot be added together to obtain a total coefficient, but their values indicate that a minimum total rainout coefficient of about $3 \times 10^{-5} \text{ sec}^{-1}$ occurs near the 0.2- μ particle diameter. This corresponds to an efficiency of 0.1, which is less than 1.0 but quite significant. Smaller cloud drops will have higher efficiencies but may have lower flux densities.

Junge introduces the equation

$$k_1 = \chi_0 \epsilon \frac{\rho}{L} \quad (5.60)$$

where k_1 = aerosol per volume of cloud water
 χ_0 = aerosol per volume of unwashed air
 ρ = density of water
 L = mass of condensed water per cloud space volume
 ϵ = rainout efficiency, or $1 - (\chi/\chi_0)$

In Eq. 5.50 t is the time the air parcel is within the cloud. With this equation, the cloud air would eventually be cleansed, and ϵ would approach 1.0. Since most clouds entrain new air continuously, however, the aerosol contained in the cloud water increases as long as solubility allows and may be better represented by

$$k_1 = \chi_0 \Psi T \frac{\rho}{L} \quad (5.61)$$

where T , the age of the cloud, is different from t .

The parameter ΨT at the onset of precipitation is quite possibly a characteristic of the cloud type since the cloud elements also grow by aerosol-collection processes. Both ϵ and ΨT can be estimated from measurements of χ_0/k_1 and estimates of L . The proper choice for L is debatable since it varies greatly with cloud type and precipitation amount, but reasonable values can be chosen which will keep ΨT or ϵ in the range 0.5-1.0. Table 5.14 lists such values.

The value of k_1 must be adjusted to allow for evaporation of the precipitation element as it falls. Aerosol scavenged or lost in the air below the cloud must also be added to k_1 . These ad-

justments are implicit in the data of Small (1960) and Hinzpeter (1958) since their measurements were taken from air near the ground.

Because of the complexity of in-cloud scavenging, it would seem that particulate scavenging by rain and snow cloud elements is currently best estimated from data of the type given in Table 5.14. However, the near certainty that χ_0 varies with elevation must be considered when such data are used. As yet, little is known about the height variation of entrainment of outside air into convective clouds (aufm Kampe and Weickmann, 1957); also the height of the cloud water that contributes to the precipitation is uncertain.

5.4.11 Treatment of Precipitation Climatology

Preceding sections have provided the means of predicting scavenging when the precipitation characteristics are specified. We have considerable latitude when applying these techniques to uncertain future precipitation, and how we make this application will depend upon the particular problem at hand. We will now discuss, in general terms, the introduction of precipitation climatology into the applied problems.

A wide variety of prediction forms can be made according to the forms of the precipitation climatology and the contamination description.

Table 5.14—SELECTED MEASUREMENTS OF SURFACE AIR TO PRECIPITATION ACTIVITY RATIOS AND VALUES OF CLOUD-WATER CONCENTRATION CHOSEN TO PRODUCE RAINOUT EFFICIENCIES BETWEEN 0.5 AND 1.0

Data source	χ_0/k_1	k_1/χ_0	L/ρ	ϵ or ΨT
Small* (Norway)				
October 1956	0.25×10^{-6}	4.0×10^6	0.25×10^{-6}	1.0
September 1959	2.06	0.47	2.0	0.95
Average (3 year)	0.9	1.1	0.9	1.0
Hinzpeter† (Germany)				
Rain, mm/day				
0.1	0.8	1.25	0.5	0.62
1.0	1.4	0.71	1.0	0.71
10.0	2.5	0.40	2.0	0.8
Snow, mm/day (water equivalent)				
0.15	0.9	1.1	0.5	0.55
1.0	1.6	0.62	1.0	0.62
10.0	3.4	0.29	2.0	0.59

*S. H. Small, 1960.

†Hinzpeter, 1958.

For instance, we can obtain total washout-area isopleths, maximum possible washout—total or rate, return periods for washout rates, joint probabilities of accidental release and specified scavenging rates, and mean yearly and seasonal washout and rainout for continuous releases.

Unfortunately the accuracy of the estimated washout coefficient will usually be so poor as to allow the assumption that Λ is linearly related to the precipitation rate. In this case the washout can be estimated from the total depth of rain or snow. Area-depth relations (e.g., Court, 1961) can be superimposed on the predicted contaminant distribution to obtain total washout-area isopleths.

The reader is by no means restricted to considering area isopleths. Often a problem consists in determining whether some total deposition can be exceeded, and for this the center-line or peak exposure and the expected total depth of precipitation are sufficient.

Special consideration must be given to the climatology of plume widths, turbulence, and wind speeds during precipitation. At many locations the wind direction during precipitation differs noticeably from the mean direction for all weather types. The new region likely to be affected may be very significant in hazards appraisals.

In the special case of horizontally uniform precipitation over a continuous plume, the washout area may be obtained mathematically (U. S. Weather Bureau, 1955). Culkowski (1963) and Guthrie and Nichols (1964) have calculated the maximum washout possible at one particular distance with a rain that starts as soon as (or earlier than) the release. This washout rate for the Gaussian plume model* is

$$\omega_{\max} = \frac{Q'}{e x \sigma_y (2\pi)^{1/2}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \quad (5.62)$$

where ω is the maximum washout rate ($\text{ML}^{-2}\text{T}^{-1}$) for source strength Q' (MT^{-1}) [or total washout (ML^{-2}) for Q (M)].

*Owing to the practical difficulty of specifying the instantaneous concentration distribution in a plume from a continuous source, the instantaneous concentration must be estimated from the continuous-source equations and considered as an effective instantaneous concentration. Since the reader will likely deal with washout rates averaged over time, this should present no problem.

When calculating maximum possible washout, one must remember that the length of release and the duration of washout are often not the same. The washout rates at some distance from a source are generally greater when there is little or no intermediate precipitation.

The washout rate for precipitation just beginning is

$$\omega_0 = \Lambda \int_0^z \chi(x, y, z, Q') dz \quad (5.63)$$

The upper limit for this integral is the height from which the rain falls. For the Gaussian plume model, Eq. 5.63 becomes

$$\omega_0 = \frac{\Lambda Q'}{\bar{u} \sigma_y (2\pi)^{1/2}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \quad (5.64)$$

Equation 5.64 assumes that the plume does not lean with elevation because of wind-direction shear.

If the rain cloud is stationary while the contaminant is moving, Eq. 5.64 will continue to apply on the upstream side of the rain cloud. Because of this, the continuous introduction of new material to an orographic precipitation cloud may result in washout rates that do not decrease in time. In this way Fuquay (1963) has explained greater radioactivity in the snow found on western mountain slopes.

Normally χ must be modified to account for previous scavenging upstream from x , which can easily reach 50% in 10 miles of rainfall. For instance, if the precipitation extends upstream to the source, Eq. 5.64 is modified to read

$$\omega = \frac{\Lambda Q'}{\bar{u} \sigma_y (2\pi)^{1/2}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{\Lambda x}{\bar{u}}\right) \quad (5.65)$$

from which Eq. 5.62 was derived.

In Eq. 5.65 the two washout coefficients are not necessarily the same. The first applies to the current precipitation, and the second, to the earlier precipitation extending back to the source. The area within a washout isopleth according to Eq. 5.65 has been obtained by numerical integration, and these results are presented in Figs. 5.13, 5.14, and 5.15 for three values of the stability parameter $\sigma_\theta \bar{u}$ (Chap. 4, Sec. 4-4.2.2) as a function of both the current and upstream washout coefficients.

Fig. 5.13—Area (divided by wind speed) within a current washout isopleth for various earlier washout rates. The curves are based on a Gaussian plume model with the crosswind concentration distribution determined from $\sigma_\theta \bar{u} = 0.4$ m/sec (see Chap. 4, Sec. 4-4.2.2 for a discussion of the quantity $\sigma_\theta \bar{u}$). The use of this diagram is explained in the text.

Fig. 5.14—Same as Fig. 5.13 but for $\sigma_\theta \bar{u} = 1.2$ m/sec.

As an example of the use of these figures, suppose that it had been snowing lightly for some time but that the snow had now intensified considerably. The reader wishes to know the area within a particular washout isopleth for the current stability and precipitation. He chooses the figure appropriate to the existing value of $\sigma_\theta \bar{u}$, then on the left side of the graph finds the value of ω/Q' of interest divided by the current wash-

out, $\Lambda/\bar{u}$. He then moves his pointer to the curve labeled with the earlier washout, then down to the scale marked $\text{area}/\bar{u}$. He multiplies this by $\bar{u}$ to obtain the area of the washout isopleth in square meters.

As a matter of interest, the calculations have also been made for the plume described by

$$\sigma_y = 0.2 x^{0.8} \quad (5.66)$$

Fig. 5.15—Same as Fig. 5.13 but for $\sigma_\theta \bar{u} = 3.0$ m/sec. Fig. 5.16—Same as Fig. 5.13 but for $\sigma_y = 0.2x^{0.8}$.

(where σ_y and x are given in meters) and are shown in Fig. 5.16. Equation 5.66 is a composite of experimental data for 30-min releases at Hanford, Wash.

Comparison of the figures will show that the area is not only quite dependent upon the earlier washout coefficient but also upon the stability parameter. Some study of the climatology of $\sigma_\theta \bar{u}$ (or of σ_θ) vs. $\Delta/\bar{u}$ should therefore be made

before the figures are used in hazards appraisals.

5-4.12 Summary and Conclusions

Chamberlain's predicted washout coefficients in rain for particles larger than 1μ in diameter (Fig. 5.9) are considered to be slight overestimates. In the case of particles smaller than 1μ ,

it is generally agreed that washout by rain is insignificant. This theory cannot be considered reliable for smaller particles, however, owing to uncertain electrical effects, and quantitative measurements of this washout are not yet available.

The washout of reactive gases can be predicted by using the theory of molecular diffusion to waterdrops. Newly calculated washout coefficients based on measured rain spectra rather than on fitted spectral equations are presented and recommended (Fig. 5.11). The prediction of washout of gases by snow must rely upon a few measurements for bromine and iodine gas since there are no theoretical predictions. In all cases the reaction rate of the gas with the rain or snow must be considered.

Snow apparently has about the same to three times the effectiveness of rain at the same precipitation rate for both washout and rainout of particles. However, definitive measurements are greatly needed.

Research is still inadequate on many of the complex in-cloud scavenging processes. Formal mathematical predictions of rainout due to various mechanisms are interesting but not decisive. It is therefore recommended that simultaneous measurements of contaminants in air and precipitation (e.g., Table 5.14) be used for prediction of rainout.

The manner in which the washout coefficient, Λ , and the ratio of surface air to precipitation activity, χ_0/k_1 , vary with storm and cloud type is unknown. Therefore recommended values of Λ and χ_0/k_1 may be directly combined with precipitation rates to predict scavenging rates.

5-5 GAS DIFFUSION NEAR BUILDINGS

(James Halitsky)

5-5.1 Introduction

The use of conventional diffusion formulas for the calculation of concentration fields produced by sources on or near buildings often gives misleading answers. Such formulas contain the implicit assumption that the flow field has straight streamlines that are parallel to each other and to the ground. Although this is reasonably accurate for flow over level uniformly rough ground, we know that flow near buildings contains curved

streamlines, sharp velocity discontinuities, and highly nonhomogeneous and nonisotropic turbulence. The complexity of these fields is so great that analytical solutions of the differential diffusion equation in this context are not likely to be found in the near future. Computer solutions may, however, prove feasible when sufficient experimental data are collected to document the flow field in detail.

At the present time the optimum procedure for estimating concentrations near buildings is to obtain experimental data for a few configurations, to interpret such data in accordance with diffusion theory and flow-field fact and theory, and to extrapolate the data to other configurations. The following sections describe the current state of development along these lines.

The descriptions of the flow near structures are based upon observations of smoke patterns described in a variety of cited references as well as in many unreported experiments. The interpretation of the generating mechanism for the composite flow is a synthesis of a number of well-known explanations of aerodynamic phenomena described in such standard texts as Schlichting (1960). Most of the experimental data on concentrations close to buildings were obtained in low-turbulence wind tunnels; the extrapolation of such data to the full-scale natural atmosphere will introduce some unavoidable error. Nevertheless wind-tunnel tests will probably continue to be the principal source of data for these problems, and methods for reducing the error analytically or by modification of the test procedure will be required. For this reason a discussion on scaling criteria peculiar to flow near buildings will be presented. Sections 5-5.5, "Experimental Data on Concentrations near Buildings," and 5-5.6, "Applications," will be of particular interest to those concerned with practical pollution problems.

It should be understood that the study of diffusion near buildings is in its infancy and much work is needed to validate and refine the material presented herein. Until that time it is suggested that the data and calculation procedures be viewed as approximations suitable for preliminary estimates of mean concentration fields.

List of Symbols

Symbols used frequently in Sec. 5-5 on gas diffusion near buildings are listed here. (The

dimensions mass, length, time, and temperature are abbreviated as M, L, T, and D, respectively. The equation, figure, or section number indicates the first appearance of the symbol.)

A	Reference area (L^2), Sec. 5-5.3.1	T_e	Temperature in effluent aperture (D), Eq. 5.24
A_e	Area of effluent aperture (L^2), Eq. 5.74	T_j	Temperature in jet (D), Fig. 5.24
C_h	Total-pressure coefficient (dimensionless), Fig. 5.24	T_1	Maximum temperature in flow field (D), Eq. 5.78
C_p	Static-pressure coefficient (dimensionless), Sec. 5-5.2.1.4	t	Time (T), appears in various equations
C_y, C_z	Sutton parameters ($L^{3/2}$), Eq. 5.72	u_a	Velocity along axis of cavity (LT^{-1}), Sec. 5-5.2.2.1
D	Dilution (dimensionless), Eq. 5.73	V	Reference velocity (LT^{-1}), Sec. 5-5.2.2.1
D_0	Diameter of sphere or cylinder (L), Sec. 5-5.2.2.3	V_e	Velocity in effluent aperture (LT^{-1}), Sec. 5-5.2.3
d	Distance normal to a surface (L), Eq. 5.85	V_i	Velocity at air-intake aperture (LT^{-1}), Sec. 5-5.3.1
Fr	Froude number (dimensionless), Eq. 5.80	V_j	Velocity in jet (LT^{-1}), Fig. 5.24
Fr'	Modified Froude number (dimensionless), Eq. 5.81	v_*	Friction velocity (LT^{-1}), Sec. 5-5.5.2
f	Frequency (T^{-1}), Sec. 5-5.4.1	z_0	Roughness height of ground surface (L), Sect. 5-5.2.2.2
H	Characteristic height (L), Sec. 5-5.2.2.2	μ	Dynamic viscosity ($ML^{-1}T^{-1}$), Eq. 5.78
i	Local turbulence intensity = σ/u (dimensionless), Sec. 5-5.3.1	ν	Kinematic viscosity (L^2T^{-1}), Sec. 5-5.6.1
K_c	Concentration coefficient (dimensionless), Eq. 5.71	ρ	Density (ML^{-3}), Eq. 5.78
K_{ce}	Concentration coefficient at effluent aperture (dimensionless), Eq. 5.73	$\sigma_u, \sigma_v, \sigma_w, \sigma_q$	Root-mean-square velocity fluctuations (LT^{-1}), Sec. 5-5.2.2.1
k	Von Karman's constant (dimensionless), Sec. 5-5.5.2	σ_θ	Root-mean-square lateral-gust angle (deg or radians), Sec. 5-5.4.1
L	Reference length (L), Eq. 5.67	φ	Angle between upwind axis and radius of a sphere or cylinder (deg or radians), Sec. 5-5.2.2.3
M	Coefficient in Clinical Center dilution formula (dimensionless), Eq. 5.87	$\bar{\chi}$	Time average concentration [M/L^3 or $L^3(L^{-3})$], Eq. 5.71
n	Sutton parameter (dimensionless), Eq. 5.72	$\bar{\chi}_e$	Time average concentration in the effluent aperture M/L^3 or $L^3(L^{-3})$, Eq. 5.73
p	Pressure ($ML^{-1}T^{-2}$), Fig. 5.21		
Q'	Source strength (L^3T^{-1} or MT^{-1}), Eq. 5.71		
q	Resultant local velocity = $(u^2 + v^2 + w^2)^{1/2}$ (LT^{-1}), Sec. 5-5.2.2.1		
Re	Reynolds number (dimensionless), Sec. 5-5.2.2.3		
r	Radial-length coordinate = $(y^2 + z^2)^{1/2}$ (L), Sec. 5-5.2.2.1		
r_w	Radius of wake boundary (L), Eq. 5.67		
s	Curvilinear longitudinal length coordinate (L), Eq. 5.86		
T	Temperature of the background flow (D), Eq. 5.78		

Overbar ($\bar{}$) represents mean value
 Prime ($'$) represents fluctuation
 Asterisk ($*$) represents prototype

5.5.2 Structure of Flow Fields near Buildings

5.5.2.1 Origin and Characteristics of Flow Zones.

5.5.2.1.1 Aerodynamic Distortion. In discussing flow around buildings, we will, for convenience, establish a background flow from which deviations caused by the presence of the building can be measured. For the atmosphere we will assume that neutral stability conditions exist over flat ground of wide extent and produce

a logarithmic mean velocity profile, homogeneous turbulence, and uniform pressure. For the wind tunnel we will assume a uniform mean velocity profile, negligible turbulence, and uniform pressure.

The introduction of a building into either of the background flows causes a change in the velocity and pressure fields. The new fields will be called aerodynamically distorted, and the amount of distortion will be measured by the difference between the distorted and the background properties. It is characteristic of aerodynamically distorted fields that distortions decay with distance from solid surfaces. For practicability we will assume that velocity distortions less than 5% of the local background velocity or pressure distortions less than 10% of the local background dynamic pressure do not exist. These assumptions effectively limit the extent of the distorted field, which may now be considered as enclosed by an imaginary isolating surface. The isolating surface of a building on the ground resembles a bubble canopy. The isolating surface of a suspended object completely encloses the object in an ellipsoid-like shell.

Figure 5.17 shows the principal characteristics of the flow field near a sharp-edged building oriented with one face normal to a wind stream with little turbulence. The back-

ground flow is shown at station 1. The region of aerodynamic distortion, lying between the solid and isolating surfaces, has three zones: the displacement zone, the wake, and the cavity. The formation of the displacement zone is intuitively evident since the air must be displaced around the solid building. The formations of the wake and cavity are less evident; they result from the aerodynamic phenomenon of separation.

5-5.2.1.2 Separation and Wake Formation. Separation occurs when fluid in a boundary layer that is initially moving parallel to a solid surface suddenly leaves the surface and moves out into the flow field. The cause of separation is thought to be the loss of kinetic energy in the boundary layer, the loss being amplified when the pressure gradient is positive, i.e., when pressure increases in the direction of flow.

In flow around buildings the adverse pressure gradient is very important in fixing the location of the line of separation. At the onset of fluid motion, the pressure gradient is established by a quasi-potential flow that follows the contours of the building. In Fig. 5.17, for example, the pressure is high in the stagnation region near the center of the upwind face and diminishes and becomes negative near the roof and side edges. At the edges the flow bends sharply to adhere to the roof and side walls

Fig. 5.17 — General arrangement of flow zones near a sharp-edged building.

and thereby experiences high local centrifugal forces and extremely low pressures. After passing the edges the fluid streamlines straighten out, the centrifugal forces disappear, and the pressure rises. Therefore the pressure gradient is negative on the upwind face but becomes highly positive on the roof and side walls just downwind of their leading edges. Accordingly, the fluid adheres to the upwind face but separates from the building at the edges and continues its radially outward motion.

The character of the flow field after separation (which occurs almost immediately after onset of motion) is determined by the properties of the boundary layer at the periphery of the upwind face: outward directed momentum, low static pressure, and high vorticity. These properties are retained by the separated layer, which in its new role as a free jet in a transverse wind bends over downwind in a parabolic shell enclosing the building. If at this stage the fluid were to lose its viscosity and the separated layer were to lose its vorticity, the resulting flow field would be described as a classical wake in a potential flow. The speed and static pressure would be constant everywhere in the layer downwind to infinity. Between the layer and the solid surface (ground or building), the fluid would be completely stagnant, and the static pressure would be constant and equal to the layer pressure. On the other side of the separated layer, a potential flow would exist with velocities and pressures varying continuously from those of the layer to those of the background flow.

In a real, viscous, turbulent fluid, the classical wake cannot be achieved because the momentum in the separated layer diffuses into the wake and quasi-potential flow, sets the wake fluid in motion, and smooths out the sharp velocity discontinuity. Consequently the wake boundary is difficult to locate precisely. We will set the boundary on the imaginary surface along which the mean velocity is 95% of the local background-flow velocity and the velocity gradient is positive radially outward.

5-5.2.1.3 Cavity Formation. The viscous shears on the periphery of the initially stagnant wake cause the wake fluid to move downwind and thereby induce a return flow along the ground to replace the lost fluid. A toroidal circulation develops in the upwind portion of the wake, dividing it into two distinct subregions

separated by the streamline d-k-l-h in Fig. 5.17. Fluid above and to the right of this streamline moves downwind continuously. Fluid in the closed region d-k-l-h-g-f-e-d recirculates. If it were not for diffusion transverse to streamlines, contaminants released into this region would be trapped, and concentrations would build up. Even with diffusion the level of concentration attained in many practical cases is high. Therefore the region is sufficiently important to be given a name. It has been called, variously, a bubble, an eddy zone, and a cavity. The term "cavity" will be used since it conveys the impression of a low-pressure hole in the wake. The term should not be confused with the classical cavity, which is the name given a classical liquid wake that has undergone a change of phase by virtue of low static pressure.

5-5.2.1.4 Velocities and Pressures. The mean flow characteristics of the displacement zone, the wake, and the cavity are given by the mean velocity profiles of Fig. 5.17. At station 2, moving from the free stream toward the building, the velocity is seen to increase to a maximum at m, reduce to zero at some point in the cavity, increase again to a smaller reverse maximum, and then decrease to zero at the roof. The same pattern occurs at station 3, but the maximum is not as high, and the gradients are less severe. At station 4 the flow is downwind everywhere, never exceeds the velocity in the background flow, and has a marked velocity defect near the ground in the vicinity of stagnation point h. At station 5 the velocity defect diminishes, but the height of the region of reduced velocity is greater.

The static-pressure coefficient C_p (local pressure change/nominal background-flow dynamic pressure) is negative at the separation edge, point d, remains constant along the separation streamline to point m, then increases gradually to zero at point o, and remains zero downwind. The static-pressure variation along the cavity boundary is a gradual rise from point d to a maximum (but still negative) value at stagnation point h. The static pressures within the cavity are lower than on its boundary. Outside the cavity, on a line downwind from h, the static pressure rises rapidly to the free-stream value.

Turbulence in the aerodynamically distorted region may originate either in the background flow or in the separated layer, or both. Close

to the building it seems likely that building-generated turbulence is predominant. As noted previously, the separated layer has a large amount of vorticity, created when the layer was still attached to the building. After separation the layer becomes unstable and breaks up into a vortex sheet consisting of discrete eddies that grow as they travel downwind. The smaller eddies transport momentum across streamlines, thereby smoothing the velocity discontinuity. Somewhat larger eddies are shed periodically, producing oscillations in the wake boundary. Very large eddies migrate down into the cavity, producing intermittent strong gusts. Farther downwind, building-generated turbulence has decayed and enough distance has been traversed for eddies in the background flow to have migrated well into the wake.

The interaction of the two types of turbulence has not been studied systematically. A few experiments (Halitsky, Magony, and Halpern, 1965) on flow downwind of a model of a mountain ridge in the wind tunnel with high and low turbulence in the background flow indicate that the aerodynamically generated turbulence intensity decays with distance from the ridge in the same manner in both cases, but the decay terminates when the intensity reaches that of the background flow. Therefore the dimensions of an aerodynamically distorted region, as determined by excess of turbulence over that of the background flow, appear to vary inversely with background-flow turbulence.

5-5.2.2 Flow near Characteristic Structures.

5-5.2.2.1 Suspended Flat Plate. The suspended flat plate is not a structure encountered in practical diffusion problems, but its flow field has been explored more thoroughly than those of buildings on the ground, and the test results are useful guides to the general magnitudes of velocities, pressures, and wake and cavity shapes that can be expected around buildings. In visualizing the plate as a building, assume for convenience that a horizontal ground boundary can be introduced through the center of the plate and that the upper half of the plate can be made coincident with the upwind face of the building. This will give the suspended square flat plate the same geometrical proportions as a building and its mirror image, with the building height being equal to one-half

its width and its length (in the direction of the wind) being very small.

The actual introduction of a solid plane through the center of the plate would impose severe restrictions on the flow in the cavity since the velocity of real viscous fluids such as air must fall to zero at all solid boundaries. In general, the plate would exert a drag force on flow along the plate, and it would prevent the transverse movement of eddies from one side of the cavity to the other. These restrictions should be borne in mind when the suspended-plate data are to be applied to buildings on the ground.

According to Fail, Lawford, and Eyre (1957), the cavity and wake dimensions of axisymmetric plates suspended normal to the wind in a low-turbulence tunnel are not very sensitive to plate shape when referred to a characteristic dimension equal to the square root of the plate area. For a square plate of side L , the following properties were found to exist in the range of $0.5 < x/L < 5$ in a uniform stream of mean velocity V . The wake axis is coincident with the longitudinal (x) axis, and the origin is at the center of the plate.

1. The wake boundary originates at the edge of the plate and develops into a paraboloid of revolution. The curve of the boundary in a longitudinal section through the axis may be approximated by

$$\frac{r_w}{L} = \left(\frac{x}{L}\right)^{1/4} \quad (5.67)$$

where r_w is the radial distance from the axis at longitudinal distance x .

2. The mean velocity $\bar{u}_a$ at the center of the cavity is about 60% of the background-flow velocity and is opposite in direction.

3. The cavity boundary originates at the edge of the plate but develops into an approximate ellipsoid of revolution of length equal to $2.83L$ and radius at midlength equal to L .

4. The pressure coefficient is -0.42 all over the lee face of the plate, -0.66 at the center of the cavity, and -0.15 at the end of the cavity.

5. The longitudinal turbulence intensity, σ_u/V , at $x = 3.6L$ varies from 0.11 at the axis to 0.22 at $r = 0.8L$ and then falls to substantially zero in the background flow beyond the wake boundary (note that the local turbulence intensity, $\sigma_u/\bar{u}$, would be higher since $\bar{u} < V$ in a wake). Cooper

and Lutzky (1955) present the properties of square-flat-plate wakes in the range of $20 < x/L < 680$ in graphical form. Equations 5.68, 5.69, and 5.70 are approximations to their data.

6. The wake-boundary radius expands with distance downwind according to

$$\frac{r_w}{L} = 1.57 \left(\frac{x}{L} \right)^{1/2} \quad (5.68)$$

7. The longitudinal variation of axial mean velocity is

$$\frac{\bar{u}_a}{\bar{V}} = 1 - 0.32 \left(\frac{x}{L} \right)^{-1/2} \quad (5.69)$$

8. The radial variation of mean velocity is similar at all stations; it has an axial minimum and increases to the free-stream value in a symmetrical bell-shaped curve.

9. The longitudinal variation of turbulence intensity is

$$\frac{\sigma_u}{\bar{V}} = A \left(\frac{x}{L} \right)^{-1/2} \quad (5.70)$$

where $A = 0.25$ at the axis and 0.32 at $r = 0.33 r_w$.

10. The radial variation of turbulence intensity is similar at all stations; it has a maximum at $r = 0.33 r_w$, a minimum at the wake boundary, and a secondary minimum at the axis.

Measurements of displacement flow around a plate are not available. Experience has shown, however, that approximations of the pressure and velocity fields at stations upwind of the center of the cavity and at large radial distances can be obtained by means of the potential-flow equations for flow around a solid object occupying the cavity.

Part (a) of Fig. 5.18 is a reconstruction of the flow near a suspended flat plate, based on potential theory and Fail's measurements. The displacement flow was obtained by first calculating the potential flow properties for a sphere of radius L placed with its center on the plate axis at station $x = L$ and then adjusting the properties near the surface of the sphere to conform to conditions at the plate and cavity boundaries.

Part (b) of Fig. 5.18 shows the relation between Cooper and Lutzky's and Fail's measurements with interpolated values in the range

Fig. 5.18 — Flow around a suspended plate.

$5 < x/L < 20$. Cooper's wake boundary given by Eq. 5.68 was found by extrapolating the velocity defect in each transverse traverse to zero; therefore it can be considered as a limiting velocity contour extending downwind to ∞ and labeled $\bar{q}/V = 1.00$, where $\bar{q}$ is the local resultant mean velocity. All other velocity contours in the wake are closed and terminate at values of x/L given by Eq. 5.69. According to our convention the wake does not exist outside the $\bar{q}/V = 0.95$ contour, and consequently the length of the wake is effectively limited to about $17L$ from the plate. The ends of the velocity contours for $\bar{q}/V = 0.96$ and 0.97 are also shown to demonstrate the very slow change of axial velocity beyond $x/L = 20$ and the strong dependence of wake length on the convention employed.

5-5.2.2.2 Sharp-edged Buildings. Experiments to determine the cavity size of sharp-edged block buildings on the floor of a wind tunnel are reported by Evans (1957) and Holdredge and Reed (1956). The variables were height, length, width, roof pitch, and orientation of the buildings to the wind. Atmospheric turbulence was not simulated. It was found that cavity lengths and heights increase with building width (transverse to wind) and roof pitch. Small increases in building length (parallel to wind) do not affect the cavity greatly, but for long buildings the cavity boundary reattaches to the roof and walls, and a separate cavity is created at the downwind face.

Changes in the orientation of the buildings to the wind produce marked changes in the cavity shape close to building surfaces. The corner orientation, in particular, produces a cavity that encloses the downwind walls and the lateral roof corners, leaving the center of the roof exposed to high-velocity flow (Figs. 5.19 and 5.20).

The sizes of real wakes and cavities associated with buildings in a natural wind may be expected to differ from those described above because of the presence of the ground boundary, the background-wind mean velocity profile, and the increased turbulence. Section 5-5.4.1 contains a discussion of the effect of profile and turbulence. Lettau and Kutzbach (1961) describe some experiments with bushel baskets at various spacings on a frozen lake. Wake lengths can be estimated from these data.

Pressure distributions on buildings were measured by Chien, Feng, Wang, and Siao (1951) and Holdredge and Reed (1956) using wind tunnels with uniform-velocity-profile airstreams. Jensen (1958) and Jensen and Franck (1965) made comparative pressure-distribution tests on a building in an open field and on a model of the building in a wind tunnel with various logarithmic velocity profiles produced by roughness elements on the tunnel floor and found considerable variation of pressure coefficient among the tests. Figure 5.21 shows the average pressure coefficient on various surfaces and the lowest value on the upwind roof as a function of building height/ground roughness, H/z_0 . Agreement with field measurements was good at $H/z_0 = 170$, corresponding to field conditions, but the variation over the range of H/z_0 was considerable. Evidently the wind profile must be reproduced in order to obtain pressure-coefficient data from wind-tunnel tests that agree with field data.

Pressures on buildings and their dependence on building shape, mean wind velocity profile, and wind turbulence have been studied at the University of Toronto (Keffer and Baines, 1963, Hamilton, 1962, Baines, 1963, and Leutheusser, 1964, 1965). Discussion of the relation between pressure coefficients and flow conditions near building surfaces in these reports augment the foregoing descriptions.

5-5.2.2.3 Rounded Buildings. A frequently used shape of containment structure for a nu-

Fig. 5.19—Flow around a sharp-edged building. (a) Normal orientation. (b) Diagonal orientation. [From J. Halitsky, *Gas Diffusion near Buildings*, *ASHRAE (Am. Soc. Heating, Refrig. Air-cond. Engr.) Trans.*, 69: 473 (1963).]

clear power reactor is a vertical cylinder topped by a hemispherical dome. Although the rounded exterior surface lacks a sharp edge for a localization of the separation phenomenon,

Fig. 5.20—Effect of wind angle on smoke emitted from a flush vent on several prisms. Sketches on top show camera position, C, and location of plane light beam, L. Building A is a cube of proportions $L:W:H = 1:1:1$. Building B is a prism, $L:W:H = 1:1:1/3$. Building C is a prism with $L:W:H = 1/3:1:1$.

Fig. 5.21—Effect of variation of mean-velocity profile on pressures on a sharp-edged building. (Based on data from Jensen, 1958.)

separation does occur, producing a wake and cavity. In contrast to the sharp-edged building, however, the location of the separation line varies.

Much available information about separation on curved surfaces comes from wind-tunnel tests in wind streams having turbulence intensities of less than 2.0%. These tests show that the controlling factor in separation is the Reynolds number, Re , which for the atmosphere is about 6000 LV, where L is a characteristic object dimension in feet and V is the wind speed in feet per second. For a sphere or

cylinder, the characteristic dimension is the diameter D_0 , and the location of the line of separation is specified by the angle φ between the radius to the line and the radius pointing directly upwind. At Re of the order of 1, no separation occurs at all. As Re increases, separation begins near $\varphi = 180^\circ$ and moves upwind until the line becomes temporarily stabilized in the range of $75^\circ < \varphi < 90^\circ$ for $2000 < Re < 300,000$. At $Re \approx 300,000$ the line of separation moves abruptly downwind to $\varphi \approx 115^\circ$, and φ increases slowly thereafter with large increases in Re . The abrupt shift in the line of

separation at $Re \approx 300,000$ is produced by a transition from laminar to turbulent flow in the boundary layer.

For a Re of 300,000, the product $D_0 V$ must be at least 50. This is usually the case for most full-size buildings, and separation will occur at $\phi \approx 115^\circ$ in a steady wind. The angle may be expected to increase even more as the background flow becomes more turbulent.

Therefore the wake will be attached to the downwind surface of the rounded structure, and the streamline distortion around the building and wake will be less than around a sharp-edged building. The condition is illustrated in Fig. 5.22.

The photographs of Fig. 5.23, taken during a model test of the EBR-2 reactor shell at Idaho Falls, show the movement of smoke released at

Fig. 5.22—Flow around a rounded building. (a) Flow in a horizontal plane near the ground. (b) Flow in the longitudinal center plane. (c) Velocity profiles in the longitudinal center plane. (From Halitsky, Golden, Halpern, and Wu, 1963.)

various points on the surface of the shell or at the ground. Separation is seen to occur at φ somewhat larger than 90° . The stagnation point of the cavity-bounding streamline is seen in frame 14 to occur at $x/D_0 = 2.25$ from the center of the shell. Frame 4 shows the effect of placing an auxiliary building upwind of the shell. The cavity of the auxiliary building extends to the shell, and the downflow causes the smoke to recirculate back to and over the roof of the auxiliary building.

5-5.2.2.4 Walls. Flow approaching a wall encounters a positive pressure gradient along the ground since a stagnation zone exists on all building faces normal to the wind. Therefore the flow separates from the ground before reaching the wall and attaches to the wall at a higher elevation. A vortex is created at the base with horizontal axis normal to the wind and direction of rotation such that the upper part of the vortex is in the direction of the wind. This condition is illustrated at point c in Fig. 5.17. A weak vortex created by the return flow in the cavity also exists at point f.

Similar vortices are shown in Fig. 5.22 for the round building. Frame 2 of Fig. 5.23 shows that the upwind vortex can cause a contaminant discharged at the base of the shell to travel upwind along the ground a distance of about $D_0/3$. Frame 3 shows that the vortex also induces a strong downflow along the cylindrical wall of the shell.

Flow downwind of two-dimensional fences of various heights immersed in a wind-tunnel-floor boundary layer have been investigated by Nagabhushanaiah (1961). He found that the cavity length was 12 fence heights long and the cavity thickness was about 1.6 fence heights high. These proportions differ from those of the suspended plate in that the cavity is longer but not as deep. It is thought that the differences may be attributed to two causes: the presence of the ground boundary and the change from a three-dimensional to a primarily two-dimensional phenomenon. Insufficient information is available to separate the two effects.

5-5.2.2.5 Terrain Discontinuities. Brooks (1961) reviews various wind-tunnel experiments dealing with flow over a sudden drop of height H in terrain and over an abrupt change of surface roughness. A cavity is shown to exist for at least a distance of $6.0H$ downwind of the drop,

and a new, stable wind profile is shown to be far from established at a distance of $7.5H$. Also, a floating layer of high turbulence ($\sigma_u/V = 0.16$) exists and is still growing in intensity at $x = 6.0H$. The elevation of the turbulent layer at $x = 1.5H$ is the same as the original terrain but at $x = 6.0H$ the layer has descended to one-half the drop.

Changes in the mean velocity profile in the earth's surface boundary layer when the flow passes from a region of one uniform surface roughness to another were analyzed by Panofsky and Townsend (1964). They indicate that flow over the second region is divided into upper and lower parts by a fairly distinct surface originating at the juncture of the two roughnesses and pitching upward at a slope of about 1:10. The surface is characterized by velocities common to upper and lower flows. The lower flow is determined by the surface roughness in the downwind region. The upper flow retains the characteristics generated in passing over the upwind region. The authors conclude that the establishment of flow characteristics in a surface layer of height H does not require an upwind fetch of uniform roughness greater than $10H$.

5-5.2.3 Transverse Jets. A common mode of gas release near a building surface is in an exhaust-air jet originating at a flush vent or stub stack on the building roof. The initial trajectory of the jet is important because fresh-air intakes are frequently located in nearby roof cupolas and the throw of the jet will determine whether the intake will be exposed to the relatively high concentration near the plume center line.

Although a number of theoretical solutions for transverse jet trajectories have been advanced, these are generally applicable only at large distances from the source. Near the aperture the jet takes on a semisolid character and creates a displacement flow, cavity, and wake in the transverse airstream. The reduced pressure at the sides of the jet cylinder causes the jet to expand laterally, and the reduced pressure in the cavity causes the jet cross section to warp into a horseshoe shape. Under these conditions simple momentum theories are not adequate to describe the initial trajectory.

Transverse jets have been studied in low-turbulence wind tunnels by Bryant and Cowdrey (1955), Jordinson (1956), Keffer and Baines

Fig. 5.23—Photographic sequence showing diffusion of smoke released at various points in the longitudinal center plane through a reactor shell. (From Halitsky, Golden, Halpern, and Wu, 1963.)

(1963), and Shandorov (1957). Jordinson measured total pressure in jets from a flush vent; typical cross sections and center-line trajectories are given in (a), (b), and (c) of Fig. 5.24. The negative total pressures are an indication of reduced static pressure in the cavity rather than reversed velocity. The jet center line is defined as the line of maximum total pressure. Bryant and Cowdrey measured temperatures in a vertical center plane through a heated chimney jet issuing at a 200°F temperature excess. Temperature contours are shown in (d) of Fig. 5.24. A review of published data on transverse jets is given by Halitsky (1966).

Transverse jets in the cavity over a building roof are exposed to highly turbulent nonuniform

mean-velocity flows. Figure 5.25 shows a flush roof jet under conditions of varying emission-velocity ratios, V_e/V , where V is the velocity of the external uniform nonturbulent flow. The shape of the jet is a reflection of the circulatory mean flow in the cavity. The jet bends upwind at low V_e/V , bends downwind at high V_e/V , and becomes forked at intermediate values. No quantitative measurements of jet characteristics in this type of flow field have been made.

5-5.3 Concentration Calculations

Because of the unavailability of explicit theoretical expressions to describe concentra-

Fig. 5.23 — (Continued)

tion distributions in distorted flow fields and the impracticability of conducting a full-scale test for each problem, it is necessary to adopt an approach that combines the results of a few experiments with a method for extrapolation of the data to other than the test conditions.

A method that has proved successful in extrapolating pressures and forces on objects in a moving fluid stream is the reduction of data to nondimensional coefficient form. In this section we shall follow the same procedure: define a nondimensional concentration coefficient K_c for any concentration field, indicate the specifications needed to give it meaning, and show how characteristic values of K_c can

be computed with a minimum of data for general types of problems.

5-5.3.1 The Concentration Coefficient and the Configuration. Any concentration field can be expressed nondimensionally by introducing reference parameters L for length, V for velocity, Q' for contaminant-release rate, and Q'/L^2V for concentration. We shall define the concentration coefficient K_c as the ratio of the actual concentration, $\bar{x}$, at any point in the field to the reference concentration, or

$$K_c = \frac{\bar{x}}{Q'/L^2V} = \frac{\bar{x}L^2V}{Q'} \quad (5.71)$$

Fig. 5.24—Transverse jet properties. (a) Isopleths of constant total pressure coefficient C_h in vertical center plane of isothermal jet with $V_e/V = 6$. (Based on data from Jordinson, 1956.) (b) Transverse section through jet at A. (c) Center-line coordinates of isothermal jets. (d) Isopleths of constant-temperature excess for heated jet with $V_e/V = 2$ and initial temperature excess $T_e - T = 200^\circ\text{C}$. (Based on data from Bryant and Cowdrey, 1955.)

In general, K_c is a function of nondimensional space coordinates x/L , y/L , and z/L , and other nondimensional parameters, collectively called the configuration.

These purely mathematical transformations are very useful in reporting concentration data in dynamically similar flow fields. If, as is generally accepted, the mechanism of contaminant diffusion is the eddy motion of the carrier fluid, then concentration fields should be similar

and K_c fields should be identical in dynamically similar flow fields having similar source arrangements. The statement of the configuration contains those specifications which will guarantee the independence of a K_c field with respect to length, velocity, and source-strength scales.

In a few simple problems for which mathematical solutions of the concentration distribution have been found, K_c can be expressed

Fig. 5.25—Smoke patterns of jets discharging into a roof cavity. Cube side = L , aperture $D_e = L/30$, nozzle $D_e = L/60$, wind velocity = 4 ft/sec, wind profile is uniform, wind turbulence <1%. [From J. Halitsky, *Gas Diffusion near Buildings*, ASHRAE (Am. Soc. Heating, Refrig. Air-cond. Engrs.) Trans., 69: 483 (1963).]

analytically. For example, the Sutton equation for a continuous point source at a large distance from the ground transforms into

$$K_c = \frac{1}{\pi \left(\frac{C_y}{H^{n/2}} \right) \left(\frac{C_z}{H^{n/2}} \right) \left(\frac{x}{H} \right)^{2-n}} \times \exp \left[- \frac{\left(\frac{y}{H} \right)^2}{\left(\frac{C_y}{H^{n/2}} \right)^2 \left(\frac{x}{H} \right)^{2-n}} - \frac{\left(\frac{z}{H} - 1 \right)^2}{\left(\frac{C_z}{H^{n/2}} \right)^2 \left(\frac{x}{H} \right)^{2-n}} \right] \quad (5.72)$$

where the reference parameters are Q' = source strength, V = mean wind velocity = $\bar{u}$ (uniform over field), and L = source height = H . Thus, K_c is seen to be a function only of nondimensionalized space coordinates x/H , y/H , and z/H , when the effective turbulence parameters n , $C_y/H^{n/2}$, and $C_z/H^{n/2}$ are given. The accompanying statement of the configuration would then read:

1. Mean flow consists of a uniform velocity field of semiinfinite extent with streamlines parallel to each other and to the plane of the ground.

2. Turbulence is homogeneous but not isotropic and is specified by the above effective turbulence coefficients.

3. Contaminant is emitted from a continuous point source at height H with temperature equal to the air temperature at the same height.

Simple algebraic expressions for K_c such as the above are possible only in flow fields having uniform mean velocity and homogeneous turbulence. This condition is satisfied approximately at large distances from the ground where emissions from tall chimneys experience the greater part of their diffusion. Many contaminant releases in distorted flow fields close to buildings, however, create concentration distributions that are so complicated that algebraic expressions are not practical even if they could be found. In such cases it is necessary to express the distribution in tabular or graphical form. Although this is not as elegant as an algebraic form, it is adequate for engineering use, and its accuracy is commensurate with that of the test data.

A K_c distribution for a specific building is easily determined experimentally by (1) releasing a quantity of contaminant at a known rate, Q' , (2) measuring the concentration, $\bar{x}$, at a number of points in the space surrounding the building, (3) selecting a reference area $A = L^2$ related to the building size and a reference velocity V at a designated height above ground, and (4) dividing each concentration measurement by Q'/AV . Isopleths of constant K_c can then be drawn for the space surrounding the building. To use these K_c isopleths for a similar building on another scale, we need to nondimensionalize the coordinates, but the appropriate choice of a reference length is not immediately evident.

No method has been found for extracting a single reference length from the properties of a distorted flow field near a building which will guarantee similitude of the field on all turbulence, mean velocity, and length scales. We may, however, reason that the field properties are determined by the hydrodynamical equations of motion plus the initial and boundary conditions, and, if we are interested in the time-mean flow, the initial conditions are unimportant, and the boundary conditions alone should suffice. Therefore we should be able to extract a reference length from the boundary conditions.

The boundaries of a distorted flow field consist of the solid ground and building surfaces, the isolating surface between the distorted field and the background flow, and the holes in the solid surface through which air enters or leaves the distorted field. The simplest length that can be formed from the boundary conditions is a geometrical dimension of a recognizable feature of the solid boundary. Although any such feature will do, it is preferable to use one that has a controlling influence on the shape of the isolating surface. For a simple building on flat ground, the side area projected on a plane normal to the wind performs this function, and an appropriate length would be the square root of this area.

The use of a geometric reference length will scale the solid portion of the flow-field boundary properly, but this in itself does not guarantee that the shape of the isolating surface will be preserved. We may infer, however, from the previously cited tests on plates that the isolating surface surrounding a sharp-edged structure

in a low-turbulence flow will also scale geometrically. This assumption will be examined more closely later with respect to the influence of Reynolds and Froude numbers and turbulence in the background flow.

We must now make some statement that will define the shape of the boundary and the distribution of velocities on the boundary. The following specifications have been found to be important:

1. Building and terrain: dimensions and orientation to the wind.

2. Background wind: mean velocity and turbulence variation with height.

3. Air jets entering distorted flow region (exhaust vents and chimneys): mean velocity and temperature excess at aperture.

4. Air removed from distorted flow region (building air intakes): mean velocity at aperture.

These boundary conditions may be nondimensionalized by dividing all lengths by the reference length, L , and by dividing all velocities by a reference wind velocity, V , at a given elevation. This results in a background mean velocity profile $\bar{u}/V$ vs. z/L , exhaust- and intake-velocity ratios V_e/V and V_i/V , and the turbulence-intensity components $i_u = \sigma_u/\bar{u}$, etc., where σ_u is the root-mean-square turbulence velocity in the mean wind direction.

The configuration, then, will include the four specifications just mentioned, the statement of how A and V are to be measured, and the source distribution. In the present context the term "source" refers to the pure-gas component of an effluent. In ordinary problems involving the release of gas-air mixtures, the amount of pure gas is so small with respect to the volume of air in the jet that the presence of the gas does not influence the air motions in the flow field. The source distribution is important, however, because steep velocity gradients in the field, sometimes accompanied by flow reversals, may cause different portions of the source to disperse in different directions. The strength of the source affects the maximum concentration in the field, but it does not appear in the K_c term and is not properly a component of the configuration.

5-5.3.2 Dilution. In practical problems we may be given the rate of release of contaminant, Q' , or the concentration in the effluent aperture, $\bar{\chi}_e$, and we wish to find the concentration, $\bar{\chi}$, at any point in the field or the dilution that will

take place as the gas travels from the effluent aperture to the point. Evidently, if the concentration field is steady, each point may be assigned a given dilution, D , defined as the ratio of concentration in the effluent aperture to the concentration at the point. Using Eq. 5.71 to express the concentrations in coefficient form, we obtain

$$D = \frac{\bar{\chi}_e}{\bar{\chi}} = \frac{K_{ce}}{K_c} \quad (5.73)$$

5-5.3.3 Magnitudes of K_c and D for Isolated Buildings. The magnitude of K_c does not vary greatly among configurations in a few regions of practical importance, such as the side walls of a building and the nearby ground when gas is released into the cavity near the top of the building. On the other hand, K_c depends markedly on configuration in regions near the source. Thus fairly good estimates of concentration can be obtained for the former regions with only a small amount of information, but serious errors can be introduced if configuration details are not taken into account in the latter case, particularly when air intakes are located close to effluent apertures on the roof of the same building.

5-5.3.3.1 K_c and D in Effluent Apertures. Let the effluent at the source have velocity V_e and concentration $\bar{\chi}_e$ in an effluent aperture of area A_e . The source must then have strength $Q' = \bar{\chi}_e A_e V_e$, and, from Eqs. 5.71 and 5.73, the concentration coefficient and dilution at the source are

$$K_{ce} = \frac{AV}{Q'} \bar{\chi}_e = \frac{AV}{A_e V_e} \quad (5.74)$$

and

$$D_e = \frac{K_{ce}}{K_c} = 1 \quad (5.75)$$

In most problems A_e and V_e are specified, but V and A must be selected. For V it is convenient to use the approach wind velocity at the elevation of the building roof. A suitable area is the side area of the building projected on a plane normal to the mean wind direction. Although basically correct, this formulation

makes computation difficult because a new area must be found for each wind direction. A more useful choice is the area of the building projected on a plane parallel to the largest side. Here A is a constant for a given building.

The release of a pure gas having $\bar{X}_e = 1$ produces $K_{ce} = AV/Q'$ at the effluent aperture. A representative configuration of an industrial laboratory building might be height, 40 ft; length, 200 ft; A , 8000 sq ft, and wind velocity V , 10 ft/sec. Here the numerator of Eq. 5.74 becomes 80,000. Let us assume that a laboratory experiment produces $Q' = 10$ cu ft/min = 0.167 cu ft/sec of pure gas. Then $K_{ce} = 480,000$. Such high values of K_{ce} are typical of small pure-gas releases.

If the gas is released in a fume hood, a large amount of initial dilution takes place prior to release to the atmosphere. Let us assume that the fume-hood air-flow rate is 1000 cu ft/min and that the discharge occurs through a 1 sq ft opening. Then $A_e = 1$ sq ft, $V_e = 16.7$ ft/sec, and $K_{ce} = 4,800$ according to Eq. 5.74. The decrease of K_{ce} from 480,000 to 4,800 represents the initial dilution of 100 in the duct system. Representative values of K_{ce} for single hood exhausts on large buildings usually fall in the range of 10^3 to 10^4 .

If several fume-hood exhausts are combined and then released through a single effluent aperture, the product $A_e V_e$ varies in direct proportion to the number of hoods, and K_{ce} varies in inverse proportion. Again, the decrease in K_{ce} is a reflection of internal dilution since it is presumed that the same amount of gas is released in either system (all hoods operate, but gas is released in only one).

5-5.3.3.2 K_c and D in the Wake at the End of a Cavity. A characteristic K_c value occurs in a cross section of the wake just downwind of the cavity when the cavity completely encloses a building having a roof exhaust. Because of high turbulence the contaminant spreads throughout the cavity and diffuses into the wake proper through the cavity boundary. In the indicated cross section, the concentration distribution is not uniform, but the entire wake is contaminated to some degree. An average concentration for the section may be estimated by dividing the source strength by the wake volume flow. For an average building the cross-sectional area of the wake is about twice the

reference area, and the mean velocity in the cross section varies from a low value near the downwind stagnation point (point h in Fig. 5.17 or point C in Fig. 5.22) to the background-flow velocity V at the periphery of the wake, with an average value of about $V/2$. The average wake concentration then is

$$\bar{X} \approx \frac{Q'}{2A(V/2)} = \frac{Q'}{AV} \quad (5.76)$$

which gives

$$K_c = \frac{\bar{X}AV}{Q'} \approx 1 \quad (5.77)$$

This estimate has been borne out by measurements. For example, the stagnation point for the reactor shell in Fig. 5.23 (panels 9 to 16) is located 2.25 diameters downwind of the shell center line. Values of K_c in the same plane (see Fig. 5.29) for different source locations range from $K_c = 0$ to $K_c = 5$, with $K_c = 1$ being a rough average.

5-5.3.3.3 K_c and D at the Walls. The value of K_c at the downwind stagnation point has great significance for contamination of the downwind walls of a building. These surfaces are bathed by the return cavity flow, which appears to originate at the stagnation point and to move along the ground upwind toward the building, around the building sides, and upward toward the roof. Thus K_c values at the downwind building walls depend principally upon the K_c value at the stagnation point, or $K_c = 1$. The variation of K_c along the downwind walls is not large. It increases somewhat toward the roof owing to spillage of gas over the roof copings and short-circuiting of the upper cavity flow to the lower flow without making the full circuit along the cavity boundary. The upwind walls, being out of the cavity, are not contaminated.

5-5.4 Scaling Requirements

Since the mechanism of turbulent diffusion is the motion of air parcels, similarity of flow fields should result in similarity of concentration fields for similar sources. We shall take the view that flow similarity will exist in regions where aerodynamic effects predominate if the wind characteristics on the boundary of the distorted flow field are reproduced and the mean-flow hydrodynamic scaling criteria in the

interior of the field are observed (geometric similarity of the solid boundary being assumed). The important wind characteristics are the vertical profiles of mean velocity, turbulence intensity, and turbulence spectrum. The important scaling criteria are the Reynolds number and modified Froude number.

5-5.4.1 Wind Characteristics. The mean-wind-velocity profile is determined by upwind flow conditions. In an adiabatic atmosphere flow over level ground with uniform roughness produces a logarithmic variation of mean velocity with height, the controlling parameter being the roughness height z_0 . In nonadiabatic conditions the profile is not logarithmic and cannot be adequately described by z_0 alone. In flow over nonuniform roughness, the profile will be affected by size, shape, and spacing of the roughness elements. When a nearby upwind ground irregularity is comparable in size to the building under consideration, the term "roughness" loses its meaning as a characteristic of the terrain, and the profile must be considered as part of an upstream wake. Excluding the last case and using the term z_0 in its broadest sense as some descriptive height based on physical dimensions of terrain and atmospheric stability, we may consider the general shape of the wind profile to be quasi-logarithmic and to originate at some point z_0 above the ground ($\bar{u} = 0$ at $z = z_0$).

Where a building of height H is immersed in a boundary layer characterized by z_0 , the mean velocity distribution in a layer comparable to H will be very sensitive to the ratio H/z_0 . Figure 5.21 shows velocity profiles calculated from $\bar{u} = (V_*/k) \ln(z/z_0)$ for a range of H/z_0 from 2 to 10,000. The table in Fig. 5.21 shows representative values of H/z_0 for several possible combinations of building height and terrain. Values of z_0 of 0.01 ft for snow and 0.1 ft for grass have been cited in several texts. A value of 10 ft for z_0 might occur in a densely built-up urban area. According to Jensen (1958) measurements of wind speed above Copenhagen extrapolated logarithmically to zero speed gave z_0 equal to about 40% of the average building height. A considerable difference is seen between profiles to which a four-story building may be exposed in a built-up region ($H/z_0 \approx 5$) and in a cleared isolated area ($H/z_0 \approx 500$).

The need for reproducing the full-scale velocity profile in model tests has not been carefully evaluated for diffusion close to buildings, but it appears to be important when H/z_0 is small. In such cases the velocity is reduced considerably over the lower part of the building, with the result that less air is provided for ventilation and the diffusion process is slowed. At the same time the wake cross section contracts since less air is displaced laterally and vertically by the building, and consequently the circulation patterns change in the cavity surrounding the roof and side walls. An indication of these effects is shown in Fig. 5.26. The streamline curvature in (b) and the wake boundary curvature in (d) of Fig. 5.26 for $H/z_0 = 60$ are less than in (a) and (c), respectively, for $H/z_0 \approx \infty$. Also, smoke released from a roof vent is seen to move upwind in the cavity in (c) but downwind in (d). These effects cannot be attributed entirely to the change in mean-velocity profile since the turbulence was greater in the case of $H/z_0 = 60$, but it is thought that the mean-velocity profile is the significant factor in controlling the shape of the wake boundary and the mean flow in the cavity. Similar behavior of the wake boundary with variation of wind-velocity profile was observed by Jensen and Franck (1965).

Two aspects of wind turbulence affect wake flow in characteristic ways. As discussed in Sec. 5-5.2.1.4, the intensity appears to influence the peripheral regions of the wake. On the other hand, if the spectrum shows considerable energy in the low-frequency range, the effect is that of a periodic change in mean wind direction, which strongly influences cavity flow. The degree of change may be seen in the change of smoke patterns in Fig. 5.20 when the wind angle changes by 22.5° . In the natural atmosphere under adiabatic conditions, the lateral turbulence intensity near the ground may be of the order of 0.15 corresponding to a root-mean-square lateral gust angle of about $\sigma_\theta = 9^\circ$. In a normal distribution the effective range of gust angles is about 2.5σ with extreme gust angles of $\pm 22^\circ$ produced. Therefore the time-average concentration pattern for a cube oriented with one face normal to the mean direction of a turbulent wind in an adiabatic atmosphere should be a weighted average of the concentration patterns shown in the two upper left photographs of Fig. 5.20 plus patterns for the intermediate

Fig. 5.26 — Effect of variation of mean-velocity profile and turbulence on streamline and cavity shape for a sharp-edged building. (a) Streamline flow. (b) Streamline flow. (c) Cavity flow for a uniform profile, $H/z_0 \approx \infty$ and $\alpha_u/\bar{u} \approx 0.005$. (d) Cavity flow for a logarithmic profile, $H/z_0 \approx 60$ and $\alpha_u/\bar{u} \approx 0.040$.

angles. The same principle applies to vertical gusts.

The transformation of cavity shape (and cavity flow field) with change in wind angle is also dependent upon the time available for the transformation to become complete. The minimum period for development of a recognizable cavity should be of the order of the time necessary for an air parcel to travel the length of the building, or $t = L/V$. In an adiabatic atmosphere it has been found (Pasquill, 1962) that the maximum energy per frequency decade in the spectrum of vertical oscillations occurs at a nondimensional frequency, $fz/V \approx 0.2$. At the roof level of a cube of side L , this corresponds to a period of $t = 1/f \approx 5L/V$. Therefore much of the energy of vertical oscillations is of long enough period to produce sustained changes in

the cavity flow field. Lateral oscillation periods are of the same order.

An interesting conjecture concerning the interaction of wind turbulence and building-generated turbulence arises from observations that circular cylinders in a nonturbulent air-stream shed periodic eddies whose frequency is given by the Strouhal number, $fD/V = 0.2$, for values of Reynolds number greater than 10^3 (Schlichting, 1960) and that measurements of pressure fluctuations on cubes in a wind tunnel show a Strouhal number for the dominant frequency around 0.25 to 0.5 (Keffer and Baines, 1963). The correspondence of eddy-shed frequency in the wake and maximum energy-carrying frequency in the atmosphere may tend to promote resonance effects and large oscillations in the cavity and wake proper.

In view of the above, it would appear that reproduction of the turbulence intensity and spectrum are both required for accurate modeling. It seems reasonable to assume that the distribution of intensity with height and the shape of the spectrum are less critical than the existence of the appropriate average intensity and the location of the maximum energy at the correct frequency.

The importance of wind scaling has not been evaluated thoroughly by field-tunnel correlation tests, but several recent experiments provide some indications of the effect of omitting wind turbulence in the tunnel.

In tests of diffusion from a flush vent on a building, Halitsky (1965a) found that the hourly mean field concentrations on the building surfaces were from 0.1 to 1.0 times the tunnel values, the greater discrepancies appearing on the roof near the point of emission. J. E. Martin (1965) reports that field and tunnel tests of diffusion from a short stack on a building show reasonably good correlation when the effluent is trapped in the cavity but that the field concentrations are lower than the tunnel concentrations by about the peak-to-mean ratio at larger distances. Islitzer (1965) reported that field tests of diffusion from a ground release in a building complex show K_c values on the ground just downwind of the complex to be about the same as the values found by Halitsky, Golden, Halpern, and Wu (1963) in tunnel tests of a different complex. At larger distances the measured concentrations approach those computed from a mathematical model of diffusion over flat terrain with coefficients appropriate to the atmospheric stability. The mechanical turbulence produced by the complex appeared to have substantially died out at a distance of 2800 ft from the source. Munn and Cole (1965) report that field tests on a heated effluent released from a short stack on a building in a complex show smaller concentrations at a distance of 500 ft than the values calculated by formulas derived from wind-tunnel tests.

These tests indicate that the conventional low-turbulence wind-tunnel test will probably yield sufficiently accurate data for making conservative estimates of full-scale time mean concentrations in the cavity. The introduction of scaled turbulence seems necessary if test data at large distances from the source are not to be overly conservative.

5-5.4.2 Hydrodynamic Scaling Criteria. Appropriate hydrodynamic scaling criteria for any given type of diffusion test have not as yet acquired the status of general acceptance. The approach described in the following paragraphs is intended for tests of diffusion in aerodynamically distorted regions. It represents a reasonable amalgam of theory and model experiments. Validation in the field must await more extensive tests.

The requirements for flow similarity can be derived by nondimensionalizing the boundary conditions and the differential equation of mean motion of a turbulent fluid. In the nondimensionalization process we use as reference quantities configuration reference length, L , wind velocity, V , air density, ρ , and viscosity, μ . The resulting equation of mean motion has the following form:

$$\left[\begin{array}{c} \text{accel-} \\ \text{eration} \\ \text{term} \end{array} \right] = \left[\begin{array}{c} \text{pressure} \\ \text{term} \end{array} \right] + \frac{\mu}{LV\rho} \left[\begin{array}{c} \text{shear} \\ \text{term} \end{array} \right] + \left[\begin{array}{c} \text{turbulence} \\ \text{term} \end{array} \right] + \frac{Lg(T_1 - T)}{V^2 T_1} \left[\begin{array}{c} \text{buoyancy} \\ \text{term} \end{array} \right] \quad (5.78)$$

In the buoyancy term we have used the approximation $(\rho_1 - \rho)/\rho_1 \approx (T_1 - T)/T_1$, assuming that the gas component of most effluents discharged close to buildings is only a small fraction of the gas-air mixture. (Temperatures in this context are absolute.)

The coefficient of the shear term is the reciprocal of the Reynolds number, Re , and the coefficient of the buoyancy term is the reciprocal of a modified Froude number, Fr' . More specifically,

$$Re = \frac{LV\rho}{\mu} \quad (5.79)$$

$$Fr = \frac{V^2}{Lg} \quad (5.80)$$

$$Fr' = \frac{V^2}{Lg} \frac{T_1}{(T_1 - T)} = Fr \frac{T_1}{(T_1 - T)} \approx Fr \frac{T}{(T_1 - T)} \quad (5.81)$$

Similar motions have identical nondimensional differential equations. This means that the numerical values of Re and Fr' must be kept

constant if similarity is to be preserved. Let us examine the requirements for exact scaling if g , ρ , μ , and T_1 are kept constant. Let the prototype configuration be identified by the quantities L^* , V^* , T^* , Re^* , and Fr'^* . If L^* is changed to L the following changes must also be made:

To satisfy Re

$$V = V^* \frac{L^*}{L} \quad (5.82)$$

To satisfy Fr'

$$V = V^* \left(\frac{T_1 - T}{T_1^* - T^*} \frac{T_1^*}{T_1} \frac{L}{L^*} \right)^{1/2} \quad (5.83)$$

To satisfy both numbers simultaneously

$$T_1 - T = (T_1^* - T^*) \left(\frac{L^*}{L} \right)^3 \frac{T_1}{T_1^*} \quad (5.84)$$

When a temperature excess $T_1^* - T^*$ exists in the prototype, the temperature excess in the model must be larger by the factor $(L^*/L)^3 (T_1/T_1^*)$. Since T_1 and T_1^* are absolute temperatures, their ratio is of the order of 1. However, a prototype building 30 ft high may be modeled by a building 1 ft high; so $(L^*/L)^3 = 30^3 = 27,000$. Evidently any significant temperature excess in full scale will require prohibitively high model equivalents, and Re and Fr' cannot be satisfied simultaneously.

We now wish to determine the effect on the flow field of a failure to observe Re and Fr' scaling. Inspection of Eq. 5.78 shows that the shear and buoyancy terms become less important as Re and Fr' increase and may be dropped when Re and Fr' are very large. In such cases neither Re nor Fr' scaling need be observed. Physically, large Re occur when lengths and velocities are large, and large Fr' occur when $T_1 - T$ approaches zero. The problem now is to assign numerical values to "large Re " and "large Fr' ."

5-5.4.2.1 Reynolds Number Scaling. Let us consider the isothermal case ($Fr' = \infty$) first. An average value of ρ/μ for the atmosphere is $6000 \text{ ft}^{-2} \text{ sec}$, and a 30-ft-high building in a 10 ft/sec wind would have $Re = 1,800,000$. A model test on a 1-ft-high building in a 4 ft/sec wind would have $Re = 24,000$. Thus Re is smaller, and the influence of the shear

term in Eq. 5.78 is greater in model tests than in the field. Whether this increase in influence is enough to produce significant changes in the K_c field must be answered by experiments. Golden (1961) measured K_c values on and near the roofs of sharp-edged cubes resting on a raised ground board in a uniform mean-velocity low-turbulence tunnel airstream and found that all K_c values were substantially constant above a Re of 11,000 in a test range of $2,000 < Re < 90,000$. As Re was decreased below 11,000, the K_c values at the roof surface changed systematically, but those in space above the roof remained invariant. This behavior may be attributed to the greater viscous stresses near the roof surface where the mean-velocity gradients are steep. Since the influence of the shear term in Eq. 5.78 decreases with increasing Re , it will be conservative to adopt $Re = 11,000$ as a diffusion-critical Re , above which changes in the flow field due to changes in Re will not produce significant changes in the K_c fields of sharp-edged buildings. A lower value may be used if measurements are restricted to regions away from the building surfaces.

With this criterion K_c fields will be invariant for LV products greater than about 2 sq ft/sec. This will be the case in full scale for all except almost-zero wind speeds. The same invariance will be expected in the tunnel if 1-ft-high models are tested at wind speeds greater than 2 ft/sec.

To determine if a diffusion-critical Re exists for rounded buildings, we can refer to tests of a model of a typical industrial nuclear-power reactor containment structure [Halitsky, Golden, Halpern, and Wu (1963) and Sec. 5-5.5.2]. Values for K_c isopleths were obtained for a leak at the top of the vessel at wind velocities of 3, 10, and 15 ft/sec, corresponding to a Re range of $15,800 < Re < 79,000$. Isopleth loops drew closer to the source as Re increased, showing that K_c at a fixed point was decreasing and that a diffusion-critical Re had not yet been reached up to a value of $Re = 79,000$.

It may be that boundary-layer tripping devices commonly used in aeronautical testing to produce a turbulent boundary layer and thereby to artificially increase Re can be employed in diffusion testing to stabilize the K_c field, but this possibility has not been explored.

In summary, then, there is reasonable assurance that Re scaling is not required when

determining K_c fields for sharp-edged buildings by model experiments as long as the LV product is greater than 2 sq ft/sec. The corresponding LV product for rounded buildings would be at least an order of magnitude higher, but an exact value cannot be specified as yet.

5-5.4.2.2 Modified Froude Number Scaling. Since the effect of a modified Froude number on the buoyancy term in Eq. 5.78 parallels that of the Reynolds number on the shear term, we may suspect that a diffusion-critical Fr' exists above which Fr' scaling need not be observed. To investigate this possibility, Golden (1961) conducted heated-effluent tests on 5-in. and 15-in. cubes in a wind tunnel, using a temperature excess of 200° F above ambient. He found that K_c isopleths did not change much as Fr' (calculated with $T_1 - T = 200^\circ \text{F}$) was varied between 0.8 and 3.9. Since we know that Fr' scaling becomes unimportant at very large values, we suggest that the range of Fr' in which Fr' scaling need not be observed in this configuration only is $0.8 < Fr' < \infty$.

In terms of full-scale conditions where L is 30 ft, V is 10 ft/sec, and effluent aperture diameter is 1 ft, this configuration could tolerate a temperature excess ($T_1 - T$) up to about 100° F without producing a Fr' lower than 0.8. This temperature excess is high enough to ensure that ordinary ventilation problems, such as occur with laboratory fume-hood exhausts of the same proportions as those tested, do not require Fr' scaling.

A common scaling problem occurs with hot effluents from power-plant chimneys. The exhaust from a chimney terminating above the wake boundary will pass initially through a distorted flow zone created by the chimney but thereafter will diffuse in a region of smooth flow. Since the model scale for buildings with tall chimneys is about 1:200, a 10-ft chimney diameter will scale down to 0.6 in. If Fr' scaling is used without temperature scaling, Fr' reduces to Fr , the velocity scale becomes $1:(200)^{1/2} \approx 1:14$, and a full-scale average wind of 14 ft/sec at chimney-top level would scale down to 1 ft/sec in the tunnel. In the distorted flow region near the chimney top, the characteristic dimension is the chimney diameter, and Re for the region becomes 300, well below the diffusion-critical value. Therefore these length and velocity scales would not give accurate

modeling in this region. When the hot plume leaves the distorted flow region and enters the quasi-potential flow, the dominant forces are the plume buoyancy and turbulence. Here Fr' scaling but not Re scaling is required. Since initial diffusion effects are relatively unimportant when measuring ground concentrations far downwind from the stack, a small amount of scaling distortion in the plume near the stack is acceptable. However, this problem should be given careful consideration when measuring plume spread in tunnel tests of diffusion from isolated stacks discharging effluents at high temperatures and high emission velocities.

5-5.5 Experimental Data

on Concentrations near Buildings

Published experimental data on concentrations close to buildings in a form suitable for prediction of full-scale concentrations apparently consist only of the wind-tunnel experiments conducted since 1958 in the 3.5- by 7-ft low-speed wind tunnel at New York University. The three tests and their important characteristics are reviewed below, and the results are presented in graphs of concentration coefficient K_c as a function of nondimensional space coordinates.

5-5.5.1 Prism Tests. [Figures 5.20 and 5.27; (Halitsky, 1963).] The models consisted of two rectangular prisms having edge-length proportions of 1:1:1 or as given in the legend for Fig. 5.20. The reference area was the area of the largest wall that could be turned normal to the wind. If the long edge is L , the reference areas are L^2 for buildings A and C and $0.33L^2$ for building B. The actual model L is 1.25 ft. The effluent was released from a flush vent with a diameter of $L/30$ located in the center of the roof. The models were mounted on a ground board and were exposed to a low-turbulence wind with a uniform-mean-velocity profile. The emission-velocity ratio V_e/V was equal to 1 unless otherwise noted. Temperatures were isothermal.

In using the K_c diagrams (Fig. 5.27) remember that all these data were obtained in an essentially nonturbulent airstream and that effective full-scale K_c values will be different. The transformation from model to full-scale

K_c values is currently being studied (Halitsky, 1965a). Preliminary results indicate that a full-scale K_c field can be approximated by weighting the test values of K_c at each point according to a probability distribution based on the variance of the wind angle for a given atmospheric condition. However, this requires the separate measurement of K_c fields at small increments of tunnel-wind angle. Since the data in the following tests were taken for only a few wind angles, study of the patterns combined with some intuition is needed to make an intelligent guess at the probable full-scale K_c field. In general, the K_c peaks and gradients on the roof will be smaller than those in the model, and concentrations will appear where none were indicated in a nonturbulent wind. On the side walls K_c values should be about the same as in the model if the wall is continually in the cavity and proportionally smaller if the wall emerges from the cavity for part of the time.

5-5.5.2 Nuclear-reactor Shell Tests. [Figures 5.23, 5.28, 5.29, and 5.30; (Halitsky, Golden, Halpern, and Wu, 1963).] The prototype of the reactor shell and auxiliary building was the EBR-2 complex at the National Reactor Testing Station, Idaho Falls, Idaho. The shell consisted of a hemisphere on a vertical cylinder of diameter D_0 , overall height, H , $1.225 D_0$, and reference area, A , $1.118 D_0^2$. The actual model D_0 was 0.833 ft. The effluent was released at several points on the surface of the shell through holes of diameter $0.0063 D_0$. The mean-wind profile represented a full-scale logarithmic profile given by $\bar{u} = (v_\infty/k) \ln(z/z_0)$ with $v_\infty = 25$ cm/sec and $z_0 = 1.5$ cm, scaled down according to a velocity scale of 1:3 and lengthscale 1:96. The emission velocity ranged from 0.2 to 8.1 ft/sec. The tunnel velocity was 5.54 ft/sec at an elevation of $2D_0$. Temperature gradients were isothermal.

In using the K_c graphs from this test, take into consideration the remarks in Secs. 5-5.2.2.3 and 5-5.4.2.1 on Reynolds-number scaling and the remarks in Secs. 5-5.4.1 and 5-5.5.1 on wind scaling. At the test wind velocity, the Reynolds number was not high enough to establish a fixed separation line. Also, even though the mean-velocity profile was logarithmic, the value of $\sigma_u/\bar{u}$ in the approach wind was probably about 0.04 at the midheight of the shell, corresponding to very low atmospheric turbulence.

In the isopleth graphs the maximum value of K_c that appeared on an imaginary surface surrounding the reactor shell at a distance d from the shell was found to be represented by the approximate relation

$$K_{c \max} = \frac{10}{(d/D_0)^2} \quad (5.85)$$

where D_0 is the diameter of the base of the shell. Equation 5.85 was found to hold in the range $0.5 < d/D_0 < 3$ for all gas-release points in all wind directions and did not show much variation over a range of wind velocities from 3 to 15 ft/sec.

5-5.5.3 Clinical Center Test. (Halitsky, 1962)

The prototype of the complex was the Clinical Center and surroundings at the National Institutes of Health, Bethesda, Md. The model was built to a linear scale of 1:240. The approach wind was the normal low-turbulence tunnel airstream with a mean velocity of 4 ft/sec, corresponding to a full-scale wind of 12 ft/sec, or a velocity scale of 1:3. The building air-intake and -discharge openings on the roof of the several wings functioned with volume flows scaled according to $1:(240^2)(3) = 1:172,800$. The average emission-velocity ratio was $V_e/V = 2.22$ at the test wind velocity. Temperatures were isothermal.

This test was carried out in a different manner from the preceding two tests since the aim was not to determine K_c fields but to establish dilutions between specific exhaust and intake openings. The test procedure was to release gas in a given exhaust jet and to determine K_c at each intake opening in eight wind directions. The value of K_{ce} at the exhaust opening was calculated by Eq. 5.71, and the value of dilution, $D = K_{ce}/K_c$, was established for each combination. A simple mathematical model of a jet in a transverse airstream resulted in the following equation relating the dilution D to a nondimensional distance $s/(A_e)^{1/2}$, where s is the shortest arc distance from exhaust to intake and A_e is the area of the exhaust opening:

$$D = \left[\alpha + \beta \frac{s}{(A_e)^{1/2}} \right]^2 \quad (5.86)$$

When the test data for all combinations of D and $s/(A_e)^{1/2}$ were plotted on a graph with D as

Fig. 5.28—Reactor shell test configuration. (a) Model and auxiliary buildings in the wind tunnel. (b) Full-scale dimensions (ft) and mean-velocity profile (ft/sec). (From Halitsky, Golden, Halpern, and Wu, 1963.)

ordinate, it was possible to select constants α and β that allowed Eq. 5.86 to be plotted as a parabola bounding the data from below. Although there was considerable scatter of the data above the curve, the absence of test points below the curve implied that at a given separation distance no dilutions less than those given by the curve had been found and therefore the curve could be used conservatively for design purposes.

The scatter above the curve, indicating greater dilution or lower concentration at the intake, was interpreted as resulting from the intake's not being on the plume center line for the given

building orientation. In fact, for some combinations the intake would never be on the plume center line. This possibility was introduced into the formula by adding a factor M , which effectively displaced the curve upward and thereby provided some relief for different configurations. With an additional adjustment for emission-velocity ratio, the final equation became

$$D = 2.22 M \left[3.16 + 0.1 \frac{s}{(A_e)^{1/2}} \right]^2 \frac{V}{V_e} \quad (5.87)$$

Fig. 5.29a— K_c isopleths for reactor shell with leaks. Logarithmic profile for wind. Release point, bottom and downwind. (From Halitsky, Golden, Halpern, and Wu, 1963.)

Fig. 5.29b— K_c isopleths for reactor shell with leaks. Logarithmic profile for wind. Release point, bottom and upwind. (From Halitsky, Golden, Halpern, and Wu, 1963.)

Fig. 2.29c — K_c isopleths for reactor shell with leaks. Logarithmic profile for wind. Release point, top. (From Halitsky, Golden, Halpern, and Wu, 1963.)

(a)

(b)

(c)

Fig. 5.30— K_c isopleths for reactor complex. (a) Downwind release. (b) Top release. (c) Upwind release. (From Halitsky, Golden, Halpern, and Wu, 1963.)

The suggested values of M were 1.5 for exhaust and intake on the same roof, 2.0 for exhaust and intake on wings separated by an air space, and 4.0 for exhaust on roof and intake in the cavity near ground level.

The factor V/V_e provides a correction for greater dilution at higher wind velocities. It does not, however, provide for changes in the vertical throw of the jet due to a change in velocity ratio. This can be quite important if the jet from a flush roof vent bends over and impinges on an intake in the side of a cupola. An increase of V_e/V may carry the jet axis over the cupola and produce low concentrations and an effectively higher dilution at the intake. The use of the V/V_e factor in Eq. 5.87 would show an opposite trend.

5-5.5.4 Dugway Urban Area Tests. (Kalinske, Jensen, and Schadt, 1945 and 1945a.) In 1945 wind-tunnel tests of diffusion from a continuous area source in the streets of an urban district were conducted in a 4- by 6-ft wind tunnel at the Iowa Institute for Hydraulic Research. The concentration field was measured vertically and horizontally among the buildings downwind of the source, and the results were converted to an equivalent K_c defined as $\bar{x}L^2V/Q'$. In the absence of a characteristic physical length, the reference length L was taken as 1 ft for the prototype and the equivalent scaled-down value for the model, and V was taken as equal to the air-stream mean velocity above the boundary layer created by the buildings on the floor of the tunnel.

Although vertical diffusion was restricted in this case by the reduction of turbulence to zero at the top of the boundary layer, a method was developed whereby steady-state tunnel results could be correlated with field burst-type measurements, and discrepancies could be eliminated by selection of appropriate numerical coefficients. It was reported that "the accuracy obtained from such conversion is at least as good as the accuracy of single field measurements."

5-5.6 Applications

5-5.6.1 General Approach. The concentration at any point in a flow field can be expressed as the product of an average concentration Q'/AV and a concentration coefficient K_c . In a prac-

tical case the source strength Q' , reference area A , and velocity V are fixed by the design specifications, and the problem becomes one of determining the values of K_c at the point where the concentration is to be estimated.

At every point in the three-dimensional diffusion field around a source, K_c has a numerical value, and it has the same value at corresponding points of similar fields. If similarity can be established between two diffusion situations differing only in scale, the distribution of K_c obtained in one situation can be used for the calculation of concentrations in the other. Concentrations near buildings can thus be estimated from wind-tunnel data if similarity can be shown to exist. The similarity requirements are given in a statement of the nondimensionalized source distribution and the flow-field boundary conditions, called the configuration, and in hydrodynamic parameters of the flow field. Similarity is established if the configuration coefficients and certain hydrodynamic parameters have the same numerical value on all scales.

The important configuration specifications for concentration fields near buildings include the source distribution, a statement of how A and V are to be measured, the geometric characteristics of the building and terrain, the orientation of the building to the mean wind, the mean and turbulent velocities $\bar{u}$ and $\sigma_{u,v,w}$ in the background flow, the mean velocities in the exhaust and intake apertures V_e and V_i , and the maximum temperature excess in the flow field over the temperature of the background flow ($T_1 - T$). The nondimensionalizing constants are V for velocities, $L = (A)^{1/2}$ for length, and the absolute temperature of the background flow, T , for temperatures. Under adiabatic conditions the logarithmic wind profile given by $\bar{u}/v_* = (1/k) \ln(z/z_0)$ will be reproduced if v_*/V and z_0/L are maintained constant.

The hydrodynamic parameters are the Reynolds number $Re = LV/\nu$, the modified Froude number $Fr' = V^2T/Lg(T_1 - T)$, and fL/V , where f is the peak frequency of the background-flow energy spectrum.

5-5.6.2 Sources Within the Cavity. Three techniques have evolved from experience in applying model data to full-scale conditions. The first is the order-of-magnitude approach using char-

acteristic values of K_c at various points near buildings without considering the details of the configuration (see Sec. 5-5.3.3). The second involves matching a given full-scale configuration to one of the model test configurations. The third seeks to specify the decrease in concentration in a hypothetical effluent jet or plume without considering the shape of the axis (see Secs. 5-5.5.3 and 5-5.6.4). It is often useful to compare the results from the three methods to judge the reliability of any one.

The accuracy of prediction of full-scale concentrations on the basis of K_c values in Sec. 5-5.5 is thought to be within a factor of 3 for short-period peak concentrations and for mean concentrations in very steady low-turbulence winds. On the basis of recent and as yet unpublished test data (Halitsky, 1965a), it would appear that the tunnel data overestimate the time-mean values in adiabatic conditions by factors up to possibly 10. The following discussions of testing procedures may be helpful in making the best choice of available K_c values and in conducting future tests with a minimum of procedural error.

In practical testing, Re and Fr' cannot be maintained constant simultaneously over a change in scale, but the errors introduced into the K_c field by ignoring these criteria have been found to be negligible for sharp-edged buildings whose LV product is greater than 2 sq ft/sec and whose maximum temperature difference, $T_1 - T$, is less than 100° F. Rounded buildings have a considerably higher critical LV product, but such values have not been established. The turbulent wind energy peak at roof level (for vertical oscillations at least) occurs in the atmosphere at $fL/V \approx 0.2$. Therefore the time for one significant oscillation of the wind is $1/f \approx 5L/V$, and the distance traveled by an air parcel in this time is $5L$. This is of the same order as the length of the cavity, a fact that indicates the time-mean cavity flow in the tunnel will not be similar if the frequency of the characteristic wind oscillation in the tunnel is greater than $0.2 V/L$. With customary tunnel values of $L = 1$ ft and $V = 5$ ft/sec, the maximum characteristic frequency of tunnel oscillations should be about 1 cycle/sec. There is no lower limit to the characteristic testing frequency, but the sampling time required to obtain a true mean K_c value should be in excess of $1/f$.

The model test data in Sec. 5-5.5 were obtained under isothermal conditions and with LV products varying from 5 to 10 sq ft/sec; therefore the prism and Clinical Center tests can be assumed to be free of Re and Fr' inaccuracies. The nuclear-reactor shell test probably had a Re scaling defect. The approach-wind profile was different in each test, and this should be noted in using the data. The failure to scale the approach-wind characteristics in the Clinical Center test was mitigated by the presence of auxiliary buildings and trees, which introduced aerodynamic flow distortions comparable to those occurring in full scale. Long-period oscillations were not introduced in any of the tests.

5-5.6.3 Sources Above the Building Cavity. When the stack height is such that the effluent is discharged near the cavity boundary over the roof, the momentum in the effluent is usually sufficient to carry the gas outside the cavity, but the lower edge of the expanding plume may pass through the cavity boundary and thus provide a secondary source of building contamination. A method for calculating the stack height needed to limit the concentration at the building surface to a stated amount is given by Halitsky (1965).

Raising the release point still higher will prevent the plume from entering the cavity and thus prevent gas recirculation to the building, but, if the release point is not high enough, the combination of aerodynamic downwash and large wake turbulence can cause the gas to reach the ground closer to the stack and produce a higher maximum ground concentration than in the absence of the building.

If the mean velocity and turbulence in the wake can be defined, ground concentrations can be estimated by conventional diffusion equations. The plume is assumed to diffuse uniformly about a curved center line whose coordinates are calculated by procedures outlined in Sec. 5-2. However, the plume rise is referred to the curved streamline through the stack top rather than to a horizontal one. This system is feasible if the curvature is small and the turbulence is fairly homogeneous.

Another theoretical approach, suggested by Burger (1964), employs a hypothetical potential flow outside the cavity to simulate the streamlines and combines the flow properties

analytically with the Fickian diffusion equation. The flow used by Burger is that around a Rankine oval, suggested originally by Arie and Rouse (1956) but modified in proportions to represent a three-dimensional building. Burger illustrates his analysis by calculating the required stack height for various locations of a stack on a building such that a given ground concentration is not exceeded.

All theoretical approaches to this problem have in common a lack of information on streamline curvature and turbulence distribution in wakes. Even the data on the wake of a suspended flat plate (Sec. 5-5.2.2.1) contain a gap about $5 \leq x/L \leq 20$, which is particularly unfortunate since a rapid wake expansion seems to take place in this region, as evidenced by the discrepancies in wake-boundary radius given by Eqs. 5.67 and 5.68 and illustrated in (b) of Fig. 5.18. The wind-tunnel work of Arie and Rouse (1956) on wake flow measurements downwind of a two-dimensional fence in a uniform flow and that of Nagabhushanaiah (1961) in a floor boundary layer are helpful in this respect, but they should be augmented by three-dimensional studies in airstreams with controlled mean-velocity profiles and turbulence. Detailed wake measurements in the lee of buildings in a natural wind would, of course, be most desirable.

Wind-tunnel testing is a feasible method for determining ground concentrations for plumes that intersect the wake beyond the cavity, but greater care must be taken to introduce appropriate background turbulence than in the case of sources within the cavity. In both cases aerodynamically generated turbulence and background turbulence contribute to plume diffusion, but in the cavity the aerodynamic turbulence is dominant, and in the wake the background turbulence assumes increasingly greater control as the wake turbulence decays with distance downwind (Islitzer, 1965).

No wind-tunnel measurements of concentrations in plumes that have descended into the wake appear in the literature owing partly to the limited number of facilities available for this type of test and partly to the policy of industrial sponsors not to release such information. It would appear that a major contribution can be made by systematically measuring the K_c fields for medium-height stacks on top of or adjacent to buildings.

Many wind-tunnel tests of power plants discharging furnace effluents at high temperature and velocity through medium-height stacks have been conducted without concentration measurements. The height of the bottom of the plume at a specified downwind distance is used as a criterion for ground contamination. At low wind velocity the plume is usually high above the ground. As the wind velocity increases, the thermal and velocity rise are progressively reduced, and a velocity is reached at which the bottom of the plume just touches the reference level. This critical wind velocity is determined by test as a function of stack height, stack arrangement, emission velocity, emission temperature, and/or other configuration variables. A suitable arrangement is chosen by estimating from weather data the number of annual hours that the natural wind can be expected to have velocities in excess of the critical and thereby cause ground contamination at distances beyond the reference station. If the critical wind velocity is sufficiently high, the hours of contamination will be few and the concentrations small. The procedure can be made increasingly conservative by placing the sampling station farther downwind. Test results of this type are reviewed by G. H. Strom in "Atmospheric Dispersion of Stack Effluents" (Chap. 6, Stern, 1962). Lord, Baines, and Leutheusser (1964) have reported more generalized tests of stacks near box-shaped buildings with various criteria relating to the character of the bottom of the plume.

Full-scale ground concentration measurements of dye released in the stub stack of a building, such as those by Munn and Cole (1965), have practical interest in that they are representative of real configurations, but the data have limited applicability to isolated buildings since effects of heated plume rise and effects of multiple wake interactions with auxiliary buildings cannot be separated.

5-5.6.4 Sources in Transverse Jets. A configuration frequently encountered in laboratory buildings is a flush roof vent or short chimney discharging a transverse jet with insufficient momentum to break through the roof of the cavity or to pass over a nearby fresh-air intake. In this arrangement the intake is exposed not only to the general cavity concentration but also to the higher concentration

in the jet plume. When the distance from the effluent aperture to the intake is greater than about 10 or 20 diameters, the formula derived from the Clinical Center test data can be used to estimate the axial plume concentration (Sec. 5-5.5.3).

At closer spacings more attention must be given to the center-line trajectory and the influence of jet velocity on the rate of decay of concentration with distance along and normal

to the jet center line. Halitsky (1966) treats this aspect in a semiempirical approach based on published data on transverse jet velocity and temperature distributions. Provision is made in the paper for extending the method to include the prism, Clinical Center, and reactor-shell test data and for estimating the location of the virtual point source for tall-chimney releases in an atmosphere with known diffusion coefficients.