Chapter 4

Diffusion and Transport Experiments

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4-1 SCOPE

The goals of diffusion experimentation are diverse, and this diversity works against the simple comparison of experiment results. The purest diffusion experiments attempt to relate the dynamic and physical characteristics of the earth-atmosphere system to the mean and turbulent atmospheric structure and, in turn, to relate these characteristics to diffusion. In other experiments, instead of investigating the genesis of the mean and turbulent flow, effort is directed toward establishing the relation between a number of particular atmospheric states and the concomitant diffusion. Some experiments are mounted to establish the diffusion climate of a particular site. Finally, there are experiments designed to evaluate the effects of a particular pollutant-releasing process. These motivational differences are reflected in experimental techniques and the resulting data.

The purposes of this chapter are to illustrate the relation between measured meteorological data and diffusion and to establish a set of diffusion parameters that can be estimated from meteorological observations at a given site. When the first edition of *Meteorology and Atomic Energy* was published in 1955, a small number of diffusion experiments had been described in the literature. These field trials were limited in range and in the type of data collected. Since 1955 a variety of tests, conducted in many topographic regimes and during a wide range of stability and wind-speed con-

ditions, has added significantly to the confidence with which the meteorologist can estimate diffusion from meteorological data.

Most of this chapter is devoted to a review and comparison of many recent diffusion experiments. A number of different criteria were observed in choosing the experiments to be discussed. Some experiments were included because of the broad range of meteorological conditions sampled, some, for the high quality and large quantity of data, and others, for the interesting features of the technique of relating meteorological data to diffusion data. A few experiments were included because they supplied measurements of diffusion during unusual or special conditions or at distances from the source at which no other measurements were available. Numerous small field studies that would add little to the discussion were excluded. Data that appeared to be presented in interim form or that were difficult to obtain owing to security restrictions were also excluded. The diffusion experiments noted in this chapter are listed in Tables 4.1a and 4.1b.

The primary concern in this chapter is the turbulent diffusion of gases and aerosols. Such effects as cloud rise, aerodynamics of flow around obstacles, deposition, washout, and changes in the effluent along its atmospheric path are discussed only when necessary to the interpretation of observed pollutant concentrations and cloud dimensions. These effects are discussed in Chap. 5.

4-2 PRESENTATION OF DATA

4-2.1 Sources and Limitations

For most continuous-source operational problems, the change of center-line axial con-

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Table 4.1a—SUMMARY OF RECENT CONTINUOUS-SOURCE DISPERSION EXPERIMENTS

Experiment	Location of experiment	Number of releases* and maximum sampling distance	Sampled material and sampling method	Height of release and release or sampling duration	Type of terrain and stability condition	Initial source size and temperature	Parameters directly measured
Elevated Sources							
Porton (Hay and Pasquill, 1957)	Porton Downs, England	19 releases; 500 m	Lycopodium spores; impaction on cylinders mounted on barrage-balloon cable	150 m; 30-min release	Gently rolling; slightly unstable to slight inversion	Small; ambient	Vertical concentration distribution
National Reactor Testing Station (Islitzer, 1961)	Idaho Falls, Idaho	16 releases; 1800 m	Uranin dye; aspirated samplers at 1.0 m	46 m; 30-min release	Flat desert; unstable	Small; ambient	Surface concentration distribution
Hanford (Hilst and Simpson, 1958)	Richland, Wash.	16 releases; 600 m	Fluorescent pigment and oil fog; impaction cylinders on blimp cable and photography	56 m; 60-min release	Flat desert; stable	Small; near ambient	Vertical concentration distribution and crosswind plume width
Harwell (BEPO) (Stewart et al., 1954)	Harwell, England	88 releases; 10^4 m	^{41}Ar ; beta counters on blimp cable and counters at surface	68 m; 15- to 60-min sampling	Built-up area and open country; stable and unstable	Stack diameter of 3.5 m; 50°C above ambient	Crosswind and vertical concentration distribution (not simultaneously)
Brookhaven National Laboratory	Central Long Island, N. Y.	Many; 5×10^4 m	Oil fog, ^{41}Ar ; and irradiated spheres; a variety of sampling methods	Surface and 115 m; short to about 1 hr	Low woods and open fields; stable and unstable	Variety; variety	Crosswind and vertical concentration distributions
Tennessee Valley Authority (Gartrell et al., 1964)	Northwestern Ala.	24 releases; 1.6×10^4 m	SO_2 in stack gases; titrillog and recorder mounted on aircraft	100 m; short sampling time during aircraft passes	Gently rolling; neutral and stable	Stack diameter of 5 m; 145°C	Crosswind and vertical concentration distribution

				<u>Surface Sources</u>			
Project Prairie Grass (Cramer, 1957, and others)	O'Neill, Neb.	70 releases; 800 m	SO ₂ ; gas drawn through hydrogen peroxide solution	0.5 m; 10-min release	Flat prairie; stable through unstable	Small; ambient	Crosswind concentration distribution at 1.5 m and limited measurements of vertical concentration distribution
Project Green Glow and 30 series (Fuquay et al., 1964)	Richland, Wash.	46 releases; 2.56×10^4 m	Zinc sulfide; aspirated filters	1.5 m; 30-min release	Flat desert; stable and unstable	Small; ambient	Crosswind concentration distribution at 1.5 m and limited measurements of vertical concentration distribution
Project Ocean Breeze (Haugen and Fuquay, 1963; Haugen and Taylor, 1963)	Cape Kennedy, Fla.	76 releases; 4800 m	Zinc sulfide; aspirated filters	2.0 to 3.0 m; 30-min release	Sand dunes and dense scrub; unstable	Small; ambient	Crosswind concentration distribution at 1.5 and 4.5 m
Project Dry Gulch (Haugen and Fuquay, 1963; Haugen and Taylor, 1963)	Vandenberg AFB, Calif.	109 releases; 5665 m	Zinc sulfide; aspirated filters	2.0 to 3.0 m; 30-min release	Rough foothills; unstable	Small; ambient	Crosswind concentration distribution at 1.5 m
National Reactor Testing Station (Islitzer and Dumbauld, 1963)	Idaho Falls, Idaho	35 releases; 3200 m	Uranin dye; aspirated filters	1.0 m; 60-min release	Flat desert; stable and unstable	Small; ambient	Crosswind and limited vertical concentration distribution
United Kingdom (Hay and Pasquill, 1959)	Porton Downs, England	8 releases; 100 m	Lycopodium spores; adhesive cylinders	2 m; 3-min release	Downland; mixed	Small; ambient	Crosswind concentration distribution
United Kingdom (Pasquill, 1962a)	Cardington, England	10 releases; 7.5×10^4 m	Fluorescent pigment; rotating-drum filters mounted on aircraft	Surface; continuous release and short sampling by aircraft	Downland; unstable	Small; ambient	Limited crosswind and vertical concentration distribution

*The number of experiments used in analyses are frequently fewer than the total number performed owing to faulty equipment, unexpected wind shifts, etc.

Table 4.1b—SUMMARY OF RECENT QUASI-INSTANTANEOUS-SOURCE EXPERIMENTS

Experiment	Location of experiment	Number of releases and maximum sampling distance	Sampled material and sampling method	Height of release and release duration	Type of terrain	Initial source size and temperature	Parameters directly measured
(Smith and Hay, 1961)	Porton Downs, England	10 releases; 300 m	Lycopodium spores; impaction on adhesive cylinders	Surface; 1 sec	Downland	1 to 4 m; ambient	Surface dosage distribution
Sand Storm (Taylor, 1965)	Edwards AFB, Calif.	43 releases; 2400 m	Beryllium powder in rocket propellant; aspirated filters	Surface (plus initial height of rise); 2 to 8 sec	Flat desert	Diameter of 15 to 45 m; above ambient	Surface dosage distribution
(Högström, 1964)	Ågesta and Studsvik, Sweden	430 releases; ≈ 5000 m	Oil fog; photography from position upwind of source	24 to 87 m; 30 sec	Low hills	Small; close to ambient	Puff width and puff depth
Dugway (Cramer et al., 1964)	Dugway Proving Grounds, Utah	33 releases; 1100 m maximum used here	BW and CW gases and particulates	Surface; 3 and 26 sec	Flat desert	Finite but accounted for by authors; near ambient	Surface dosage distribution and limited measurements of vertical distribution
Point Arguello (Smith et al., 1964)	Naval Missile Facility, Pt. Arguello, Calif.	17 releases; $\approx 10^4$ m	Zinc cadmium sulfide; rotorods and aspirated filters	Surface; 1 min	Rugged coastline	Small; ambient	Dosage along irregular arcs
Reactor Destruction Test (Islitzer and Markee, 1964)	National Reactor Testing Station, Idaho Falls, Idaho	4 releases; 6100 m	Fission products; aspirated filters	Surface; <30 sec	Flat desert	10 meters; above ambient	Surface dosage distribution
Texas (MacCready, Smith, and Wolf, 1961)	Dallas TV tower, Cedar Hill, Tex.	37 releases; $\approx 10^4$ m	Zinc cadmium sulfide; aspirated filters on tower	110 to 320 m; small (aircraft-released line source upwind of tower)	Rolling terrain	Finite but accounted for by authors; ambient	Vertical dosage distribution on tower

Table 4.2—SUMMARY OF DIFFUSION COEFFICIENTS*

Identification	Diffusion coefficients	Plume dimensions
Sutton	C_y, C_z, n_y, n_z	$\sigma_y = \frac{1}{2^{1/2}} C_y x^{2-n_y/2}$ $\sigma_z = \frac{1}{2^{1/2}} C_z x^{2-n_z/2}$
Fickian	K_x, K_y, K_z	$\sigma_y = (2K_y t)^{1/2}$ $\sigma_z = (2K_z t)^{1/2}$
Cramer	$\sigma_\theta, \sigma_\phi, p, q$	$\sigma_y = \sigma_\theta x^p$ $\sigma_z = \sigma_\phi x^q$
Pasquill	$\sigma_{\theta(T,t)}, \sigma_{\phi(T,t)}$	$\sigma_y = \sigma_{\theta(T,t)} x$ $\sigma_z = \sigma_{\phi(T,t)} x$

*The symbols T and t represent the sampling time and averaging time, respectively.

centration must be known as a function of distance. In addition, the horizontal and vertical dimensions of the plume are usually required, and the ground surface area contained within a particular isopleth of air concentration or exposure may be required. The diffusion coefficients needed to compute these quantities from the various diffusion models for a continuous point source (discussed in Chap. 3) are listed in Table 4.2. Symbols used frequently in Chap. 4 are included in the list of symbols given at the beginning of Chap. 3.

For instantaneous-point- or instantaneous-line-source concentration calculations, diffusion along the direction of the mean wind also must be considered. This requires diffusion coefficients along the x-axis. Sutton's derivation actually considered a single value for n, but it has been shown by Barad and Haugen (1959) among others that different values of n along the y- and z-axes are needed to fit the measured diffusion data and that neither n_y nor n_z can be obtained from the wind profile. Therefore identification of the coefficients in Table 4.2 with Sutton is primarily for historical convenience since their original meaning has been lost by the use of empirical constants.

In some studies the data were not presented in a manner compatible with the format; so recomputation or replotting was necessary. However, every attempt was made to ensure that the findings and conclusions emphasized by the original authors were not violated.

A review of the diffusion experiments summarized in Tables 4.1a and 4.1b cannot but impress the reader with their overall inade-

quacy in some respects. This is not a criticism since, in most cases, the inadequacies were engendered by logistical and technical difficulties, funding limitations, operational requirements, and other similar problems that preclude truly comprehensive diffusion experiments. Some of these shortcomings are:

1. Limited extent of sampling grids. The diffusion experiments described later in the chapter can be divided into two types: those in which the sampling was carried out on geometrical grids involving hundreds of samplers and those in which sampling was carried out by a limited number of mobile sampling systems individually placed for each experiment. The former experiments usually have supplied the more comprehensive data. The data from dense surface sampling grids, except for a few percent of the observations, have been confined to distances of less than 5 km. This is probably a consequence of funding and manpower limitations since the technical feasibility of surface sampling has been demonstrated to distances of over 25 km and aircraft sampling using various tracers has been accomplished to distances in excess of 100 km.

Even the extensive horizontal grid experiments, however, lacked similarly extensive vertical measurements of turbulence and diffusion. Although the detailed description of the vertical plume distribution presents a probably insurmountable logistic and funding problem, a considerable amount of information can be obtained from the careful use of a limited number of tower and balloon- and aircraft-borne samplers.

In addition to limited vertical measurements, orientation of the grids in fixed directions frequently precluded sampling during conditions characterized by shifts and large angular changes in wind direction, conditions not described by theory but certainly within the realm of experimental measurements.

2. Diffusion during nonhomogeneous turbulence conditions. Although homogeneous turbulence is called for by most diffusion theory, the atmosphere never approaches vertical and infrequently approaches horizontal homogeneity. This is particularly true during radiational inversions, which are marked by strong vertical gradients of wind speed, wind direction, and turbulence. The limited angular extent of the grids and the paucity of elevated meteorological sensors and tracer samplers in most experiments limit the description of diffusion during just those times that diffusion is of greatest interest. Furthermore, diffusion experiments in regions of topographic complexity have not been of the scope necessary for general solutions.

3. Time interval of tracer release and sampling. The release of pollutants from single sources in the nuclear-energy industry varies from virtually instantaneous releases to continuous releases over periods of years. The major experimental studies have, with few exceptions, been conducted for release and sampling times in the range of a few minutes to a few hours. Only rarely has an experimental series been designed to furnish data over a variety of release and sampling times.

4. The effects of deposition. The data from most diffusion experiments conducted using sources in the lowest hundred or so meters of the atmosphere probably include the effects of deposition of the tracer used. Because of the difficulty of experimentally determining deposition, the study of this effect has not always been a part of a diffusion-experiment series. Since deposition will affect the absolute value of concentration, the rate of concentration decrease with distance, and the vertical concentration distribution, the lack of these data can be considered an important gap in experimental knowledge.

4-2.2 Concentration, Exposure, and Dosage

The diffusion data presented in this chapter will usually be discussed in terms of instantane-

neous concentration, χ , exposure ψ , or average concentration, $\bar{\chi}$. As noted in Chap. 3, Sec. 3-3.5.8, these quantities may be defined as:

$$\chi = \frac{\text{amount of pollutant}}{\text{volume of mixture}} \quad (4.1)$$

$$\psi = \int_{T_0}^{T_0+T} \chi \, d\tau \quad (4.2)$$

$$\bar{\chi} = \frac{1}{T} \int_{T_0}^{T_0+T} \chi \, d\tau \quad (4.3)$$

where χ in each case is the concentration at a given moment. Note that the definition of dosage as the product of exposure and flow rate is in wide use and will be adopted here.

In practice extensive measurements of χ are not at all common because the relative complexity of the real-time or sequential samplers required for such measurements usually prohibit their use in large numbers.

The major diffusion experiments, those with numerous sampling arcs and many hundreds of samplers, usually involved measures of exposure rather than of average concentration. In these experiments the samplers were actuated before the dispersing tracer arrived and were deactivated after the last of the tracer was assumed to have passed. These times were estimates only since real-time or sequential samplers were not in wide use. (The reason for this sampling mode in experiments which are considered to describe continuous-source characteristics over finite time intervals is that the cost of the equipment necessary to activate and deactivate hundreds of samplers simultaneously during the emission of a continuous plume is inordinately large.)

Among the detached plume surface-source experiments in the group just discussed are the Prairie Grass tests (Sec. 4-4.2.1), Green Glow and 30 tests (Sec. 4-4.2.2), Projects Ocean Breeze and Dry Gulch (Sec. 4-4.2.3), and the National Reactor Testing Station (NRTS) series (Sec. 4-4.2.4). In each of these experiments, one must assume some elapsed time interval in order to compute a value of $\bar{\chi}$. In the Prairie Grass and NRTS series, this time interval was assumed to be equal to the release time. For the comparatively short distances investigated during these experiments, this assumption is probably reasonable if the problem to be in-

investigated is the average concentration in a continuous plume. Some error must be introduced, however, since the total time required for the passage of all the material in a detached plume at a point downwind must be greater than the release interval because of the effects of along-wind turbulent diffusion and the along-wind spreading introduced by vertical wind shear in a turbulent medium. Unpublished estimates indicate that, at measurement distances greater than those of the Prairie Grass and NRTS series, detached plumes may require as much as twice the release time to pass a given point. Dividing the exposure by a time interval equal to the release time will indeed give an average concentration in such cases of elongated plumes (as does the assumption of any time interval), but the meaning of such average concentrations must be very precisely known if they are to be related, for instance, to meteorological indices. If the entire elongated detached plume is sampled, however, one would expect nearly the same level of exposure as would be obtained by sampling a continuous-source plume for a period of time equal to the release time of the detached plume.

Since the experiments just noted were all performed in a similar manner, normalization of the exposure or the average concentration by the appropriate source strength (total amount of source or amount of source per unit time, respectively), as usually done in this chapter, yields values which are identical dimensionally and similar numerically and which therefore may be directly compared.

4-2.3 Summary Diagrams

The data from the various experiments discussed in this chapter are summarized in the nine diagrams listed below:

- Fig. 4.5 σ_z , elevated continuous sources
- Fig. 4.6 $\bar{x}_p \bar{u}/Q'$, elevated continuous sources
- Fig. 4.21 σ_y/σ_θ , surface and elevated continuous sources
- Fig. 4.22 σ_y , long travel time
- Fig. 4.23 σ_y , long travel distance
- Fig. 4.24 $\bar{x}_p \bar{u}/Q'$, surface continuous sources
- Fig. 4.38 σ_{y1} , surface and elevated instantaneous sources
- Fig. 4.39 σ_{z1} , surface and elevated instantaneous sources
- Fig. 4.40 $\psi_p \bar{u}/Q$, surface instantaneous sources

These diagrams generally contain measured values of the data (reduced to some common

basis) determined during the individual experiments. On occasion, where insufficient data are available, computed values have been entered. The effects of deposition and finite source size have been accounted for in certain cases. Such manipulations of observed data are noted in appropriate sections of the text.

4.3 DIFFUSION-ESTIMATION METHODS

Over the years three methods of estimating diffusion from a minimum of measured meteorological data have come into common use. The first of these, by Sutton, is described in Chap. 3, Sec. 3-2.2.4. The analytic form of the equations, the variety of equations for many specific calculations, and the body of experimentally determined values of the diffusion coefficients C_y , C_z , and n recommended this method to many.

In 1957 Cramer published a set of three graphs from which the plume dimensions σ_y and σ_z or the concentration, $\bar{x}$, for distances up to 1.6 km could be determined directly from a knowledge of the horizontal wind-direction standard deviation (Cramer's σ_A). The curves in these graphs were based on the Project Prairie Grass and the Round Hill data (Cramer, 1957). The completeness of this system (estimates could be made by simple reference to one or two graphs) and the simplicity with which it could be applied recommended this approach to an increasingly large audience. If σ_A (referred to as σ_θ) and σ_E the vertical wind-direction standard deviation (referred to as σ_ϕ) are known, Cramer suggests that the equations credited to him in Table 4.2 be used.

An effort was made by Pasquill, in an unpublished note the substance of which was later presented in a paper by Meade (1959) and, again, by Pasquill (1961), to develop a simple system of downwind concentration estimation. Pasquill suggested that both σ_y and σ_z be estimated in accordance with the suggestions of Hay and Pasquill (1959). The Hay and Pasquill paper presented a convenient method of estimating both vertical and lateral cloud spread from measurements of wind-direction fluctuations made with a suitably responsive instrument. Recognizing that the data on vertical wind-direction fluctuation required by this

method were not generally available, Pasquill suggested values for the appropriate degree of vertical spreading which could be estimated from stability considerations. He suggested that stability be estimated from wind speed and the degree of insolation. He also indicated how the lateral spreading of the plume could be estimated from the range of the wind-direction trace for long (about 1 hr) pollutant releases and suggested a series of wind-direction-range values to be used in lieu of actual wind measurements for short releases during steady wind-direction conditions. These direction-range values were related to the same estimates of stability used to infer the vertical spreading.

As pointed out by Pasquill and also by Gifford (1961), the values of plume height (h) and width (θ) described by Pasquill can be expressed in terms of the diffusion coefficients σ_y and σ_z of the generalized Gaussian plume model. Gifford performed this conversion and presented the resulting curves (Gifford, 1961). In Gifford's scheme diffusion estimation is achieved by estimating both σ_y and σ_z from the appropriate curves representing the various thermal-stability values, which are, in turn, estimated from cloud cover, wind speed, and (by day) insolation intensity. These curves are presented in Sec. A-3 of the Appendix for comparison with experimental data in diagrams in this chapter. To date no one has systematically related the estimated stability categories to Cramer's σ_θ categories or to values of σ_θ and σ_ϕ computed as suggested by Hay and Pasquill in their 1959 paper.

The diffusion experiments described in this chapter will fall under one of two headings depending on whether the releases were instantaneous (or in practice quasi-instantaneous) or continuous. The experimental data were neither observed nor published in sufficient detail to allow the presentation of a complete selection of diffusion parameters as a function of meteorological conditions or height above the surface.

4-4 CONTINUOUS SOURCES

4-4.1 Continuous Elevated Releases

Continuous elevated releases are of interest in practical applications since many real releases take place at some distance above the earth's surface. Measurements of axial con-

centration are difficult to obtain because of the problem of positioning samplers at a sufficient distance above the surface. Elevated-source plume-center measurements have rarely been made from a grid of towers. Consequently axial concentration measurements have involved manually positioned samplers suspended from large balloons in the plume center or traverses by helicopters or light aircraft. Since the elevated plume will usually disperse toward the surface, the conventional surface sampling grids have been used successfully to infer the rates of crosswind spreading under all but very stable conditions.

In some cases, particularly during strong inversions, estimates of diffusion are simplified by the comparative unimportance of surface deposition of the plume material. In others, such as the Hanford elevated-source releases, the plume released under strong inversion conditions did not reach the ground for great distances, and thus deposition did not occur.

4-4.1.1 Porton, United Kingdom. Some of the first organized attacks on the problems of diffusion experimentation were initiated in 1921, the year that the Meteorological Department of the Chemical Defense Experimental Station at Porton, England, began operation. Some of the most important work done at the station during the 1920's and 1930's centered about determinations of the shape and magnitude of the downwind lateral diffusion from continuously maintained sources. These early measurements, by hand-operated instrumentation quite crude by today's standards, were adequate for describing the crosswind concentration distribution, the change of this distribution with distance, at least in the first few hundred meters, and the stability dependence of the magnitude of the spreading. An excellent summary of these early measurements, partially based on hitherto unpublished data, may be found on pp. 127-137 of *Atmospheric Diffusion* by Pasquill (1962).

In 1957 Hay and Pasquill published some of the first results of their various experiments designed to relate atmospheric diffusion directly to concurrent wind fluctuations. A continuous source of Lycopodium spores was generated at 150 m above the ground and sampled at distances from 100 to 500 m downwind by a series of samplers suspended along the cable

of a barrage balloon. Hay and Pasquill gave the results of 10 such experiments, each lasting approximately 30 min. It was found that σ_ϕ , measured in angular units at the height of the source, was remarkably similar to σ_z , the particle distribution, also measured in angular units, to distances of 500 m. This indicated to the authors that, to a fair approximation, the particles traveled in almost straight lines from the source to the samplers. From this fact they concluded that the Lagrangian correlation coefficient remained close to unity over the travel times of these experiments. The ratio σ_z/σ_ϕ varied from 0.94 to 1.25 in eight of the experiments; the other two experiments exhibited values outside this range owing to marked inhomogeneity in the turbulence. The arc average value of σ_z for essentially neutral conditions was about 3.9° . The average σ_z value is shown by the Hay-Pasquill line in the summary diagram, Fig. 4.5.

4-4.1.2 National Reactor Testing Station (NRTS), Idaho Falls. The NRTS test was a series of 16 releases of a fluorescent tracer, uranin dye in solution, made in unstable atmospheres from the top of a 46-m tower (Islitzer, 1961). The terrain at this site is fairly flat with desert characteristics. The tracer was released for 30-min periods over a dense grid consisting of six arcs of samplers extending 150 to 1800 m from the 46-m-tower release point. The meteorological tower was instrumented at several levels with bivanes and anemometers.

One of the most interesting aspects of the NRTS test was the direct evaluation of plume width from horizontal wind-direction-fluctuation data. The wind direction at the 46-m level was read as 5-sec end-to-end averages for the period of the test. The standard deviation of this series was computed, multiplied by the distance from the source, and plotted against the measured particle-distribution standard deviation values computed for each of the 16 releases at each of the six arcs. The result of this rather simple use of the wind-direction fluctuation is given by the expression

$$\sigma_\phi x = 1.23 \sigma_y \quad (4.4)$$

and is shown in Fig. 4.1. The horizontal component of the wind direction was also averaged over a time period equal to $x/\bar{u}\beta$ (where x is distance from source to arc, $\bar{u}$ is average wind

Fig. 4.1—The relation between measured values of σ_y and those estimated from wind fluctuation data. The data are taken from elevated-source experiments. (From Islitzer, 1961.)

speed, and β is 4.0) for each sampling arc. The improvement in correlation by equating the time-averaged σ_ϕ values to σ_y was not significant, partly because of the rather slow change of σ_ϕ with averaging time for the time scales in these experiments. A mean travel time of 100 sec for the 82 cases used implies a mean averaging time of only 25 sec. The effect of ignoring the variation of the wind-direction fluctuations with height may have also tended to prevent a better agreement.

The mean value of the cloud standard deviations for the 16 releases is plotted in the summary diagram, Fig. 4.21. Islitzer also showed that, on the basis of measurements of the distance from the source to the point of maximum ground-level air concentration and assuming rectilinear dispersion,

$$\sigma_\phi x = 1.23 \sigma_z \quad (4.5)$$

a direct use of the 5-sec averaged vertical wind-direction-fluctuation data at source height. The use of σ_y and σ_z values obtained from Eqs. 4.4 and 4.5 in the Gaussian plume-concentration formula results in downstream computed surface-concentration values closely matching the observed at all distances.

The measured meteorological data for each release including the distance to the point of maximum ground-level air concentration ($d_{\max}$) are shown in Table 4.3. There is a rather good

Table 4.3—METEOROLOGICAL DATA AND $d_{\max}$. FOR
ELEVATED-SOURCE STUDIES DURING LAPSE
CONDITIONS AT NRTS*

Test	$\bar{u}$ (46 m), m/sec	ΔT (46 to 3 m), °F	σ_θ (46 m), deg	σ_φ (46 m), deg	$d_{\max}$, m
2	5.7	-2.5	6.9	4.5	700
3	6.5	-5.4	8.8	7.8	300
4	7.0	-1.6	5.4	3.5	800
5	8.9	-4.8	6.2	5.0	530
6	9.7	-3.5	7.0	4.6	650
7	7.8	-4.0	8.9	6.4	600
8	7.2	-4.0	12.6	6.8	560
9	10.0	-6.1	7.7	4.2	600
10	7.7	-5.3	7.9	5.0	800
11	6.7	-5.6	25.6	10.2	315
12	8.1	-3.4	4.2	4.1	940
13	11.3	-1.9	6.7	4.3	600
14	9.0	-5.4	8.4	6.0	480
15	6.5	-2.8	14.6	8.4	300
16	10.6	-3.9	6.6	4.4	730
17	6.5	-6.1	20.8	10.6	250
Mean	8.1	-4.1	9.9	6.0	572

*From Islitzer, 1961.

correlation between σ_φ and $d_{\max}$, in contrast to the poorer relation between the vertical temperature gradient and $d_{\max}$.

The problem of deposition, probably minor for these elevated source experiments, was not considered.

4-4.1.3 Hanford, Washington. Measurements of vertical diffusion in elevated plumes during various degrees of inversion intensity were made at Hanford, Wash. (Hilst and Simpson, 1958). A fluorescent pigment was emitted from the 56-m level of a tower for 60-min periods simultaneously with a continuous plume of smoke used to observe the visual width of the dispersing particles. The vertical concentration distribution of the fluorescent pigment was obtained from an array of cylindrical impaction samplers held aloft by tethered blimps and centered in the visible smoke plume during the tests. Simultaneous observations at a variety of distances to 600 m from the source permitted the empirical determination of the distance dependency of σ_z .

The horizontal spread of the smoke plume was photographed at 1-min intervals from an altitude of 1800 m. From these photographs both the horizontal width of the plume and the displacement of the plume center from the time-mean axis, as defined by the mean wind direction, were obtained. By making assump-

tions about the horizontal concentration distribution in a plume segment, Hilst (1957) deduced values for the short-period horizontal particle variance about the instantaneous-plume axis. This variance, when added to the meander, i.e., the variance of the plume center about the time-mean axis, gives the total horizontal particle-distribution variance.

The range of the σ_z data is summarized in Fig. 4.5, and the average of the σ_y data, in Fig. 4.21. Peak-to-average air-concentration values based on this experiment are presented in Sec. 4-5.

4-4.1.4 Harwell (BEPO), United Kingdom. Measurements of diffusion using the radioactive ^{41}Ar from the 68-m reactor stack of the Harwell Pile (BEPO) were reported by Stewart, Gale, and Crooks (1954). Vertical profiles of beta activity through the axis of the plume were measured out to 1000 m with a large blimp and an array of 10 beta counters on a cable. Ground-level surveys of both gamma and beta measurements were carried out to 10,000 m. A variety of meteorological conditions were sampled for times up to 60 min. The test site consisted of reactor buildings and built-up area to 500 m downwind from the stack with open country beyond. In addition to inhomogeneous terrain, the large finite size of the stack (3.5 m in diameter) and the efflux conditions of

the ^{41}Ar gas (50°C temperature excess above ambient air and 10 m/sec stack velocity) introduced mechanical turbulence and buoyant plume rise that influenced the sampling results.

From the vertical profiles of radioactivity, Stewart, Gale, and Crooks (1954) computed σ_z and then obtained σ_y from the air concentration, $\bar{\chi}_p$, in the plume center by

$$\sigma_y = \frac{Q'}{\pi \bar{\chi}_p \sigma_z \bar{u}} \quad (4.6)$$

The values of σ_z and σ_y found in this manner would be appropriate for computations of air concentration in the elevated plume. In addition, crosswind surveys of ^{41}Ar radioactivity were carried out to 10,000 m on the ground, and σ_y was determined. The σ_z values appropriate to diffusion from the elevated source to the ground could then be computed from Eq. 4.6 when σ_z and σ_y are interchanged. Apparently, simultaneous crosswind and vertical surveys were not attempted or were inadequate for the determination of σ_y and σ_z at the same time. The diffusion coefficients C_y and C_z derived by Stewart et al. from the measured σ_y and σ_z values (Table 4.4) are appropriate for a 40-min sampling time. Average values of σ_z are presented in Fig. 4.5.

The values for C_y and C_z in Table 4.4 were computed with the assumption that $n = 0.25$ for all conditions. The decrease of the diffusion coefficients with distance is attributed to the dying out of the mechanical turbulence downwind of the buildings, and Stewart et al. deduced that a value of $n = 0.16$ is appropriate for both C_y and C_z over the open country surrounding the BEPO installation. The decrease of C_y with

distance in Table 4.4 is not surprising, but the relatively large values of C_z compared to computed values of C_y from elevated sampling, even during stable conditions, is contrary to experience at most sites. Stewart et al. ascribe these high C_z values to the mode of discharge of the ^{41}Ar from the stack. The effluent was measured to rise about 80 to 135 m above the stack with an inverse relation between effective stack height and wind speed.

The strong tendency for elevated plumes to remain aloft for large distances during stable conditions suggested by the studies at Hanford, Wash., was also found at Harwell. No area of ground-level ^{41}Ar concentration was found within 10,000 m of the stack during any of the six surveys under inversion conditions. The inversion plume rode above the region dominated by the building turbulence and undoubtedly experienced largely laminar flow instead of the vertical turbulence measured near the stack.

The average measured ground-level axial air concentrations for all the runs are shown in Fig. 4.2 for the Harwell and Idaho sites. The effect of different stack heights on $\bar{\chi}_{\max}$ and $d_{\max}$ is evident and in accord with theory. For instance, from Sutton equations assuming similar diffusion coefficients for both sites, one can derive the relations

$$\frac{\bar{\chi}_{\max,2}}{\bar{\chi}_{\max,1}} = \left(\frac{h_1}{h_2} \right)^2 \quad (4.7)$$

and

$$\frac{d_{\max,1}}{d_{\max,2}} = \left(\frac{h_1}{h_2} \right)^{2/2-n} \quad (4.8)$$

Table 4.4—EXPERIMENTAL DIFFUSION COEFFICIENTS*

Type of survey	Meteorological conditions	Sampling range, m	C_y		C_z	
			Computed	Measured	Measured	Computed
Vertical	Unstable	150 to 1000	0.16		0.27	
	Adiabatic		0.10		0.22	
	Stable		0.10		0.12	
Ground	Adiabatic	590 to 620		0.46		
	and	880 to 1050		0.28		0.32
	unstable	1200		0.33		
Ground	Adiabatic	2400 to 2800		0.26		
	and					
Ground	unstable	6000 to 9700		0.18		0.19
	Stable	1000 to 10,000				<0.04

*From N. G. Stewart, H. J. Gale, and R. N. Crooks, The Atmospheric Diffusion of Gases Discharged from the Chimney of the Harwell Reactor BEPO, *Intern. J. Air Pollution*, 1(1-2): 93 (1954).

The ratio of stack heights squared is $(61/46)^2 = 1.8$; $\bar{\chi}_{\max,2}/\bar{\chi}_{\max,1}$ from Fig. 4.2 is 2.8. If $n = 0.25$, $d_{\max,1}/d_{\max,2} = (61/46)^{1.14} = 1.4$, which is nearly the same as the measured value of this ratio from Fig. 4.2. Allowances for the effec-

tive stack height of the BEPO plume would improve the agreement.

4-4.1.5 Brookhaven National Laboratory, New York

Figures 4.3 and 4.4 summarize the results of atmospheric diffusion experiments conducted over a period of 15 years at the Brookhaven National Laboratory. The Brookhaven site is situated in central Long Island, N. Y., a region characterized by terrain rising to no more than 100 m above sea level with most relief being less than 50 m. The ground cover consists of alternating open fields and areas of scrub oak and pine extending to 10 m. A 130-m meteorological tower is instrumented with Aerovane and temperature instruments boomed toward the west-southwest.

The diffusion trials at this site can be divided into three groups: surface-release (2 m) diffusion-deposition tests to distances of about 100 m (Raynor and Smith, 1964), a series of elevated-source (110 m) diffusion experiments between 1949 and 1956 using oil fog (Smith, 1956), and aircraft sampling of the plume released from the Brookhaven reactor.

The data from the diffusion-deposition experiments are based on releases of irradiated ^{64}Cu particles, carefully elutriated to achieve a single size range. These particles and a solu-

Fig. 4.2—Comparison of average normalized ground-level axial air-concentration measurements from elevated-source experiments conducted at Harwell (BEPO) and at the National Reactor Testing Station (NRTS).

Fig. 4.3—Values of σ_y measured at the Brookhaven National Laboratory in a variety of continuous-source experiments. The trace types are based on the appearance of the wind records collected on the Brookhaven tower (See Sec. 4-4.1.5).

Fig. 4.4—Normalized concentration data from elevated oil fog releases at 110 m on the Brookhaven tower.

tion of uranin dye were sprayed from two separate nozzles over a 100-m square grid instrumented with 100 primary and 92 secondary samplers.

The oil fog experiments were generally conducted during daytime conditions when the existing turbulence was sufficient to carry the plume to the surface. The Brookhaven type D (stable) data in Fig. 4.4 were plume-center measurements made from an aircraft traversing the plume. The oil fog was measured by two different techniques. Photometric densitometers, operating on the principle of the 90-degree scattering of visible light, were used for continuous measurements at ground level.

No more than three densitometers were in operation simultaneously in any of the experiments. A second method requiring a membrane filter was also used. This method permits measurements to be made at a large number of points but gives no indication of short-term variation in the concentration levels. Both systems were calibrated independently and against each other.

The two types of measurement systems were used in three different ways. The densitometers were used to provide continuous concentration data at a fixed point at times ranging from a few minutes to several hours. These data were used to obtain peak-to-mean values.

The densitometers were also transported crossplume to obtain ground-level concentration-distribution patterns. The third method consisted of mounting 10 or more filter samplers in a crossplume direction to obtain plume-width statistics.

The appropriately marked σ_y values in Fig. 4.3 were obtained during aircraft measurements of the ^{41}Ar in the reactor plume. The data were obtained during temperature inversions by equipping a light aircraft with dual Geiger-tube detectors mounted under the wings. The detectors were identical except that one permitted free passage of air through an aluminum shield container and the other did not. Thus the former detector responded to both gamma and beta radiation from the ^{41}Ar , whereas the latter was effectively shielded against beta radiation. Individual disintegrations as detected by the Geiger tubes were recorded on a stereo tape recorder.

The σ_y data in Fig. 4.3 are stratified by the Brookhaven gustiness types. These types are subjective estimates of the lateral intensity of turbulence determined from analogue wind-direction recordings. The trace types have been found to correspond in the mean to the values of σ_θ given in Table 4.5. No σ_θ value is given for type A since the wind direction as defined in this case is too variable for the computation of this statistic. Using the σ_θ values corresponding to the trace types, one can see in the σ_y summary diagram (Fig. 4.21) that the Brookhaven values fit the other data very well.

The $\bar{x}\bar{u}/Q'$ data points presented in Fig. 4.4 were fitted by the values of the Sutton diffusion coefficients given in Table 4.6.

4.4.1.6 Tennessee Valley Authority, Colbert, Alabama. During the period 1957 to 1962, the Tennessee Valley Authority under the sponsorship of the Public Health Service conducted a diffusion research project at the Colbert coal-fired generating station in extreme northwestern Alabama (Gartrell et al., 1964).

The Colbert plant has four 200-Mw units each served by a 100-m stack. Stack diameter is 5 m, flue-gas exit velocity is 14 m/sec, and gas temperature at exit is about 145°C.

Sampling was accomplished by helicopter-mounted instrumentation including a portable Titirlog and recorder for measuring SO_2 con-

Table 4.5—VALUES OF σ_θ AND $\bar{u}$ CORRESPONDING TO THE BROOKHAVEN TRACE TYPES*

Trace type	σ_θ , deg	$\bar{u}$, m/sec
A		2
B ₂	20	3
B ₁	13	7
C	7	13
D	4	5

*Values were derived from wind measurements at 355 ft made with a 1-hr sampling time and a 6-sec averaging interval.

Table 4.6—VALUES OF SUTTON DIFFUSION COEFFICIENTS DETERMINED FROM BROOKHAVEN EXPERIMENTS

Trace type	n	C_y	C_z
B ₂	0.15	0.48	0.50
B ₁	0.26	0.44	0.38
C	0.48	0.54	0.32
D	0.57	0.41	<0.08

centrations, temperature probes, an altimeter, and an air-speed indicator. The sampling procedure consisted of flights perpendicular to the plume axis at distances from 0.8 to 16.0 km from the source during stable conditions and from 0.8 to 3.2 km during neutral conditions. A sufficient number of traverses were made at different altitudes at each distance from the source to ensure a complete sample of the width and depth of the plume. The lateral standard deviation of the concentration distribution as well as the peak concentration was obtained from the pass showing the highest concentration. The vertical standard deviations at each distance from the source were obtained from all passes at that distance. The plume statistics derived by this method of sampling are representative of a sampling time of a few minutes at the most. The measurements of the releases from the four Colbert stacks were adjusted by Gartrell et al. to approximate a point-source (single-stack) release.

Representative values of the plume measurements σ_z and $\bar{x}\bar{u}/Q'$ are plotted in Figs. 4.5 and 4.6, respectively. During very stable conditions the σ_z values show no increase with distance. This observation, identical to the Hanford experience, reflects the almost complete lack of vertical turbulence during such conditions. The initial rather large values of σ_z are probably caused by strong vertical mixing

Fig. 4.5—Summary diagram for measurements of σ_z , the standard deviation of the vertical material distribution in continuously maintained plumes from elevated point sources. The dotted lines represent the Pasquill estimates discussed in the text (Sec. 4-3).

as the hot plume is ejected from the stack. The slightly stable and neutral σ_z values have slopes that seem consistent with other data from elevated releases. The values of σ_y (not plotted) are curious in one respect. Although the rate of increase of σ_y with distance for neutral conditions is only slightly less than that observed in other experiments, the stable values show a considerably smaller slope (i.e., 74 m at a distance of 0.8 km and 247 m at 16.0 km).

The values of normalized center-line concentration are shown in Fig. 4.6. The similarity of the three TVA values plotted at 0.8 km may, again, be due to the dispersive characteristics

of the source configuration. The rather slow decrease of axial concentration with distance during the stable regimes is similar to observations at Hanford, and the neutral curve fits well with the other data.

4-4.1.7 Summary of Elevated Continuous-source Data.

The elevated continuous-source data are summarized in Figs. 4.5 (σ_z) and 4.6 ($\bar{x}_p \bar{u}/Q'$). Where possible, the σ_y data measured in these experiments have been included in the σ_y summary diagram (Fig. 4.21).

The elevated-source σ_y data plotted in Fig. 4.21 agree quite well in slope and magnitude both with the surface σ_y data and with the

Fig. 4.6—Summary diagram for normalized axial-concentration measurements for elevated releases. The Pasquill estimates are shown as dotted lines.

generally held opinion that σ_y is approximately proportional to $x^{0.65}$.

The few measured values of σ_z in Fig. 4.5 do not show the consistency of the lateral data. The difficulty in vertical measurement and the effects of nonhomogeneity of wind characteristics in the vertical, particularly during stable conditions, work against the simple comparison of data taken under different conditions at different sites.

The most interesting feature of Fig. 4.5 is the apparent cessation of vertical plume growth during stable conditions. There is no way to compare the degree of stability between the Hanford and TVA experiments, but it appears

from these experiments and from more subjective observation that vertical plume growth essentially ceases during strong inversions in the region above a few tens of meters over a rural area. The neutral curves from the Harwell and TVA experiments agree well with each other. The large values indicated at 100 m probably reflect the mode of emission from the large stacks.

The measured values of normalized concentration are presented in Fig. 4.6. The NRTS data did not include axial measurements and thus are not included. The most striking feature of Fig. 4.6 is the slow decrease of concentration with distance during stable condi-

tions when compared with the Pasquill curves. Again, the data representing warm jets from large stacks seem to show the effect of initial nonmeteorological dilution. The TVA (stable) and the Hanford (7A) curves indicate that the use of the Pasquill model might result in an underestimate of normalized axial concentration of an order of magnitude or more at distances of 10 km. The use of typical stable Sutton coefficients would similarly underestimate the measured data. It should be kept in mind, however, that wind speeds at typical stack heights during strong inversions will usually be considerably higher than those measured near the surface.

4-4.2 Continuous Surface Releases

The term "surface release" has been used to classify those experiments in which the height of release was within a few meters of the surface. More detailed diffusion data are available from continuous-source surface experiments than from any other type. Measurements of vertical distribution are noticeably lacking although effective vertical distribution data may be estimated from the excellent and copious measurements of the lateral spread and center-line (peak) concentration if an estimate of the deposition can be made.

A number of problems arise during surface-release experiments. During unstable (daytime) conditions the emitted plume disperses rapidly with distance from the source. Therefore measurement of tracer concentrations at the longer distances is difficult. Furthermore, the rapid vertical spreading rules out tower measurements of the vertical distribution of the tracer except at distances on the order of only a few hundred meters. Vertical distributions have been measured by aircraft- or tethered-balloon-borne sensors in such cases. However, the aircraft measurements, which are logistically the most flexible, provide only an instantaneous slice across the plume. Moreover, during extreme instability, such as might occur over a desert in summer, convective cells of sizes near the range of the total plume length can result in significant departures from the assumed state of turbulent homogeneity and thus preclude simple relations between turbulence information and concurrent diffusion.

During moderate instability the atmosphere is usually well mixed over reasonably regular

terrain. Diffusion experiments conducted under such conditions usually provide regular and reproducible patterns.

A variety of important effects must be considered when estimates of diffusion during stable situations are studied. As noted in Chap. 2, Sec. 2-6.1, the mean horizontal wind vector shows a decided shear in the lower levels of the atmosphere during inversions. Furthermore, the horizontal wind-fluctuation characteristics vary considerably with sampling time (Smith and Abbott, 1961) and also with height (Chap. 2, Sec. 2-6.3). The effect of steady-state shear on diffusion has been discussed by Barad and Fuquay (1962). The problem of the various possible vertical configurations of horizontal wind fluctuations and their effect on diffusion near the surface has rarely been treated in a systematic way. During a strong surface-based nocturnal inversion, the horizontal wind fluctuations above 100 m, or even less, will be small, with the wind direction frequently appearing as an almost laminar trace on conventional wind-recording equipment. At the surface, however, wind fluctuations ranging from those which give a 10-min σ_θ value of a few degrees to those which touch momentarily at every point of the compass are possible. This variety of wind-fluctuation values and their vertical gradients are reflected in a wide range of possible center-line concentration values.

A final feature of diffusion from surface sources during stable conditions is the rather large rates of aerosol deposition or active-gas adsorption that are possible. Since much of the material released from a surface source will remain within the region of the surface-roughness elements, the opportunity for plume depletion is large. This depletion lowers the downstream concentration values from those computed on the basis of turbulent diffusion and further modifies the shape of the vertical distribution of the effluent.

For the reasons discussed above, it is likely that a definitive surface-source stable-atmosphere diffusion experiment has yet to be accomplished.

4-4.2.1 O'Neill, Nebraska (Project Prairie Grass), and Round Hill Field Station, Massachusetts. Project Prairie Grass, a comprehensive turbulence and diffusion research project, was carried out

Fig. 4.7—The relation between plume width at 100 m and the standard deviation of the azimuthal wind direction. The data include both day and night experiments, and the regression line applies to both. (From Cramer, 1957.)

during the summer of 1956 over a large flat field in the Great Plains. A complete description of the experimental details and tabulations of diffusion and meteorological data has been presented (Barad, 1958, and Haugen, 1959). Numerous papers based on these measurements have been written (notably, Cramer, 1957, and Barad and Haugen, 1959). Cramer related the diffusion data taken during the experiments to the concurrent wind-fluctuation measurements (Table 4.2) and also summarized the results of a similar, although more limited, series of tests conducted at the Round Hill field station of the Massachusetts Institute of Technology.

The two studies present diffusion data for 90 field experiments: about 70 at the O'Neill site and 20 at the Round Hill station. Diffusion measurements at O'Neill were determined from sulfur dioxide gas released at 46 cm above the surface and sampled along semicircular arcs at from 50 m to 800 m from the source. The gas collectors were placed at a height of 1.5 m above the surface and were located along the arcs at 1- or 2-deg intervals. In addition, the vertical concentration distribution was available from six 20-m towers mounted along the 100-m arc. The tracer was released for 10 min in each experiment, sampling beginning prior to the arrival of the tracer at the first arc and ending after the last of the material had passed the last arc. The actual measurement was of exposure, but the authors assumed that the difference between the exposure and the aver-

age concentration computed for a 10-min sampling time was small and chose to use the concentration in their discussions. Similar measurements were made at the Round Hill site at arcs located 50 m, 100 m, and 200 m from the source. Here a continuous plume was sampled for 10 min. Meteorological measurements at both sites included the mean wind speed, the azimuth wind direction determined at a height of 2 m near the gas source, and vertical profiles of the mean wind speed and temperature. The O'Neill site is unusually smooth (z_0 less than 1.0 cm) with an unobstructed upwind fetch of at least 1.0 km. The Round Hill site is considerably rougher (z_0 greater than 10 cm) with roughness elements in the form of trees and small buildings. Differences in elevation on the order of 30 m were found within the first 0.5 to 1.0 km upwind from the test area.

The crux of Cramer's thesis is presented in Fig. 4.7. Of immediate interest is the very close dependence of plume width on σ_θ over the entire range of conditions sampled for the two dissimilar sites. This dependence of plume spreading on wind fluctuation is an interesting contrast to the fact that the value of σ_θ for neutral conditions at the rough site (Round Hill) is twice that at the smoother site (O'Neill).

Having established the relation between horizontal plume spreading and the horizontal wind-direction fluctuations, Cramer then investigated the distance dependency of σ_y , σ_z , and concentration (Cramer et al., 1964). These data are reproduced in Table 4.7 where p and q are the

Table 4.7—DISTANCE DEPENDENCY OF DIFFUSION COEFFICIENTS BASED ON PROJECT PRAIRIE GRASS DATA* IN WHICH $\sigma_y = \sigma_\theta \times p$ AND $\sigma_z = \sigma_\theta \times q$

σ_θ , deg	p (200 to 800 m)†	q (50 to 800 m)†
3	0.45	0.86
4	0.56	0.86
5	0.64	0.88
6	0.71	0.91
7	0.80	0.96
8	0.85	1.13
10	0.85	1.29
12	0.85	1.55
20	0.85	1.74
25	0.85	1.89

*From Cramer et al., 1964.

†Distance interval on which the estimates are based.

exponents noted in Table 4.2. Cramer relates all his diffusion data to σ_θ and makes no use of the collected vertical-fluctuation data except to show the quasi-dependence between the vertical and horizontal fluctuations. The distance dependency of normalized concentration and plume width for 46 of the O'Neill tests is shown in Figs. 4.8 and 4.9, where the data in each

Fig. 4.8—Normalized axial concentration measurements from the Prairie Grass experiments. The σ_θ values are averages for various groups of observed plume-spread data.

Fig. 4.9—Measured values of σ_y observed during the Prairie Grass experiments and stratified by average σ_θ values.

diagram are indexed by σ_θ values. The scatter that may be expected about these averaged curves is discussed in Sec. 4.6.

Barad and Haugen (1959) showed that the slopes of the σ_y and σ_z curves with x could not be obtained from the wind profiles, one of the fundamental claims of the original Sutton theory. There has already been a growing tendency to recognize this in practical problems. In addition, they showed that $n_y \neq n_z$ in many cases, and thus the use of four adjustable diffusion parameters is required for an adequate fit of measured diffusion data to a Sutton type equation, i.e., C_y , C_z , n_y , and n_z .

4-4.2.2 Hanford, Washington (Project Green Glow-30 Series). During the period 1959–1962, a series of 66 diffusion experiments was carried out at Hanford, Wash. The results of analyses of 46 tests have been reported by Fuquay, Simpson, and Hinds (1964). Details of the early experiments in this series, as well as tabulations of

diffusion and meteorological data, have been described by Barad and Fuquay (1962). Other publications based on these experiments include discussions of tracer-deposition characteristics and computations of vertical diffusion (Simpson, 1961), the area contained within specified isopleths and tracer travel time (Elliott, Engelmann, and Nickola, 1961), diffusion during conditions of shear flow (Barad and Fuquay, 1962a), and other general descriptions of the experimental results (Fuquay, Simpson, Barad, and Taylor, 1963).

The fluorescent tracer, zinc sulfide, was sampled at 833 locations on arcs at 200, 800, 1600, 3200, 12,800, and 25,600 m from a source 1.5 m above the ground. The last two arcs were not operated during 26 of the 46 experiments analyzed. Drum samplers at the last two arcs were used to obtain the time of arrival of the tracer at these distances.

Vertical diffusion to heights of 62 m was measured at the first four arcs by five towers on each arc. Spaced 8 deg apart, each tower

supported 15 samplers. The test site was quite flat to gently rolling with sagebrush cover some 1 to 2 m high. The tracer with water as a carrier was released for 30-min periods through two fog generators. The field samplers were in operation well before and after the passage of the tracer cloud, thus providing measures of exposure rather than average concentration. The fluorescent particles were collected on filters, and their total mass was determined by a technique that involved irradiating the particles with an alpha-emitting isotope and counting the scintillations with an automatic electronic counter.

The analysis techniques used on this project differed somewhat from those of other experiments. Although plume-spread data are commonly evaluated in terms of distance from the source, the data from these experiments are related to time of travel from the source. Fuquay et al. felt that this was closer to the concepts originally introduced by Taylor. The lateral spread of the plume was related to the

Fig. 4.10— σ_y vs. travel time for various values of $\sigma_\theta \bar{u}$ based on the Green Glow and 30 series experiments. Solid lines are based on measured data and dashed lines are suggested extrapolations. (From Fuquay, Simpson, and Hinds, 1964.)

value of $\sigma_\theta \bar{u}$ (σ_θ being computed from wind records of 30-min duration with a 20-sec averaging interval). Measurements of the lateral spread of the plume, when expressed in terms of distance from the source rather than time of travel and stratified by values of σ_θ , agree with other data on lateral spreading from sources near the ground. These data are presented in Fig. 4.21.

Figure 4.10 presents observed values of σ_y for various classes of $\sigma_\theta \bar{u}$ as a function of travel time. The data indicate that the slopes for short times of travel are about unity but become smaller as the travel time increases. A slope of 0.5 appears likely at large travel times and corresponds to that deduced by Taylor from theoretical considerations. The dashed lines are speculative estimates of σ_y

for large values of travel time. The data imply a convergence of the curves at some large travel time.

Figure 4.11 is a different representation of the growth-travel time relation. The irregular curvature in the region $0.25 < \sigma_\theta \bar{u} < 0.50$ separates the curves into two sets: one converging at $\sigma_y = \sigma_\theta \bar{u} = 0$ and the other set converging at negative values of these quantities. This irregularity is believed to be caused by differences in the wind-direction shear associated with $\sigma_\theta \bar{u}$. The greatest shear is observed during stable atmospheric conditions (i.e., large Richardson number), which, in turn, are associated with small values of $\sigma_\theta \bar{u}$. The shearing in stable atmospheres results in comparatively large values of the lateral spread, σ_y . At the travel times shown in Fig. 4.11, the plumes

Fig. 4.11— σ_y vs. $\sigma_\theta \bar{u}$ for various travel times. The irregularity in the curves is believed to be due to wind shear during very stable conditions. (From Fuquay, Simpson, and Hinds, 1964.)

have usually spread upward so that this effect is amplified.

The observed normalized exposures are presented in Figs. 4.12 and 4.13. Curves representing the Pasquill moderately stable (F), neutral (D), and very unstable (A) conditions (with assumed typical wind speeds) have been entered for comparison and appear to bracket the observed data although there is the sug-

gestion that, at travel times beyond 1000 sec, the observed data show a more rapid decrease with travel time than do the Pasquill curves.

Simpson (1961) computed by material balance methods rather large losses of tracer due to deposition within 3200 m of the source. These losses amounted to as much as 90% of the source for one test. The effect of deposition upon the air concentration is shown in Fig.

Fig. 4.12—Normalized exposure values as determined during the Green Glow and 30 series experiments. The data are presented in terms of travel time and are arranged according to observed values of Richardson number and $\sigma_\theta \bar{u}$. The Pasquill curves for typical conditions have been entered for comparison. (From Fuquay, Simpson, and Hinds, 1964.)

4.14, which relates the total mass transport, Q_x , past a certain distance to the total released tracer, Q_0 , for four runs during stable conditions.

In order to compute σ_z , the standard deviation of the vertical tracer distribution in the absence of deposition, Simpson used flux concepts and the measured vertical distributions at the various towers along with mass-transport data in an iterative procedure. The resulting σ_z curves are shown in Fig. 4.15 for various degrees of stability. The limited vertical diffu-

sion during stable conditions, as well as the tendency for a nonpower law relation between σ_z and x , is immediately apparent, just as Hilst and Simpson (1958) measured for the elevated source. The σ_z values derived by Simpson from the Green Glow data are, however, somewhat smaller than those found by Hilst and Simpson in spite of the fact that the releases by the latter workers took place at 56 m above the surface. It would be expected that the smaller values of the vertical turbulence during inversions at this elevated level would result in

Fig. 4.13—Similar to Fig. 4.12 but showing exposure values obtained during conditions of greater stability. (From Fuquay, Simpson, and Hinds, 1964.)

Fig. 4.14—Relative mass transport through vertical planes perpendicular to the average plume direction as observed during the Green Glow and 30 series tests. The decrease in the ratio Q_x/Q_0 indicates the extent of deposition processes operating during these four tracer releases. (From Simpson, 1961.)

smaller values of σ_z than would be found in releases near the surface.

Barad and Fuquay (1962a) discuss a diffusion model in which the tracer exposure at a point downwind from the source is given by the normal frequency function of two variables (the lateral and vertical coordinates of a point) and the correlation coefficient between the lateral and vertical coordinates of the tracer particles. The inclusion of the nonzero correlation coefficient results in elliptical isolines of exposure in the $y-z$ plane which are inclined with respect to the horizontal. From inspection of the exposures received at towers mounted on the first four arcs of the grid, this model appeared to be a reasonable representation of the plume cross section during stable conditions when the plume is sheared by the clockwise turning of the wind with height (see Figs. 2 to 5, Barad and Fuquay, 1962a). Comparison of the total plume width or depth, as might be obtained from a vertical or lateral photograph of the plume, with the exposure-distribution standard deviations computed from the model and tower data indicates that the photographs might provide an overestimate of the plume dimensions and, thus, lead to a lower than actual exposure estimate.

Based on the experimental results of the Green Glow and 30 series and on experience

Fig. 4.15—Values of σ_z for three of the four tests shown in Fig. 4.14. These computed values are those expected in the absence of deposition. (From Simpson, 1961.)

and experiments of the last 20 years at the Hanford site, two forms of the bivariate normal model have been adopted to assess the consequences of releases to the atmosphere at this location. The Sutton formulations are used for unstable and neutral conditions, and the generalized Gaussian form is used for stable situations. Another deviation from general practice adopted at the Hanford location is the use of travel time rather than travel distance for organizing the diffusion data. Although these procedures have worked well at the Hanford site, caution should be observed before extrapolating this information to sites of different topography and wind regimes. A detailed description of the Hanford models is given in the following paragraphs.

In a stable atmosphere the exposure at ground level is determined from

$$\frac{\psi}{Q_0} = \frac{Q_x/Q_0}{\pi \sigma_y \sigma_z \bar{u}} \exp \left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2} \right) \right] \quad (4.9)$$

where $\bar{u}$ is the average wind speed at the height of emission, Q_0 is the total amount of material released, and Q_x is the apparent amount of material released as measured at a given downwind travel distance or travel time, i.e., the difference between the total amount of material released and the amount deposited on the surface between the source and the measurement point.

The value for σ_y in Eq. 4.9 is determined from

$$\sigma_y^2 = At - \frac{A^2}{2(\sigma_\theta \bar{u})^2} \left\{ 1 - \exp \left[-\frac{2(\sigma_\theta \bar{u})^2 t}{A} \right] \right\} \quad (4.10)$$

where t is the travel time and A is a constant related to the scale of turbulence and is evaluated from the experimentally determined relation

$$A = 13.0 + 232 \sigma_\theta \bar{u} \quad (4.11)$$

Equations 4.10 and 4.11 are the relations used in constructing the smooth isopleths in Fig. 4.10.

The variance of the vertical distribution of exposure for stable conditions at the Hanford site is determined from

$$\sigma_z^2 = a[1 - \exp(-k^2 t^2)] + bt \quad (4.12)$$

where a , b , and k^2 are functions of the degree of stability. Values of these terms, derived for use at the Hanford site, are shown in Table 4.8.

Table 4.8—VALUES OF PARAMETERS USED AT HANFORD FOR DETERMINING THE VARIANCE OF THE VERTICAL DISTRIBUTION OF EXPOSURE

Parameter	Degree of stability	
	Moderate stability	Strong stability
a	97 m ²	34 m ²
b	0.33 m ² /sec	0.025 m ² /sec
k^2	2.5×10^{-4} sec ⁻²	8.8×10^{-4} sec ⁻²

During neutral and unstable conditions, the Sutton form of Eq. 4.9 is used:

$$\frac{\psi}{Q_0} = \frac{2Q_x/Q_0}{\pi C_y C_z \bar{u} x^{2-n}} \exp \left[-\frac{1}{x^{2-n}} \left(\frac{y^2}{C_y^2} + \frac{h^2}{C_z^2} \right) \right] \quad (4.13)$$

The values of the Sutton parameters used at the Hanford site for unstable and neutral conditions are given in Table 4.9.

Table 4.9—VALUES OF SUTTON PARAMETERS USED AT HANFORD FOR UNSTABLE AND NEUTRAL CONDITIONS

Parameter	Release level	Wind speed, m/sec	Unstable	Neutral
C_y	Ground	1.0	0.35	0.21
		5.0	0.30	0.15
		10	0.28	0.14
	Elevated	1.0	0.30	0.15
		5.0	0.26	0.12
		10	0.24	0.11
C_z	Ground	1.0	0.35	0.17
		5.0	0.30	0.14
		10	0.28	0.13
	Elevated	1.0	0.30	0.15
		5.0	0.26	0.12
		10	0.24	0.11
n			0.20	0.25

The depletion factor, Q_x/Q_0 , for use with depositing material is determined from the following equations for stable or neutral and unstable conditions, respectively:

$$\frac{Q_x}{Q_0} = \exp \left[-\left(\frac{2}{\pi} \right)^{1/2} \left(\frac{v_d}{\bar{u}_0} \right) \left(\frac{\bar{u}_0}{\bar{u}} \right) \bar{u} \times \int_0^t \frac{\exp(-h^2/2\sigma_z^2)}{\sigma_z} dt \right] \quad (4.14)$$

$$\frac{Q_x}{Q_0} = \exp \left[-\frac{2}{C_z(\pi)^{1/2}} \left(\frac{v_d}{\bar{u}_0} \right) \left(\frac{\bar{u}_0}{\bar{u}} \right) \int_0^x x^{(n-2)/2} \times \exp \left(-\frac{h^2}{C_z^2 x^{2-n}} \right) dx \right] \quad (4.15)$$

where v_d is the deposition velocity, $\bar{u}_0$ is the wind speed at the surface, and $\bar{u}$ is the wind speed at the height of emission. The Hanford group have found it more practical to work with the ratio $v_d/\bar{u}_0$ and refer to this quantity as their deposition coefficient. Values of the deposition coefficient for very fine reactor particulates and for the halogens are presented in Table 4.10. This table also contains values of

Table 4.10—GROUND-DEPOSITION PARAMETERS USED AT HANFORD

Atmospheric conditions	Deposition coefficient ($v_d/\bar{u}_0$)		Wind-speed ratio ($\bar{u}_0/\bar{u}_{60m}$)
	Fine reactor particulates	Halogens	
Very stable	1.5×10^{-4}	2.4×10^{-3}	0.17
Moderately stable	2.2×10^{-4}	3.4×10^{-3}	0.35
Neutral	3.0×10^{-4}	4.6×10^{-3}	0.50
Unstable	6.0×10^{-4}	8.0×10^{-3}	0.70

the wind-speed ratio, $\bar{u}_0/\bar{u}$. Interpolation of the shear factor for different levels can be accomplished by assuming either a logarithmic or power function relation for the wind profile.

Solutions for the deposition equations can be obtained with numerical techniques; so the entire system of equations can be programmed for any combinations of parameter values necessary. Solutions of this form permit the extensive calculations necessary for assessing the consequences of a broad variety of chemical or radioactive releases.

4-4.2.3 Cape Kennedy, Florida (Project Ocean Breeze), and Vandenberg Air Force Base, California (Project Dry Gulch). Field diffusion programs were conducted at Cape Kennedy, Fla. (Ocean Breeze), and Vandenberg Air Force Base, Calif. (Dry Gulch), during 1961 and 1962 (Haugen and Fuquay, 1963, and Haugen and Taylor, 1963). These programs were undertaken to establish quantitative prediction equations for use as safety tools at these missile-test ranges.

The programs culminated at each range with the installation of an automatic computer-controlled meteorological-data acquisition and processing system. Tracer emissions were planned for periods of onshore flow which, at these seaside locations, were usually accompanied by daytime instability. In all, 76 experiments were carried out at Cape Kennedy and 109 at Vandenberg; not all, however, could be used in the analyses.

Zinc sulfide particles were released from ground-level sources for 30-min periods at both sites. The diffusion course at Cape Kennedy consisted of three concentric arcs 1.2, 2.4, and 4.8 km from the source. Samplers were positioned 1.5 and 4.5 m above the ground surface. The complexity of the terrain at Vandenberg led to sampling over two different courses. The first course, with samplers at arcs 2.3 and 5.7 km from the source, was oriented so that the flow from the source ascended in its path to the arcs. The other course consisted of three arcs at 0.85, 1.5, and 4.7 km with the radius connecting the midpoints of these arcs oriented approximately up a valley. Samplers were positioned at 1.5 m above the ground surface. The terrain at Cape Kennedy is fairly flat with thick vegetation extending to 5 m, whereas the Vandenberg site is quite rugged with elevations at the arcs varying by more than 60 m. Comprehensive supporting meteorological measurements were available at both sites. These measurements included σ_θ data for a variety of running averaging times and vertical temperature-difference data.

Early in the program the decision was made to develop a diffusion equation using statistical techniques, such as multiple regression analysis, rather than to work from physical principles. The technique involved combining half of the Prairie Grass, Ocean Breeze, and Dry Gulch diffusion data into one set and deriving the constants in a diffusion equation by machine analyses. The other half of the data from each of the three series could then be used to verify the predictions. The derived equation is

$$\frac{\bar{x}_p}{Q'} = 0.00211x^{-1.96} \sigma_\theta^{-0.506} (\Delta T + 10)^{4.33} \quad (4.16)$$

where $\bar{x}_p/Q'$ = normalized peak concentration in sec/m^3

x = downwind travel distance in meters

σ_θ = standard deviation of azimuthal wind direction in degrees (15-sec running average over 30-min observational interval)

$$\Delta T = T_{54\text{ft}} - T_{6\text{ft}}$$

On the basis of tests with the independent data, this equation predicted 72% of the cases within a factor of 2 of the observed values and 97% within a factor of 4. Figure 4.16 is a graphical representation of the results based on this equation.

4-4.2.4 National Reactor Testing Station (NRTS), Idaho Falls, Idaho. A study of atmospheric diffusion and deposition from a surface source was reported by Islitzer and Dumbauld (1963). The grid was similar to that used in the elevated diffusion experiments except for the addition of five sampling towers 30 m high and 70 m apart installed at the 400-m arc to obtain mass-balance measurements for some releases. Direct measurements of deposition were also made at the 100- and 200-m arc on flat plates constructed to simulate a bare soil surface. The uranin dye tracer was released at a height of 1.0 m for 1-hr periods during a wide range of stability conditions.

Fig. 4.16—Observed vs. predicted values of $\bar{X}_p\bar{u}/Q'$ based on independent data from the Prairie Grass, Ocean Breeze, and Dry Gulch surface-diffusion experiments. (From Taylor, Nou, and Tucker, 1964.)

The measured lateral plume spreads during lapse conditions were related to the lateral wind-direction standard deviation for each measurement distance by an averaging time determined for $\beta = 5.0$, an experimentally determined average value. Measured vs. com-

puted values of σ_y from the vertical wind-direction fluctuations. These, together with the equations for σ_y , are shown in Table 4.11.

Lateral wind-direction standard deviations for 5.0-sec averaged data and 1.0-hr sampling

Fig. 4.17—Measured values of σ_y compared to those estimated from σ_z data computed with $\beta = 5.0$ during unstable conditions at the National Reactor Testing Station. (From Isiltzer and Dumbauld, 1963.)

puted values of σ_y using the mean β factor are shown in Fig. 4.17 for lapse conditions.

The prediction of lateral diffusion during stable conditions using a mean measured β was less successful. A 10-sec averaging time was found to give a better prediction of σ_y at all distances (Fig. 4.18).

times at 4.0 m above the surface are given in Table 4.12.

The normalized air-concentration measurements along the mean plume axis are shown in Figs. 4.19 and 4.20. These measured data are compared with the computations from the diffusion equation using the relations in Table

Fig. 4.18 — Measured values of σ_y compared to those estimated from σ_θ data during stable conditions at the National Reactor Testing Station. An averaging time of 10 sec was applied to the wind-direction trace before computation of σ_θ . (From Islitzer and Dumbauld, 1963.)

4.11 and assuming total reflection of the plume. This postulation overpredicts the measured concentrations in all cases, presumably because deposition was ignored although a similar result could occur if the models in Table 4.11 were incorrect.

Deposition velocities were determined for 11 of the diffusion tests by two different techniques. The first method was based on computations involving the total amount of released material deposited between the source and 400 m (as determined from tracer material-balance measurements). The results along with the concurrent meteorological data are given in Table 4.13. The results of the second technique, based on measured air concentration and the assumed relation for σ_z given in Table 4.11, are given in Table 4.14. The higher values of the deposition velocity during unstable conditions, as opposed to stable conditions, are

Table 4.11 — FORMULAS USED AT NRTS FOR COMPUTING σ_y AND σ_z^*

Lapse	Inversion
$\sigma_y = \sigma_{\theta(x/\bar{u}\beta)} x$	$\sigma_y = \sigma_{\theta(10 \text{ sec})} x$
$\sigma_z = \sigma_{\phi(x/\bar{u}\beta)} x$	$\sigma_z = \sigma_{\phi(x/\bar{u}\beta)} x$
$\sigma_z = \sigma_{\phi(10 \text{ sec})} x$	$\sigma_z = \sigma_{\phi(10 \text{ sec})}^{200}$ (for $x \geq 200 \text{ m}$)

*Subscripts refer to averaging times. The sampling time was 1 hr in each case.

Table 4.12 — WIND-DIRECTION STANDARD DEVIATIONS MEASURED DURING SURFACE-RELEASE TESTS AT NRTS*

	σ_θ , deg		σ_θ , deg	
	Range	Average	Range	Average
Lapse	5.6 to 22.6	11.7	1.7 to 4.5	2.4
Inversion	4.4 to 14.8	9.3	0.5 to 2.5	1.8

*Data from Islitzer and Dumbauld, 1963.

evident in the results of the two methods. This is the same trend noted at Hanford (Table 4.10). As a general rule, however, ground-level concentrations from surface sources are from one to two orders of magnitude larger during stable conditions than during instability; so the opportunity for depletion could be greater during stable conditions despite a perhaps smaller deposition velocity.

4-4.2.5 United Kingdom. This section includes two series of surface-release continuous-source experiments. The first, a short-range series (Hay and Pasquill, 1959), was designed to evaluate the factor β , ratio of the Lagrangian

Fig. 4.19 — Computed and measured axial concentrations for unstable conditions at the National Reactor Testing Station. The quantities in parentheses refer to averaging times applied to the raw wind data. (From Islitzer and Dumbauld, 1963.)

Table 4.13—METEOROLOGICAL DATA AND DEPOSITION VELOCITIES COMPUTED FROM TRACER
MATERIAL-BALANCE MEASUREMENTS AT NRTS*

Test	$\bar{u}_{4m}$, m/sec	$\Delta T_{16 \text{ to } 4 m}$, °F	Travel distance, m	σ_θ (measured), deg	σ_ϕ (measured), deg	Amount deposited, %	σ_z (measured),† m	σ_z (computed),‡ m	v_d , cm/sec
C	6.3	-0.3	400	5.6	2.1	54	14.6	10.8	9.2
D	4.9	+0.5	400	14.8	2.0	35	9.5	8.6	2.3
E	6.0	-2.4	200	15.9	3.9	32	13.5	13.0	8.0
F	4.7	-1.1	200	12.9	4.1	24	13.2	12.6	4.4
G	6.2	-1.9	200	15.3	2.3	22	13.7	8.1	5.4
I	6.0	-1.6	400	14.9	3.1	48	13.4	15.5	6.8
M	3.9	-0.7	400	12.2	2.7	32	12.2	13.3	2.4
N	4.7	+0.7	400	10.9	2.3	38	10.0	9.8	2.6
O	2.6	+3.4	400	12.1	0.8	10	5.0	4.7	0.2
Q	2.5	+4.1	400	5.9	0.5	14	5.5	3.5	0.2
S	8.4	-2.3	400	11.1	2.5	37	17.8	14.0	8.9

*From Islitzer and Dumbauld, 1963.

† σ_z measured at travel distance.

‡ σ_z computed from $\sigma_{\phi(x/\bar{u}\beta)} \times$ for $\beta = 5.0$ and a sampling time of 1 hr.

and Eulerian autocorrelogram time scales, for use in the expression

$$\bar{y}^2 = \bar{v}_{(T,t)}^2 t^2 \quad (4.17)$$

where t , the averaging time, is given by $x/\bar{u}\beta$ (see Chap. 3, Sec. 3-2.3.2). The data from these experiments are summarized in Table 4.15. The average value of σ_y/σ_θ , although not plotted on summary diagram Fig. 4.21, falls on the daytime curve for Project Prairie Grass at 100 m.

A series of 10 long-range continuous-source releases has also been described by Pasquill (1962a). Fluorescent pigment was released during lapse conditions and sampled to distances

Fig. 4.20—Computed and measured axial concentrations for stable conditions at the National Reactor Testing Station. (From Isiltzer and Dumbauld, 1963.)

Table 4.14—DEPOSITION VELOCITIES (IN CM/SEC) COMPUTED FROM MEASURED AXIAL AIR CONCENTRATIONS

	Unstable [$\sigma_z = \sigma_{\varphi(10 \text{ sec})}x$]					
	Distance, m					
	100	200	400	800	1600	3200
Mean*	6.4	5.3	4.0	4.5	5.2	5.6
Standard deviation	3.3	2.9	2.4	1.6	1.5	1.8
Number of observations	13	24	13	20	14	14

	Stable [$\sigma_z = \sigma_{\varphi(x/5\bar{u})}x$]					
	Distance, m					
	100	200	400	800	1600	3200
Mean†	2.6	1.6	1.3	1.1	1.0	0.80
Number of observations	39					

*Grand mean 5.2.

†Grand mean 1.5.

of about 75 km by aircraft equipped with rotating-drum samplers. Sampling extended from near the surface to about 1000 m and was accompanied by wind measurements through this layer taken with pilot balloons. Data on the crosswind spread are presented in Table 4.16, and the plume-width measurements are included in summary diagrams Figs. 4.22 and 4.23.

A number of elevated line-source releases are also discussed in Pasquill (1962a). The released material was sampled in this case by samplers strung along a balloon cable. These

Table 4.15—DATA ON CROSSWIND SPREAD AND WIND-DIRECTION FLUCTUATION LEADING TO VALUES OF β *†

Experiment	1	2	3	4	5	6	7	8
$\bar{u}$, m/sec	4.4	5.3	8.3	3.8	3.3	4.3	3.8	2.8
Temp. diff. (23 ft to 4 ft), °F	-1.3	-1.1	-0.6	-1.3	0	0	0.7	1.5
σ_θ at source, ‡ deg	7.9	6.3	8.2	15.3	6.8	7.2	5.4	4.8
σ_y at 100 m downwind, deg	6.8	5.4	5.6	12.8	5.5	6.7	4.6	3.1
β	3.5	5.4	1.1	1.6	5.2	8.5	4.3	3.2

*From J. S. Hay and F. Pasquill, Diffusion from a Continuous Source in Relation to the Spectrum and Scale of Turbulence, *Adv. Geophys.*, 6: 351 (1959).

†All wind measurements, as well as the particle release point, were at a height of 2 m.

‡The values of σ_θ refer to a sampling duration equal to the period of particle release and an averaging time of 1 sec.

Table 4.16—DATA ON CROSSWIND SPREAD*

Experiment	Distance downwind, km	Plume spread,† radians
8	18.5	0.33
9	14.9	0.23
10	15.3	0.19
11	16.5	0.38
13	14.4	0.23
14	33.8	0.23
15	27.4	0.31
16	16.1	0.21
17	72.5	0.21
18	18.5	0.49

*From Pasquill, 1962a.

†Defined as $4.3 \sigma_y$.

experiments are discussed in greater detail in Sec. 4-8.

4-4.3 Summary of Continuous-source Lateral-diffusion Measurements

Figure 4.21 presents a summary of lateral-diffusion data for most of the experiments discussed in previous sections. The σ_y values for each test in each series were divided by the appropriate σ_θ values, and an average curve for each series was constructed. The data are ordered quite well when normalized by the use of the wind-fluctuation data. Averaging times for σ_θ range from 2.5 sec for the Prairie Grass

Fig. 4.21—Summary diagram for normalized σ_y measurements for both surface and elevated sources. Average curves are given for most of the experimental series discussed.

information to 20 sec for the Green Glow and 30 series. Sampling times range from 10 to 60 min, and both surface and elevated sources are considered.

The values of σ_y in Fig. 4.21 were obtained from the diffusion experiments on short distance or time scales, generally less than 10 km. Heffter (1965) has presented a summary of lateral-dispersion measurements for travel distances or times considerably in excess of

those measured in the shorter range experiments. The summary material in Heffter's paper is presented in Table 4.17 and Figs. 4.22 and 4.23. The σ_y values shown in the two figures were obtained from a wide variety of sources including continuous smoke plumes, multiple balloon releases, and clouds from nuclear detonations. The diagrams include data for a wide range of release durations measured by many different techniques over a height

Fig. 4.22—Long-distance individual and average σ_y values obtained from measurements described in Table 4.17 as a function of travel time. The lines of constant K_h have been computed from the relation $K_h = \sigma_y^2/2t$. (From Heffter, 1965.)

Table 4.17—A KEY TO THE SYMBOLS IN FIGS. 4.22 AND 4.23 INCLUDING REFERENCE, SOURCE AND MEASUREMENT INFORMATION, AND A GENERAL CLASSIFICATION FOR THE INDIVIDUAL AND AVERAGE σ_y VALUES*

Key	Reference	Classification of plotted σ_y value	Source		Measurement		Height above surface, ft	General classification
			Continuous	Instantaneous	Continuous	Instantaneous		
1	Gifford	Neutral conditions	Plume			Primarily stationary surface samplers	Primarily surface	Instantaneous
2	Braham et al.	Average	Plume			Aircraft samplers	Surface to 4000	Instantaneous
3	Crozier and Seely	Individual	Plume			Aircraft samplers	Surface to 5000	Instantaneous
4	Barad and Fuquay	Average	Plume			Stationary surface samplers (30 min)†	Surface	Instantaneous—continuous
5	Pasquill	Average	Plume			Aircraft or motor-vehicle samplers	Surface to 4000	Instantaneous
6	Pack and Angell	Average	Tetroons (12 hr)†		Separation distances		1500 ± 400	Continuous
7	Pack and Angell	Average		Tetroons		Separation distances	1500 ± 400	Instantaneous
8	Classified Project (I)	Individual	Plume			Aircraft samplers	1500	Instantaneous
9	Sakagami	Average	Balloons (1 hr)†		Separation distances		Surface (from flights at low levels to approx. 30,000)	Continuous
10	Angell	Average	Transosondes (24 hr)†		Separation distances		30,000 ± 1000	Continuous
11	Richardson and Proctor	Average	Balloons (10 hr)†		Separation distances		Surface (from flights at low levels)	Continuous
12	U. S. Weather Bureau (1957)	Individual		Nuclear clouds		Aircraft samplers	9000 to 16,000	Instantaneous
13	Allen et al.	Individual		Nuclear cloud		Aircraft samplers	7000 to 14,000	Instantaneous
14	Wilkins	Average		Nuclear clouds		Aircraft samplers	8000 to 25,000	Instantaneous
15	Machta et al.	Average		Nuclear clouds		Aircraft samplers	8000 to 30,000	Instantaneous
16	U. S. Weather Bureau (1954)	Individual		Nuclear clouds		Aircraft samplers	5000 to 25,000	Instantaneous
17	Moore et al.	Individual		Constant-level balloons		Separation distances	30,000	Instantaneous
18	Classified Project (II)	Individual	Plume			Aircraft samplers	1000 to 3000	Instantaneous
19	Ferber	Individual		Nuclear cloud		Aircraft samplers	50,000	Instantaneous

*Heffter, 1965.

†Duration for individual σ_y computations.

Fig. 4.23—Long-distance σ_y values from Fig. 4.22 plotted as a function of travel distance from the source. (From Heffter, 1965.)

range of 50,000 ft above the surface. Examining the data from the viewpoint of the relation between K and statistical diffusion theories, namely,

$$K_h = \frac{\sigma_y^2}{2t} \quad (4.18)$$

the author suggests that an average value of $K_h = 4 \times 10^8 \text{ cm}^2/\text{sec}$ seems to apply to travel periods of 1 to 4 days bearing in mind that fairly reliable values that are lower by a factor

of 10 or more have been observed. A more detailed discussion of the sources and of the nature of the data presented, as well as the identification of the references noted in Table 4.17, can be found in the original paper.

4-4.4 Summary of Continuous-source Surface-concentration Measurements

There are many possible avenues for summarizing the diffusion experiments that have

been presented. In a useful summary the measurements of diffusion parameters should be related to objective meteorological measurements. Only in this way can the gains made in relating diffusion to meteorological parameters be realized in the direct utilization of meteorological data to estimate diffusion without further laborious and expensive diffusion experiments.

A variety of meteorological predictors were used in the various diffusion experiments. Specifically, σ_θ (for both fixed and varying averaging times), $\sigma_\theta \bar{u}$, σ_θ , ΔT , Ri , and $\bar{u}$ were used individually or in combination. The fluctuation data were computed for a variety of sampling and averaging times. Vertical temperature-difference data were computed over a number of different height intervals originating at different levels above the surface.

From the results of the various experiments, it appears that a measure of the horizontal wind-direction fluctuation (σ_θ) can be used to construct a set of diagrams for summarizing diffusion-experiment data. Such diagrams are also useful for estimating diffusion directly from the meteorological measurement. The use of σ_θ only results in more scatter than would be expected if some measure of stability or vertical wind-fluctuation were included. However, no variable of this type was measured in a consistent manner in most of the experiments.

Figure 4.24 shows the relation between normalized axial concentration and travel distance from the source for approximately 200 individual diffusion experiments selected from the Green Glow-30, Prairie Grass, National Reactor Testing Station, Ocean Breeze, and Dry Gulch series. The normalized concentration data for each travel distance were grouped according to the observed σ_θ values, and the median values of concentration for each 5-deg range of σ_θ were plotted. The Pasquill type A and F categories have been added for comparison. The relations for $\sigma_\theta \approx 2.5^\circ$ and 25.0° are partially based on extrapolated data since there were but few occasions during which measured σ_θ values were either this small or large.

The observed data fit the broad band of values postulated by Pasquill quite well except during the more stable conditions (smaller values of σ_θ) at the longer distances. Here the observed values of normalized concentration are

almost an order of magnitude lower than indicated by the Pasquill type F curve. However, the observed data associated with the smaller values of σ_θ probably reflect the effects of deposition, the results of which should be most evident during stable conditions and at the greater distances for the aerosol tracers used in these experiments. The Prairie Grass data, obtained with a nominally nondepositing tracer, are included in Fig. 4.24 for the first 800 m and generally show higher concentrations for the same meteorological conditions than the other experimental results. If the effect of deposition is removed from the observed data by techniques such as indicated in Chap. 5, Sec. 5-3.2.2, the six Pasquill curves are matched quite well by the six corrected σ_θ curves. This circumstance suggests that an estimate of the diffusion climatology at a site may be made directly from wind measurements obtained at that site. Accordingly the reproductions of the Pasquill curves given in Sec. A.3 of the Appendix have been labeled with the appropriate values of σ_θ (2.5° for type F, 5.0° for type E, etc.).

A diagram similar to Fig. 4.24 but using $\sigma_\theta \bar{u}$ as the meteorological index and travel time rather than travel distance could also be constructed. In practice there is little difference between results obtained with either of these two methods.

As noted in Sec. 4-4.1.7, the downstream concentration from elevated sources during stable conditions appears to decrease more slowly than the concentration from a surface source. Therefore the Pasquill curves associated with stable conditions may underestimate the average concentration from elevated sources. A curve labeled $F_{(elev)}$ has been added to Fig. A.1 in the Appendix to account for the cessation of vertical plume growth during strong inversions.

Editor's Note: A series of 43 field experiments using fluorescent-particle tracers was conducted between 1963 and 1965 to investigate the transport and diffusion of airborne material over urban areas [Francis Pooler, Jr., A Tracer Study of Dispersion over a City, *J. Air Pollution Control Assoc.*, 16(12): 677-681 (1966)]. St. Louis, Mo., meets two experimental criteria for such a study: (1) it is a reasonably flat city, remote from significant topographic influences on the large-scale airflow; so the influence of the city itself could be studied, and (2) the Weather Bureau Office there operates

Fig. 4.24—Summary diagram for observed normalized surface-release axial-concentration measurements. The sloping lines connect median values of concentration for various ranges of concurrently observed σ_θ data. The experimental data include approximately 200 individual tests from the Green Glow-30, Prairie Grass, National Reactor Testing Station, Ocean Breeze, and Dry Gulch series.

a weather radar that could be modified to track transponder-equipped constant-level balloons.

Two tracer-release sites were selected, and sampling sites for three concentric 180° arcs were picked at nominal distances of $\frac{1}{2}$, 2, and $4\frac{1}{2}$ miles from the west site and at $1\frac{1}{4}$, $2\frac{1}{2}$, 5, and, later, 10 miles from the south site. With these two release sites and associated sampling arcs, experiments could be conducted with winds from any quadrant except the northeast.

Although numerous analyses of the data from the St. Louis dispersion study remain to be completed, several results can be noted. Influences of the urban area on daytime dispersion patterns are not clearly evident; expressing the crosswind spread of the tracer cloud in terms of a root-mean-square length,

or standard deviation, σ_y , yields no great departure from the results summarized in Sec. 4-4.4.

The St. Louis dispersion data indicate that the influence of the city brings about a slightly larger spread in the tracer cloud at shorter travel distances. Vertical dispersion over a city during the daytime is comparable to that observed over open country, particularly if an initial plume dimension on the order of typical building size is included.

The St. Louis data also indicate that the vertical spread of a plume can be expressed as a function of travel time with much greater confidence than as a function of travel distance. Data from the evening experiments indicate that vertical dispersion rates over a city are much greater than rates observed over open country; the St. Louis data suggest that

a limited weak convective overturn layer forms as air passes over a city. However, the data available from the St. Louis study are not adequate to specify either the depth or the overturning rate of the weak convective layer in terms of causative factors, i.e., wind speeds, preexistent structure of the air as it approaches the city, city roughness, and relative heating rates.

4-5 PEAK-TO-AVERAGE AIR CONCENTRATION

The discussion of the environmental hazards of many toxic materials requires a knowledge of the short-period or peak air concentration that can be experienced. The previous discussions of diffusion data dealt with average concentrations for sampling periods of 10 min to 1 hr. It is appropriate therefore to consider the effect of sampling time upon measured air concentrations and the ratio of peak-to-average air concentration.

The extensive ^{41}Ar radiation measurements from the Harwell stack, described in Sec. 4-4.1.4, yielded some information on the effect of sampling time. From a time history of the total integrated measured radiation, it was found that the measured average concentration decreased with the fifth root of sampling time. This relation was found to be the most appropriate for the 3- to 60-min range of sampling times reported by Stewart, Gale, and Crooks (1954).

An experiment to study the close-in ground hazard from an elevated source during convectively unstable conditions, commonly called looping, was conducted by Barad and Shorr (1954). An oil fog was emitted from a portable generator at the 56-m level of a tower while observers with theodolites noted the time, the position, and the relative intensity of the smoke puffs hitting the ground. Two tests indicating the wide spectrum of possibilities during convective instability are summarized in Fig. 4.25, which shows the cumulative distribution of the puffs hitting the ground as a function of radial distance from the tower. Of the 22 puffs coming to the ground during run 1, about half came down within 150 m from the tower. A later test with equally unstable atmospheric conditions but stronger and steadier winds was conducted. From a 51-min release of smoke, 42 puffs coming to the ground were counted (run 2). In

Fig. 4.25—Number of puffs from an elevated source at 56 m reaching the ground during unstable conditions. (From Barad and Shorr, 1954.)

this case, however, none were within 120 m of the tower, and only 28 were within 300 m of the tower. This indicates the effect of stronger winds, which tend to transport the pollutant farther from a stack before coming to the ground. The meteorological conditions for the two tests are listed in Table 4.18.

During similar experiments (Shorr, 1953), a mobile air sampler was rushed to the area where a puff came to the ground, and measurements of the short-period peak air concentrations were made using the fluorescent properties of oil fog. A total of 172 puffs from a source at the 56-m level of the tower were sampled along a circular ring 120 to 180 m

Table 4.18—METEOROLOGICAL DATA FOR TWO DIFFUSION TESTS DURING LOOPING CONDITIONS*

	Run 1	Run 2
Sampling time	45 min	51 min
Temp. diff. (120 to 2 m)	-2.6° to -2.9°C	-2.4° to -2.9°C
Wind speed (60 m)	1.8 m/sec	4.9 m/sec

*From Barad and Shorr, 1954.

from the tower. The short-period sampling time in the 120- to 180-m sector ranged from 5 to 120 sec with a mean of 30 sec. It was observed that from 0 to 15 puffs per hour could be expected to reach the ground at this distance. A cumulative frequency distribution of the percentage of the puffs that exceeded a certain air concentration has been taken from Shorr's report and is shown in Fig. 4.26. Short-period peak concentrations of 10^{-3} for a unit release of 1 g/sec represent the likely upper limit. This is on the order of five times the longer term axial concentration at the measurement distance during unstable conditions.

Estimates of the peak-to-average air concentration in the center of elevated plumes during stable meteorological conditions were noted by Hilst (1957) based on his measurements of plumes described in Sec. 4-4.1.3. By forming the ratio of the crosswind particle variance measured with respect to the plume axis to the crosswind particle variance of the time-averaged plume, Hilst deduced estimates of the peak-to-60-min average air concentrations in the center of such elevated plumes. The results given by Hilst for three distances are shown in Table 4.19 for 16 diffusion trials. Generally the ratios are between 1.5 and 3, but they can be as high as 8.

Fig. 4.26—Percentage of puffs above a given concentration reaching the ground during unstable conditions. (From Shorr, 1953.)

Table 4.19—RATIO OF PEAK TO 60-MIN MEAN AIR CONCENTRATIONS*

	Distance from source, m		
	200	400	600
Average value	2.28	2.39	2.51
Range	1.39 to 6.77	1.34 to 7.71	1.31 to 8.29

*From Hilst, 1957.

Fig. 4.27—Peak-to-mean concentration ratio as reported by Singer, Kazuhiko, and Gonzalez del Campo. The lettered lines refer to Brookhaven data and the Brookhaven trace types. (From Singer, Kazuhiko, and R. Gonzalez del Campo, 1963.)

The lettered lines in Fig. 4.27 summarize experimental peak-to-average (P/A) concentration data collected at Brookhaven National Laboratory by Singer, Kazuhiko, and Gonzalez del Campo (1963) using an oil-smoke tracer from a 105-m stack. The slopes of the lines are functions of gustiness and stability. The greatest slope (line B₂) occurred with the most unstable conditions where large portions of the plume were brought down rapidly to the ground by convective turbulence. The smallest slope (line C) occurred with strong-wind conditions where fluctuations are smaller.

Singer, Kazuhiko, and Gonzalez del Campo (1963) obtained additional data that further affirm the existence of the power relation between P/A and sampling time. These data are also presented in Fig. 4.27. Others have also shown that a power function is valid. For short periods Stewart, Gale, and Crooks (1954) have demonstrated this, and for long periods Wipper-

mann (1961) and Meade (1960) have done likewise for periods of 4 days and 1 day, respectively.

Singer believed that the data of Wippermann and of Meade (Fig. 4.27) pertain to a city where short-term fluctuations might be smoothed out. In terms of roughness the city can practically obliterate all short-term fluctuations of concentration depending on the location of the receptor with respect to the source.

The problem of determining peak-to-average air concentrations owing to plume meander has been treated analytically by Gifford in his fluctuating-plume model (see Chap. 3, Sec. 3-3.2). Gifford (1960) also has analyzed peak-to-average data and discusses the results of many measurements. From his study Gifford cites the following guides that can be laid down for the estimation of peak-to-average air-concentration ratios (P/A):

1. For source and receptor located at the same level, P/A can be expected to be in the range from 1 to about 5.

2. For increasing difference in height between source and receptor or increasing distance from the plume axis, P/A increases, and values as great as 50 to 100 or greater may occur at the ground near a moderately tall (50- to 100-m) stack.

3. With increasing distance downwind from an elevated source, the ground-level P/A value will decrease toward its lower limit of unity but will attain values of this order only at considerable distances (perhaps 20 to 50 stack lengths or more) from the source.

4-6 EVALUATION STUDIES

4-6.1 Variability and Prediction of Diffusion

At the present time no comprehensive evaluation of the various diffusion models has been reported in the literature although numerous verification programs have been accomplished, usually with the data from one or a few experimental series. It is worthwhile to consider, at this point, the reason such a comprehensive evaluation might be very difficult.

An attempt is made in a diffusion model to relate meteorological variables to simultaneously measured diffusion statistics. There-

fore the appropriate meteorological and diffusion information must be available for each attempted application of the model. However, in the experiments performed to date, a broad variety of meteorological and diffusion quantities have been measured. These, in many instances, are not reducible to some common set of values. Thus the vertical gradients of wind speed and temperature, for instance, called for by one model and collected during one experiment cannot be uniquely related to the wind-fluctuation data required and measured in another set.

Another major problem in the comparison of diffusion models arises because of the diversity of effects that may influence a particular tracer release, effects that are not usually accounted for explicitly in any one model. The downstream concentration in a diffusing plume will, over short distances, be well related to the degree of turbulent mixing. Thus the Prairie Grass data respond quite well to normalization by a surface-wind fluctuation criterion. As the plume moves to greater downstream distances, it spreads vertically and responds increasingly to the changes of the mean flow and turbulence with height. It may even encounter a lid to vertical mixing. During any part of the travel of most gas and all aerosol plumes, contact of the plume with the ground results in material depletion, which affects both the apparent rate of downstream concentration decrease and the vertical profile of the tracer. Finally, the meteorological situation accompanying a tracer test may change in either time or space over the measurement network. To date, no one model sufficiently general to treat all phases of this complex problem has been developed. The models in use give results that are not dissimilar when comparable meteorological values can be specified as inputs.

Since most working models make use of the Gaussian assumption coupled with some measure of thermal stability and wind fluctuation, a discussion of these criteria in terms of observed diffusion data is of interest. The σ_y measurements from the Idaho surface tests for all runs in which the Richardson number (Ri) ranged between 0 and -0.05 as computed from

$$Ri = 2g (z_1 z_2)^{1/2} \frac{(\Theta_2 - \Theta_1) \ln (z_2/z_1)^{1/2}}{\Theta_2 (\bar{u}_2 - \bar{u}_1)^2} \quad (4.19)$$

have been examined for scatter. The wind speed, $\bar{u}$, and potential temperature Θ (the temperature that a parcel of dry air would have if it were brought dry adiabatically from its initial level to the arbitrary standard level of 1000 mb) at 1.0 and 8.0 m were used to evaluate Eq. 4.19. The selected Ri values are appropriate for weak to moderately unstable conditions. The frequency distribution of the ratio of the measured σ_y at each arc to the average at that arc is shown in Fig. 4.28. More than 90% of the cases in Fig. 4.28 fall within a factor of 2 of the average value for this particular stability type. A similar frequency distribution for $\bar{\chi}_p$ is shown in Fig. 4.29 for moderate instability. Once again 90% of the cases fall within a factor of 2 of the average.

A similar type of study was made of the concentration and lateral-diffusion measurements of the Prairie Grass experiments, which cover a wider range of stabilities than the Idaho experiments. The lateral-diffusion data were grouped by different σ_θ values for stable and unstable conditions. The percentage frequency of the ratio of measured σ_y values for each test to the mean for all tests at an arc in an appropriate stability- σ_θ category is shown in Table 4.20. Four class intervals, encom-

Fig. 4.28—The distribution of ratios of individual σ_y measurements to the average value for tests during unstable conditions at the National Reactor Testing Station.

Fig. 4.29—The distribution of the ratios of individual $\bar{\chi}_p$ measurements to the average value for all tests during unstable conditions at the National Reactor Testing Station. The concentration data are normalized to unit source strength and a wind speed of 5 m/sec.

passing most of the cases, are used. The scatter of $\bar{\chi}_p$, normalized to a unit source strength and $\bar{u} = 5$ m/sec, is also shown in Table 4.20. The variation of $\bar{\chi}_p$ about the mean is larger than the variation of σ_y about its mean. This apparently is due to the sensitivity of vertical diffusion to stability. However, separation of the concentration measurements into smaller ranges of stability by the appropriate σ_θ values reduces the scatter considerably. A similar study of Hanford measurements (Fuquay, Simpson, Barad, and Taylor, 1963) has been made using both Green Glow and 30 Series data. The results are shown in Table 4.21.

4-6.2 Deviations from a Gaussian Model

Most of the practical methods for computing diffusion require a Gaussian distribution of the diffusing substance. In practice, deviations from a Gaussian distribution are common but in an apparently nonsystematic way. The concentration profiles through a plume may be too peaked, too flat, or too skewed to be classified as Gaussian curves. Since no single class of functions, however, seems to adequately describe all the possibilities, it appears practical to maintain the Gaussian interpolation formulas and to inquire into the magnitude of possible resulting errors.

Table 4.20—SCATTER OF PRAIRIE GRASS σ_y AND $\bar{\chi}_p$ VALUES ABOUT THE MEAN EXPRESSED AS PERCENTAGE FREQUENCY OF RATIO OF MEASURED VALUES TO AVERAGE IN A GIVEN CLASS INTERVAL

Unstable						Stable					
No. of cases	σ_θ , deg	Class interval				No. of cases	σ_θ , deg	Class interval			
		0.9-1.1	0.7-1.3	0.5-1.5	0.3-1.7			0.9-1.1	0.7-1.3	0.5-1.5	0.3-1.7
σ_y											
30	>16	13	60	86	100	14	9 to 16	0	36	64	100
85	9 to 16	38	77	95	98	64	6 to 9	37	82	98	98
40	6 to 9	35	90	100	100	85	0 to 6	24	69	86	90
170	All cases	21	57	81	90	168	All cases	13	44	71	88
$\bar{\chi}_p$											
24	>16	17	58	88	92	12	9 to 16	17	59	76	92
67	9 to 16	19	55	81	90	52	6 to 9	26	61	88	92
31	6 to 9	12	64	90	100	68	0 to 6	4	10	54	82
134	All cases	6	36	53	63	136	All cases	8	32	52	75

Table 4.21—SCATTER OF GREEN GLOW AND 30 SERIES σ_y AND ψ_p VALUES ABOUT THE MEAN EXPRESSED AS PERCENTAGE FREQUENCY OF RATIO OF MEASURED VALUES TO AVERAGE IN A GIVEN CLASS INTERVAL

Unstable						Stable					
No. of cases	σ_θ , deg	Class interval				No. of cases	σ_θ , deg	Class interval			
		0.9-1.1	0.7-1.3	0.5-1.5	0.3-1.7			0.9-1.1	0.7-1.3	0.5-1.5	0.3-1.7
σ_y											
20	10 to 20	16	48	90	100	14	15 to 20	44	72	86	100
19	3 to 10	5	55	80	95	22	10 to 15	64	100	100	100
39	All cases	10	62	86	97	91	5 to 10	20	59	88	96
						37	<5	22	74	90	97
						164	All cases	28	68	89	96
ψ_p											
20	10 to 20	15	40	65	85	15	15 to 20	20	40	53	60
20	3 to 10	15	35	50	65	22	10 to 15	23	78	97	100
40	All cases	15	37	58	76	93	5 to 10	17	44	65	79
						38	<5	18	53	66	83
						168	All cases	18	50	68	80

The Project Prairie Grass data were analyzed by Elliot (1960) in this regard. The crosswind integrated concentration, $\bar{\chi}_{CWI}$, the axial concentration, $\bar{\chi}_p$, and σ_y are related by

$$\bar{\chi}_{CWI} = (2\pi)^{1/2} \sigma_y \bar{\chi}_p \quad (4.20)$$

if the crosswind distribution of particles is Gaussian. From the measured values of $\bar{\chi}_{CWI}$ and σ_y , $\bar{\chi}_p$ was computed and compared to the measured $\bar{\chi}_p$. The value of $\bar{\chi}_{CWI}$ is obtained by integrating the area under crosswind profiles of measured air concentration. The ratios of the computed to measured values of $\bar{\chi}_p$ for about 100 cases have been taken from Elliot's data, separated into lapse or inversion cases, and plotted as a frequency distribution in Fig. 4.30. These results show that computed values usually will not vary from measured results to a significant degree owing to the assumption of Gaussian distributions. The σ_y values used in

Fig. 4.30—Ratios of computed to measured values of $\bar{\chi}_p$ for both lapse and inversion conditions under the assumption of a Gaussian distribution. Data are presented for the Prairie Grass and National Reactor Testing Station surface experiments.

Eq. 4.20 were found by Haugen (1959a) to be statistically stable. By eliminating every second sampler from the analysis, Haugen found virtually no effect on the computed diffusion.

A similar type of study was made from the ground-level-source data reported by Islitzer and Dumbauld (1963). The ratio of $\bar{\chi}_p$ computed from Eq. 4.20 to the measured $\bar{\chi}_p$ was determined. These results are also shown in Fig. 4.30.

4-7 AREA WITHIN AN ISOPLETH

In some pollution problems, such as those dealing with the concept of total population dosage, the area enclosed within a certain isopleth of air concentration or exposure must be estimated. The Prairie Grass and Green Glow data were analyzed by Elliot (1959) and by Elliot, Engelmann, and Nickola (1961) to determine the variation of measured areas within isopleths with changing meteorological conditions. Elliot found a high correlation between the area within a given isopleth of exposure, ψ , expressed in units of g sec/m^3 , and the value of that isopleth normalized by source strength and wind speed for a range of stability conditions. Elliot derived empirically the relations between area and normalized exposure for the Green Glow and nighttime Prairie Grass data:

$$(\text{Green Glow}) A = 10.3 \left(\frac{\psi \bar{u}}{Q} \right)^{-0.95} \quad (4.21)$$

$$(\text{Prairie Grass}) A = 33.1 \left(\frac{\psi \bar{u}}{Q} \right)^{-0.91} \quad (4.22)$$

The plots of Eqs. 4.21 and 4.22 on log-log paper are virtually parallel lines displaced slightly from one another. Elliot surmises that this displacement may have resulted from the maximum air concentrations being frequently located some height above the ground during the Green Glow experiments but near the ground during the Prairie Grass experiments.

The Idaho elevated-source data (Islitzer, 1961) and ground-level-source data (Islitzer and Dumbauld, 1963) were analyzed in a similar manner, but the vertical and horizontal wind-direction standard deviations, σ_θ and σ_ϕ , also were introduced (Yansky and Islitzer,

1962). The Prairie Grass data were also analyzed in this manner. All the cases for the entire range of stability could be well represented by a single straight-line plot of the logarithm of the area vs. the logarithm of $(\bar{u}\sigma_y\sigma_z\bar{x}/Q')$; therefore the need for different curves for varying stability found necessary by Elliot was eliminated. Yanskey and Islitzer found that the correlation between area and predictor steadily improved as more meteorological variables were introduced into the predictor although the correlation was quite high for all the various selected predictors. The results given graphically in Fig. 4.31 show that the area within an isopleth is considerably less for ground-level concentrations from an elevated source than from ground-level sources. This is due to the reduced width of the plume at the ground from an elevated source. The slopes of the lines in Fig. 4.31 are fairly similar despite differences in the experimental and meteorological conditions of the three field studies. The correlation coefficients are all quite high for the various plots.

In an unpublished report Gifford (1962) compared measured area to computed area within a given isopleth. The ground-level air-concentration isopleths were computed from the generalized Gaussian diffusion model using the Pasquill diffusion categories as modified by Gifford (1961).

Fig. 4.31—Lines of best fit between the area within an isopleth of relative air concentration and meteorological predictors.

The results are shown in Fig. 4.32, which was taken from the original report. The range of Elliot's (1959) data from the Prairie Grass experiments is fairly well approximated by the range of computed curves, and the nighttime or stable cases tend toward the region of the figure occupied by Pasquill's cases E and F for slight and moderate stability. The line representing the Green Glow measurements, which represent moderate stability, tends to be most nearly represented by Pasquill's case C. Since case C is intended to apply to slightly unstable conditions, the agreement is poorer than for the Prairie Grass data. This may be due to such factors as the range of the measured data, i.e., 800 m for the Prairie Grass and 25.6 km for the Green Glow data, and differences in terrain.

4.8 SPEED AND DIRECTION OF TRAVEL

For very short distances of travel, perhaps in the range of a few hundred meters, the mean wind speed and direction measured at a source of pollution will provide a good estimate of the mean speed and direction of motion of the emitted effluent. For greater distances, i.e., of the order of kilometers and tens of kilometers, the speed and direction of the effluent will become increasingly dependent on the vertical profile of wind velocity. The arrival times of the fluorescent tracer released during the Green Glow tests at the 12.8 and 25.6 km arcs were obtained with rotating drum samplers and analyzed by Elliot, Engelmann, and Nickola (1961). The typical increase of wind speed with height resulted in travel times that were somewhat shorter than would have been computed from the wind at 1.5 m, the height of the source. The wind at 15 m was found, in the mean, to fairly represent the average travel speed of the tracer as measured at the surface.

The continuous-point-source and instantaneous-line-source data from the experiments discussed in Secs. 4-4.2.5 and 4-10.1.1 have furnished some information on particle travel speed and direction. Pasquill (1962a) gives the following mean deviations of particle travel speed and direction (averaged over all levels) from the average wind speed and direction as measured with pilot-balloon ascents and theodolite tracking: Direction: -17° to $+4^\circ$, mean

Fig. 4.32 — Comparison of measured area to computed area within a relative concentration isopleth.

-6° (point source; negative values are counterclockwise). Speed: -9% to $+14\%$, mean $+4\%$ (line source).

A tendency was evident for the direction of particle travel to back (counterclockwise) somewhat from the average wind direction, averaged for 150-m layers, and for the particle speed to exceed the mean wind speed in the layer. However, there were some exceptions to this trend. One sampling cross section, 127 km downwind from a line source, showed a distinct lag of the passage of the bottom section of the cloud from the upper sections. Pasquill attributes this to the reduction of the vertical intensity of turbulence, i_w , from a midday value of 0.1 to near 0.02 by the time the plume passed the sampling point. With this reduction in vertical mixing as the particles traveled

downwind, the decrease of wind speed with decreasing height in evidence during this experiment had a noticeable effect on the final stages of travel of the surface layer of the cloud. On the other hand, there was a lag in the passage of the cloud at higher levels during another test at 137 km from a line source. In this test the wind speed decreased with height above 300 m, and i_w decreased with time from 0.1 to 0.02 at the 900-m height by the time the cloud passed. Another experiment at 117 km showed more rapid travel of the cloud above 1200 m owing to stronger winds at 1800 m and a lower i_w (0.07 at 1800 m compared to 0.12 at 1200 m and 0.15 at 600 m). These were evidently all cases in which vertical mixing was insufficient to prevent some shearing of the cloud in accordance with the wind profile.

An attempt to determine an "effective" wind speed, a uniform wind speed throughout the diffusing cloud that will produce the same effect on the cloud as the actual wind profile, was made by Smith and Singer (1965). Assuming a Gaussian vertical concentration distribution and a power-law wind profile, Smith and Singer found that the effective wind speed may be found at the height given by

$$h = 0.62\sigma_z \quad (4.23)$$

4.9 LONG-PERIOD AVERAGE AIR-CONCENTRATION MEASUREMENTS

The literature on diffusion experimentation shows that almost all the experiments have been concerned with release times of a few hours or, usually, less. Source-receptor relations for periods of days or months are important in pollution problems from continuously emitting industrial sources and also for the slow leak of fission products from reactors. Techniques of computing long-period average air concentrations or exposures with diffusion equations developed for shorter releases are discussed in Sec. 3-3.5.4.

A study of long-period average air concentrations was made by Meade and Pasquill (1958) from the routine surveys of sulfur dioxide in the neighborhood of power stations in the United Kingdom. Since Meade and Pasquill were dealing with low average concentrations superimposed on relatively high backgrounds, they analyzed the sulfur dioxide data with respect to the equation (in their notation)

$$p = a + \frac{b f(\theta) S}{\bar{u}} \quad (4.24)$$

where p = the average concentration over any octant around a power station

a = the background concentration

S = the discharge rate of sulfur dioxide

$\bar{u}$ = the mean wind speed

$f(\theta)$ = the frequency of the wind direction in a given octant

b = the term containing the diffusion equation

In this case

$$b = \left(\frac{2}{\pi}\right)^{1/2} \frac{K}{x\sigma_z} \exp\left(-\frac{h^2}{2\sigma_z^2}\right) \quad (4.25)$$

where a doubling due to ground reflection is introduced and the constant, K , depends upon the units used and the width of the sector over which the pollution is averaged.

From routine wind records values of $f(\theta)/\bar{u}$ were obtained for each octant for each season. Smooth isopleths of pollution were drawn in from the 14 observation sites available and then used to estimate the average pollution, p , on each 45-deg arc at a radius of 1500 m from the power station. The relation between measured and computed pollution is shown in Fig. 4.33, where p is given in units of deposition of sulfur on the lead peroxide candles used for the measurements. The conversion factor to sulfur in terms of concentration units would be included in the constant term in Eq. 4.25. Despite some scatter of points, the regression equations obtained by the method of least squares shown in Fig. 4.33 were found to be statistically significant. Moreover the values of the constant, a , from the regression equations in Fig. 4.33 were in good agreement with the seasonal background values of pollution observed at Staythorpe before the power station began to function. The higher values of p observed in wintertime are a reflection of the increased average atmospheric stability in that season as compared to summer. Studies such as the one described above indicate that reasonably reliable estimates of long-period average air concentration or exposure can be made from routine meteorological observations and the appropriate diffusion equations. Furthermore, from the slopes of the lines in Fig. 4.33, values of b can be obtained and used to determine σ_z by Eq. 4.25. Meade and Pasquill give mean values of σ_z as 90 m in winter and 150 to 180 m in summer.

In another form of the long-term average-concentration equation, the equation is applied for short time periods (perhaps an hour), and the resulting hourly concentrations are then totaled for each sector during the long period of interest. This form of the equation has been mentioned frequently in the literature, but experimental evidence is, as yet, meager.

Fig. 4.33—Measured vs. computed long-period average sulfur dioxide pollution. [From P. J. Meade and F. Pasquill, A Study of the Average Distribution of Pollution Around Staythorpe, *Intern. J. Air Pollution*, 1(1-2): 66-67 (1958).]

4-10 DIFFUSION FROM INSTANTANEOUS SOURCES

The practical evaluation of the diffusion parameters in the instantaneous-point-source diffusion equation, Eq. 3.118, has received little attention when compared with the effort expended in determining the characteristics of continuous point-source plumes. Certainly part of the reason for the paucity of instantaneous-source experiments has been the traditional interest in the vast number of continuously emitting chimneys. By comparison instantaneous sources are usually associated with accidents (by definition), unusual occurrences, and occasional military requirements.

It should be remembered in instantaneous-source diffusion problems that the instantaneous

(snapshot) mass distribution of a puff or plume is a result of a finite number of discrete turbulent fluctuations. Turbulence theory deals statistically, not deterministically, with atmospheric motions. Therefore turbulence theory cannot be invoked to determine the details of an instantaneous observation of a diffusing pollutant. As indicated by the bar over the left hand side of Eq. 3.97, only the mean diffusion, the characteristics of an ensemble of puffs, can be discussed in terms of turbulence theory.

4-10.1 Instantaneous-point-source Experiments

Because of the difficulty of measuring the instantaneous values of concentration simultaneously at a sufficient number of positions, early observations of relative diffusion tended

to rely mainly on the visual methods and especially on the observation of the growth of puffs of smoke. Observations of smoke puffs were made by Kellogg (1956) and by Frenkiel and Katz (1956). In Kellogg's New Mexico experiments, vials of titanium tetrachloride and water were attached to trains of balloons and exploded at predetermined altitudes by small charges of cordite set off by baroswitches. The release altitudes ranged from 7.1 to 18.9 km, and the resulting puffs of smoke were observed by phototheodolites. From the records of the phototheodolites both the positions and visible sizes of the puffs were obtained. Eighteen usable sets of observations were reported in the form of graphs of visible diameter against time up to a maximum time between 3 and 11 min. The smoke puffs observed by Frenkiel and Katz were released within the first 100 m above the surface over a water surface during unstable conditions. The puffs were generated by exploding small charges of gunpowder carried aloft by a tethered balloon. Positions and sizes of the smoke puffs were obtained from photographs at 1-sec intervals, and the data on smoke-puff radius were tabulated by Frenkiel and Katz for 19 cases with total durations of observation ranging from 7 to 20 sec.

An interesting result from relative diffusion theory, as discussed in Chap. 3, is the prediction that the particle variances from an instantaneous source, σ_{x1}^2 , σ_{y1}^2 , or σ_{z1}^2 , initially increase as the third power of the travel time. Gifford (1957) reexamined individual runs from Kellogg's data and found that the stratospheric data tended to support a t^3 regime initially and to change to a t^2 regime for particle-variance growth after some characteristic time of travel. The upper tropospheric smoke studies, however, best followed a t^2 dispersion regime throughout all travel times. A similar t^3 regime was found for the smoke-width measurements given by Frenkiel and Katz (1956) for about 12 sec with a definite transition to a t^2 law after that time. For Kellogg's stratospheric data the transition time was usually about 3 min.

4-10.1.1 Smith and Hay, United Kingdom. Current experiments designed to relate simply measured meteorological values to the diffusion of a puff have involved the use of the relation presented by Smith and Hay (1961),

$$\frac{\Delta\sigma_1}{\Delta x} = \frac{2}{3} \beta i^2 \quad (4.26)$$

which relates the maximum spread of a cluster of dispersing particles to a meteorological variable. Here β is the Lagrangian-Eulerian time-scale factor, i is the intensity of turbulence along the appropriate coordinate, and σ_1 is the standard deviation of the material distribution. Equation 4.26 applies strictly only in the case of homogeneous isotropic turbulence, conditions usually grossly violated near the ground. Smith and Hay state, however, that Eq. 4.26 can be applied in an empirical sense during conditions of inhomogeneous or anisotropic turbulence.

Smith and Hay carried out two sets of experiments to evaluate Eq. 4.26. The first set consisted in catapulting charges of Lycopodium spores to heights of 2 m above the surface and making measurements of σ_{y1} on crosswind arcs at distances to 300 m. Continuous measures of wind speed and direction were made during each experiment. These data are presented in Table 4.22.

The particle spread, σ_{y1} , had no obvious relation to the intensity of turbulence, but this is not surprising in view of the fact that the 3-min sampling time for the turbulence intensity included the effect of eddies much larger than those eddies which could possibly have contributed directly to the spread of the clouds. By comparing the measurements listed in Table 4.22 to the σ_y/σ_θ values in Fig. 4.21 for a continuous point source during lapse conditions, we see that the horizontal particle spread in a puff is considerably less than for releases on the order of 10 min or more.

A set of medium-range experiments is summarized in Table 2 of the Smith and Hay (1961) article. In these experiments zinc cadmium sulfide particles, which fluoresce when irradiated with ultraviolet light, were used as the tracer element. The particles were released from an aircraft flying on a crosswind track, the center of which was several miles upwind of sampling apparatus mounted on the cable of a captive balloon. Measurements of wind speed and vertical direction variation were made from instrumentation mounted on the cable.

The results of these two experiments are presented in Fig. 4.34. Equation 4.26 seems to furnish a fairly good estimate of the spread of

Table 4.22—EXPERIMENTAL σ_{yI} DATA OBTAINED DURING NEAR-NEUTRAL CONDITIONS*

Experiment	$\sigma_{yI}, \dagger \text{ m}$			$\sigma_{\theta}, \ddagger$ radians	$\bar{u}$, m/sec
	At 100 m	At 200 m	At 300 m		
1	4.76	10.80	17.70	0.136	6.1
2	3.16	7.64		0.153	5.6
3	3.68	6.80	13.98	0.151	6.1
4	5.04	10.28	14.40	0.126	5.0
5	5.38	11.92		0.147	4.3
6		5.80	9.24	0.140	5.9
7	3.48			0.113	9.5
8	4.70			0.085	9.1
9	2.20			0.091	9.7
10	5.37			0.095	9.0

*From F. B. Smith and J. S. Hay, The Expansion of Clusters of Particles in the Atmosphere, *Quart. J. Roy. Meteorol. Soc.*, 87(371): 94 (1961).

$\dagger \sigma_{yI}$ is the standard deviation of the crosswind distribution.

$\ddagger \sigma_{\theta}$ is the standard deviation of wind direction for an averaging time of 1 sec and a sampling time of 3 min. All wind measurements at a height of 2 m.

a cluster of particles over a tenfold range of the intensity of turbulence, a thousandfold range of distance, and a thousandfold range of cluster size.

Figure 4.34 indicates that a value of 4.5 for β gives a reasonable fit to the observed data. Thus Eq. 4.26 may be rewritten

$$\frac{\Delta \sigma_I}{\Delta x} = 3i^2 \quad (4.27)$$

To date, this relation has been investigated in both the vertical and lateral directions but not in both directions simultaneously. Therefore there has been no direct verification of the usefulness of this formulation for estimating the exposure or concentration from an instantaneous point source.

4-10.1.2 Project Sand Storm, California. Project Sand Storm, an atmospheric diffusion program aimed primarily at the development of quantitative statements of dilution rates of pollutants released as quasi-instantaneous volume sources, was carried out at the Air Force Rocket Propulsion Laboratory test facility at Edwards Air Force Base, Calif. (Taylor, 1965). All 43 experiments were carried out under unstable conditions. The sources consisted of solid-propellant rocket motors that contained known amounts of finely divided metallic beryllium in mixture with the propellant. Firing

Fig. 4.34—Experimental values for the spread of clusters of particles. Open circles represent crosswind spread from instantaneous point sources at distances to 300 m. Closed circles represent vertical spread from aircraft-released line sources at distances of 3 to 100 km. Lines through the origin are based on Eq. 4.26 for the indicated values of β . [From F. B. Smith and J. S. Hay, The Expansion of Clusters of Particles in the Atmosphere, *Quart. J. Roy. Meteorol. Soc.*, 87(371): 99 (1961).]

durations ranged from 2 to 8 sec, and puffs were produced with initial visible diameters of 15 to 45 m. The tracer was collected on membrane filters located along circular arcs about the firing point. Originally the grid consisted of 10 such arcs extending from 100 to 2400 m. After 14 experiments all the samplers were consolidated on six arcs extending from 200 to 2400 m, thus increasing the sampler density.

Meteorological data were obtained from a 60-m tower located 60 m upwind of the release point. Temperature sensors, as well as high-response wind systems and bivanes, were mounted on the tower. Information on the visual appearance of the puffs and some measurements of puff dimensions were available from phototheodolite camera photographs.

Using the equation for exposure from an instantaneous point source and the relation between instantaneous-source diffusion and meteorological data given by Smith and Hay (1961), Taylor reasoned that the equation

$$\frac{\psi_p}{Q} \propto [\pi(\sigma_y^2 x)(\sigma_z^2 x)\bar{u}]^{-1} \quad (4.28)$$

might describe the observed exposures. The first problem was the determination of the appropriate sampling and averaging times to apply to the horizontal and vertical direction-fluctuation data to ensure that the proper portion of the turbulent energy spectrum was used in computing the direction variances. After satisfying the Smith and Hay requirement that the initial size of the puffs was small in comparison with the length scale of turbulence, Taylor computed correlation coefficients between σ_y^2 and $\Delta\sigma_y/\Delta x$ using a variety of non-trivial values of sampling and averaging times and measured puff widths. The resulting matrices of correlation coefficients indicated that (1) of the four wind-measurement heights used, i.e., 4, 15, 30, and 60 m, the 4-m values furnished the highest correlation, (2) the shortest averaging time, 1 sec, gave correlations as high as or higher than those obtained with longer averaging times, and (3) there was a trend for higher coefficients to be associated with longer wind-sampling intervals at the greater puff-travel distances. For the range of travel distances in these experiments, a sampling time of 128 sec and an averaging time of 1 sec were adopted. No measurements of the vertical distribution of the tracer were made.

Since all the experiments were conducted under thermally unstable conditions, it was assumed that the vertical rate of growth was positively correlated with the lateral rate of growth. Therefore an attempt was made to use measured values of σ_y^2 , wind speed, and distance to estimate the normalized exposure. Regression analyses using the measured ex-

posures and meteorological data yielded the somewhat surprising result that the inclusion of the wind speed and fluctuation data contributed little to the reduction of the variance obtained when distance was used as the sole criterion. The authors surmise that, since all the Sand Storm tests were conducted under thermally unstable conditions, the meteorological and diffusion data tended to occur within a very limited range. Had tests also been conducted under stable conditions, a greater range of data would have been observed, and it is quite likely that the correlations would have been higher.

Since the authors showed that most of the reduction of variance could be explained by distance from the source, a representation of the data in a probability framework (Fig. 4.35) was adopted. This format is well suited to operational usage. The data from the Sand Storm experiments are presented in summary diagrams Figs. 4.38, 4.39, and 4.40.

4-10.1.3 Högström, Sweden. An extensive set of measurements of the spreading of very short plume segments released from elevated sources was reported by Högström (1964). The tests were conducted at a coastal and an inland site near Stockholm, Sweden. Oil fog plumes were generated over a 30-sec period and released from masts at heights of from 24 to 87 m above the surface. Photographs of the plume segments taken from a point immediately upwind of the release point yielded measures of the vertical and lateral dimensions of plume segments that were assumed to be equivalent to those of an instantaneously generated point-source puff situated at the midpoint of the plume segment. The use of a 30-sec release time permitted photographic observation of the oil fog to much greater distances than would have been possible with true instantaneous releases.

The photographs were suitably enlarged, and the contours representing the visible edges were traced. These contours were assumed to represent some integrated value of concentration according to the tenets of opacity theory. The contours were usually elliptical. The lengths of the lateral and vertical axes of the ellipses were measured and related to standard deviations about the puff center by assumptions regarding the rate of change of

Fig. 4.35—Normalized peak exposures plotted as a function of distance for 38 Sand Storm experiments. The curves represent the probability of observing a given value of exposure at a given distance. (From Taylor, 1965.)

the standard deviation with travel time and a process of successive approximation. The lateral and vertical motions of the puff centers were also measured. In all cases the downwind distance of the center of the released material was estimated from the mean wind speed at the height of release and the elapsed time. Högström discusses the magnitude of the possible error in this procedure.

The usual experimental procedure consisted of the sequential release of four to six puffs over an interval of an hour. Each interval was considered as one experiment. In all, 430 puffs were released during 111 separate experiments.

With few exceptions all the puffs were released during conditions ranging from near neutral to very stable. Högström developed the stability parameter, λ (the justification for which is discussed at some length in the portion of the paper devoted to theoretical development),

$$\lambda = \log_{10} \left(10^5 \frac{\partial \Theta / \partial z}{\bar{u}_f^2} \right) \quad (4.29)$$

where $\partial \Theta / \partial z$ is the local vertical gradient of potential temperature between 30 and 122 m and $\bar{u}_f$ is the free wind. The free wind was obtained from twice daily rawinsonde ascents at a point over 100 km from the point of observation. The correlation of this stability parameter with the measured data was greater than for a variety of combinations of other predictors including potential temperature gradient, wind-speed gradient, and actual wind speed,

all measured within the height range of the releases.

The basic measurements were of σ_{y_r} and σ_{z_r} (Högström's notation), the lateral and vertical standard deviations of the mass distribution within a puff relative to its moving center, and σ_{y_c} and σ_{z_c} , the standard deviations, in the appropriate directions, of the puff centers. The dispersion of the puff centers was computed from groups of about 25 individual puffs for each of the stability-distance combinations within the range of the measurements. The values σ_y and σ_z , the standard deviations applicable to a continuous release of the length of one of the experiments (about 1 hr), were computed from the relations

$$\begin{aligned} \sigma_y^2 &= \sigma_{y_r}^2 + \sigma_{y_c}^2 \\ \sigma_z^2 &= \sigma_{z_r}^2 + \sigma_{z_c}^2 \end{aligned} \quad (4.30)$$

The author noted that all the terms in the above equations are stability dependent with the exception of σ_{y_c} . He suggests that the effect of stability is unimportant at the long wavelengths effective in the lateral dispersion of the puff centers. Both σ_{y_r} and σ_{z_r} data at the various distances show a high correlation with curves of the form

$$\sigma_r(x, s) = \frac{\sigma_r(x, 0)}{1 + as} \quad (4.31)$$

where $\sigma_r(x, 0)$ is the value of σ_r at a given distance for neutral conditions, a is an experi-

Fig. 4.36— (a) Measurements of σ_{zr} , the vertical standard deviation of the puff concentration distribution, at 1000 m as a function of the stability parameter, λ . (b) The diffusion of a puff about its center (σ_{zr}), the dispersion of the puff centers (σ_{zc}), and the total dispersion (σ_z) as a function of distance for two different values of the stability parameter, λ . [From U. Höglström, An Experimental Study on Atmospheric Diffusion, *Tellus*, 16(2): 213 (1964).]

mentally determined constant, and s is the quantity in parentheses in Eq. 4.29. In (a) of Fig. 4.36, σ_{zr} is shown as a function of the stability parameter at a distance of 1000 m from the source. In (b) of Fig. 4.36, the values of σ_{zr} , σ_{zc} , and σ_z at various distances from the source are shown for two different values of the stability parameter, λ , corresponding to almost neutral and quite stable conditions. Equivalent data for σ_{yr} are not given explicitly but can be inferred from some of the graphs presented.

The remainder of Höglström's paper deals largely with the development of formulas for the variation of diffusion with height, distance from the source, and stability. General formulas for downstream concentration from surface and elevated sources are also developed. It is interesting to note that the variation of downstream concentration from continuous surface sources based on these formulas and the observed diffusion statistics compare quite well with the results of the other diffusion experiments reported in the literature. The last

two sections of the paper deal with the effects of local terrain inhomogeneities and wind shear on diffusion.

The lateral and vertical puff-spread data from this experimental series are shown in summary diagrams Figs. 4.38 and 4.39.

4-10.1.4 Dugway Proving Grounds, Utah. A series of bomblet-produced puffs, both gaseous and particulate, released at the Dugway Proving Grounds in Utah were the subject of an intensive investigation by Cramer et al. (1964). The purpose of the investigation was the determination of an empirical generalized diffusion model that would have the property of separating the source parameters (initial size of the puff or plume cross section and release length) from the turbulence-induced spreading. Such a model would be expected to be of use with sources of a wide range of sizes, for release times ranging from the quasi-instantaneous to the continuous, and over a variety of different surface roughnesses.

Thirty-three different experiments were used in the analysis. These experiments consisted of

small explosive releases carried out primarily during the night over densely instrumented sampling grids extending to about 1700 m from the source in the case of the particulates and to over 100 m for the gaseous-release series. Release times were either 3 or 26 sec. Continuous records of wind speed and direction were available for each experiment and were used to furnish the values of σ_θ and $\bar{u}$ required by the models. No estimates of deposition or absorption were made. Since the efficiency of the various disseminators used in the tests varied widely, source strengths were estimated from measures of the flux of material through a dense array of towers surrounding and close to the source point.

Five diffusion quantities were observed directly or estimated from the experiments. The observed crosswind spread, σ_{yI} , and the observed crosswind integrated exposure, ψ_{CWI} , were computed from the observed sampler exposures at the various arcs. The vertical plume spread, σ_z , was computed at the close-in distance from a two-dimensional grid of samplers mounted on the array of towers. An "observed" σ_z at arcs further from the source was calculated from the inverse relation between σ_z and the crosswind integrated exposure as a function of distance. The observed peak exposure, ψ_p , at any arc was defined as the highest exposure reported for that arc with no attempt at interpolation. The fifth quantity studied, the area enclosed within a given exposure isopleth, was computed from planimeter readings and, also, was checked by an independent method.

Prediction models were developed for each of the five observed quantities. The first step in the construction of these models was the specification of expressions for virtual-distance computations. Such expressions were necessary to account for the lateral and vertical puff dimensions at the source. Expressions for the two virtual distances were obtained by a rather complicated manipulation involving (1) the actual puff width or depth measured at the row of samplers and towers closest to the source, (2) the assumption of puff expansion rates for the region between the virtual source and the first measurement distance, and (3) estimates of the lateral wind-direction standard deviation applicable to short-term re-

leases obtained from turbulence measurements made during each release.

As in the analysis of the Project Prairie Grass data, Cramer et al. (1964) used σ_θ as the sole meteorological predictor. Average 4-sec wind-direction values were obtained for 8.5-min intervals encompassing each release time. The σ_θ data were reduced to values appropriate to a 2.1-min sampling time via the results of an approximate spectral-analysis technique. These standard deviations were further reduced by the application of the formulation

$$\sigma_\theta(T) = \sigma_\theta(T_0) \left(\frac{T}{T_0} \right)^{1/2} \quad (4.32)$$

where T_0 is an arbitrary sampling time, 2.1 min in this case, and T is the required sampling time, 3 or 26 sec in these experiments. Cramer et al. present considerable justification for this procedure. According to the authors, values of T larger than T_0 in the above formulation would result in estimates of σ_y appropriate to continuous releases.

The source configuration and turbulence formulations were combined to produce the model formulas. The models for the five diffusion quantities to be studied in the experiments were evaluated for each release on the basis of observed turbulence and initial puff size. The predictions for each of the quantities for each of the 33 experiments were compared on a case by case and on a statistical basis with the observed values.

The results of the comprehensive statistical comparison of the observed and measured diffusion data lead the authors to the general conclusion that, on the average, about 90% of the observations were within a factor of ± 2 of the predicted model values. The model σ_{yI} furnished the best fits of the various models to the data with 90% of the data between the limits $0.65 < \sigma_{yI(\text{obs})}/\sigma_{yI(\text{mea})} < 1.38$. The limits for the area exposure were the widest (90% of the data between 0.40 to 2.52). Bias in some of the prediction models may be noted in the detailed graphs of the statistical comparisons.

In summary, the authors' contention that the models have demonstrated their ability to estimate quasi-instantaneous diffusion from measures of lateral turbulence and initial source configuration seems well supported. From other research accomplished by the authors,

Cramer in particular, it would seem that the basic premises involved in the construction of the models are useful for exposure estimation for a variety of release times at other sites.

In the interest of documenting the peak exposures and lateral and vertical plume spread observed during these experiments, average values of these data are presented in the summary diagrams Figs. 4.38, 4.39, and 4.40. The lines representing the average values of the two sets of longer range tests in each of the three diagrams contain the corrections for initial finite puff size derived by the authors. The two individual points at 100 m in Fig. 4.40 are averages of 14 stable and 3 unstable shorter range tests. These contain corrections for the initial puff widths, σ_{y10} , which were quite large in these tests.

4-10.1.5 Point Arguello, California. Another experiment that may be used to furnish instantaneous-source diffusion information was conducted at the Naval Missile Facility at Point Arguello, Calif. (Smith et al., 1964). This experiment consisted of both quasi-instantaneous and longer releases of zinc cadmium sulfide and uranin dye over an irregular network of sampling stations at the coastal California site. The site itself is quite irregular with individual ridges and peaks rising to well over 300 m. Sampling was conducted along irregular lines surrounding the release point. It was not possible to obtain puff dimensions and exposures at a number of distances downwind for each puff. However, the number of samplers was sufficient to obtain the width of a puff and an estimate of the maximum exposure at one distance for each release. The results of a number of 60-sec releases, which were not complicated by release or sampling in the vicinity of a pronounced ridge, are presented in Figs. 4.38 and 4.40 for puff width and exposure, respectively.

4-10.1.6 Reactor Destruction Tests (NRTS), Idaho. Islitzer and Markee (1964) report quasi-instantaneous releases that consisted of puffs of radioactive material emitted during reactor destruction tests at the National Reactor Testing Station in southeast Idaho. Release times for four tests were about 30 sec, and the resulting material was sampled over instrumented grids to 750 m in three cases and to over 6000 m in the fourth case. The lateral puff spread was found to be more closely approxi-

mated by the square, rather than the first power, of the lateral turbulence intensity. It is interesting to note that Smith et al., in their Point Arguello studies, also found such a relation. Although there is some doubt as to the sampling and averaging times to apply to the wind data to obtain the appropriate intensity of turbulence for the Smith-Hay (1961) expression $\sigma_{y1} = 3i_v^2 x$, there appears to be merit in the use of this formulation for predicting puff dimensions directly from wind-fluctuation measurements.

Since the source strength was not accurately known in these experiments, only relative exposure data were obtained. The plume-width measurements for the one long-distance experiment are given in Fig. 4.38.

4-10.2 Instantaneous-line-source Experiments

4-10.2.1 Dallas Tower, Texas. A series of diffusion tests using elevated line sources released from low-flying aircraft was carried out in the vicinity of the 430-m Dallas television tower at Cedar Hill, Tex. (MacCready, Smith, and Wolf, 1961). Thirty-seven tests were carried out in three two-week intervals in April, June, and August of 1961. Extensive use was made of wind and temperature measurements made by the Air Force at various levels of the tower. Mean-wind and turbulence information was obtained from Aerovane and bivane instrumentation. Vertical sampling of the zinc cadmium sulfide tracer material was accomplished by sequential filter samplers at various levels on the tower and by rotorod samplers located on the ground 1.6 km apart to a distance of about 48 km downwind of the release line. During a portion of the tests, a crosswind rotorod line was added near the downwind end of the main ground sampler line. All releases were made during the night. Source lines ranged between 14.5 and 42 km in length, between 1.6 and 11 km upwind of the tower, and between 110 and 320 m above the tower base.

The primary objective of the program was to relate the measured diffusion characteristics of the cloud to the observed turbulence, wind velocity, and temperature in a quantitative manner.

The principal analysis effort was concerned with the explanation of the observed vertical

cloud width on the tower, the distance from the release line to the first appearance of the cloud at the ground, and the location and magnitude of the maximum exposure at the ground. The basic theoretical relation investigated was that of Smith and Hay (1961) where i_w , the intensity of turbulence (vertical turbulence in this case), was estimated from tower measurements of σ_v , the standard deviation of the vertical wind-direction distribution. The quantity σ_v generally increases with the sample length up to some point where it becomes asymptotic to a maximum value. In the case of the Dallas tower data, it was found that almost all the increase occurred within 3 min.

The results of the tests showed that the vertical dimensions of the cloud, as given by σ_v , were consistently larger than calculated from Eq. 4.27. One reason for this discrepancy was that the initial size of the cloud at release was appreciable because of the turbulence created by the releasing aircraft.

The rate of growth ($3i_w^2$) leads to a model of ground exposure given by

$$\psi = \frac{2Q}{3i_w^2 x \bar{u} (2\pi)^{1/2}} \exp - \left(\frac{H^2}{18i_w^4 x^2} \right) \quad (4.33)$$

where ψ = ground exposure at a distance x from the release

Q = source strength

$\bar{u}$ = mean speed in the layer from the ground to the release height

i_w = in this case, a weighted average of the vertical-turbulence intensity between the release height and the ground

Plots of the calculated and observed exposures are shown in Fig. 4.37. Observed ground exposures were in good agreement with the model described by Eq. 4.33 when the release was made within a well-developed turbulent layer above the ground. Observed maximum exposures averaged 23% higher than forecast for the 14 cases that satisfied this condition. For releases above this turbulent layer, ground exposures were much more erratic than predicted by the model.

Calculations of i_w for all tests were used to estimate the probability that a release would reach the ground. If a criterion is assumed which requires that the particle cloud reach the

ground in reasonable quantity in the first 24 km, then this criterion would be satisfied 86% of the time for line-source releases at a height of 135 m, 37% of the time for releases at 225 m, and 3% of the time for releases at 315 m.

Dilution of the cloud from the ends of the release line was measured during nine of the tests in which adequate sampling was available along a crosswind line at the downwind end of the main sampler line. It was found that the cloud diluted laterally at a rate corresponding to

$$\frac{d\sigma}{dx} = i_v \quad (4.34)$$

where i_v was computed from the root-mean-square value of the horizontal direction variation over the period of interest. This rate is in marked contrast to the vertical spreading rate of $3i_w^2$.

4-10.2.2 Rough and Irregular Terrain, United States.

Experiments similar to those conducted at the Dallas tower were carried out over sites in Oklahoma, Texas, Washington, and Nevada (Smith and Wolf, 1963). The most important difference between these tests and the Dallas experiments was the absence of a tall tower for measuring the turbulence values and the vertical distribution of tracer material from the aircraft-released line source.

In each of these four experiments, sampling was accomplished along a line of rotorods about 40 km in length oriented in a direction approximately normal to the aircraft line release of zinc cadmium sulfide. Meteorological information was obtained from a 30-m tower and two 10-m towers situated along the line of release as well as from a high-frequency turbulence-measurement system mounted on the tracer-releasing aircraft.

The experimental hypothesis consisted of the assumption that the effective turbulence computed for the Dallas experiments could be estimated from the more-limited meteorological measurements available during these experiments, and thus the estimate of the effective turbulence could be used to estimate the ground-exposure patterns. At the Oklahoma site, where the terrain was similar to that at Dallas, the computed exposures were in good agreement with those observed.

Fig. 4.37—Comparison of calculated and observed exposures from an elevated line-source release. (From MacCready, Smith, and Wolf, 1961.)

The Texas sampler line extended inward from the coast in the immediate vicinity of Corpus Christi. The observed exposure patterns bore little resemblance to those calculated. This result was ascribed to the possible

existence of helical circulations in the air moving off the ocean over the very flat terrain. Two different results were obtained at the Washington site. During a few afternoon runs, atmospheric fluctuations of lower frequency

than could be sampled with the project instrumentation tended to bring higher than predicted exposure values to the ground. The remainder of the runs, taken at night, showed small ground exposures that were in accord with the small predicted values based on the low levels of turbulence.

Perhaps the most interesting of the four studies was that conducted at the Nevada site. The sampler line crossed a ridge with a maximum height of about 300 m above the lower land at each end of the line. During stable night conditions the highest ground exposures were invariably experienced on the lee side of the ridge. The authors surmised that the tracer, embedded in the stable flow, experienced an upward transport along the windward slope and little tracer reached the surface. The indications are that a more complex turbulence field in the lee of the ridge resulted in a greater degree of vertical mixing and thus in higher surface exposures.

These experiments point out with great clarity the effect of nonregular terrain on expected diffusion patterns. The classical methods, as well as those developed more recently over the flat diffusion grids, offer little help in estimating diffusion in the more complicated terrain. The meteorologist must in more complicated terrain use his total experience to assess, even qualitatively, the nature of the resulting diffusion.

4-10.3 Summary of Instantaneous-source Experiments

The data presented in this section, as can be seen from Table 4.1b, are quite inhomogeneous with respect to source configuration, release height, meteorological and terrain conditions, and, probably, scavenging effects. Since a variety of different meteorological predictors, which cannot be quantitatively compared, were used by the various investigators, the diffusion data in the summary diagrams are classified according to the broad categories of unstable, near neutral, and stable. Not all the data are plotted in the summary diagrams. Only those averages, regression lines, and, occasionally, individual runs that give some idea of the range of values encountered during these experiments have been used.

In general, the observed slopes of σ_{yI} , σ_{zI} , and $\psi_p \bar{u}/Q$ should not be expected to conform closely to any theoretical considerations unless such formulations include corrections for initial source size and deposition. Some of the data presented include corrections for initial source size, either given by the authors or estimated from other considerations. None, however, include any correction for deposition.

Figure 4.38 presents a summary of σ_{yI} values for quasi-instantaneous releases. The point labelled "approximate limit of most stable data" was estimated from a few of the most stable runs reported by Högstöm and from an extrapolation of his functional relation between σ_{yI} and his stability parameter, λ . The neutral

Fig. 4.38 — Summary diagram for measured σ_{yI} data. Note that measured data have been differentiated from those to which some adjustment has been applied.

curve for the Högstöm experiments appears to be an extension of that for the Smith and Hay data despite the source-height difference. The Point Arguello data represent individual determinations of σ_{yI} at various distances from the source over the rugged coastal site. The turbulence induced by the terrain may account both for the large individual values of σ_{yI} and for the similarity between the stable and unstable cases. In situations such as this, a measurement of turbulence or stability at the source may not be sufficient information to estimate the terrain-induced diffusion along the puff trajectory.

The Dugway measurements of σ_{yI} are represented by the regression lines for two test

series and contain a correction for lateral source dimensions. Two sets of Sand Storm curves are presented. The upper curve represents the average of the four highest values of σ_{y1} at each measurement distance, and the lower line is the average of all the data. It is interesting to note, in the original data, that the individual σ_{y1} curves generally increase quite steadily in comparison with the erratic decrease of exposure with distance. The observations of the vertical meander, or skipping, of the puffs during unstable conditions are consistent with this behavior.

Fig. 4.39—Summary diagram for measured σ_{z1} data. Computed data have been added for the Sand Storm series because of the lack of information on instantaneous-source vertical spreading during unstable conditions.

Considerably fewer direct measurements are available for instantaneous-release values of σ_{z1} (Fig. 4.39). By far the most numerous are those resulting from the photographic investigations of Högström. Again, an approximate lower limit for σ_{z1} at 1000 m is indicated. The regression line for the Dallas experiments is based on one measurement of σ_{z1} per experiment at source distances varying from about 10^3 to 10^4 m from the tower. The observed values have been reduced by factors indicated by the authors to remove the spreading due to the aircraft-induced turbulence. About 85% of the observations are included between the boundaries of ± 2 about the regression line. The data exhibit some dependence on the weighted vertical-turbulence intensity as derived from measurements made on the television tower.

In practical applications this meteorological predictor cannot be measured unless a suitably tall tower exists.

The Dugway σ_{z1} data are basically computed values since they are based on measurements of σ_{z1} made at only one distance close to the source, and are derived from an adjusted crosswind integrated exposure at other distances. Although all the Dugway data presented in Fig. 4.39 were obtained during the night hours, the stability ratio and turbulence-intensity values indicate neutral or near-neutral conditions in every case.

The curve for σ_{z1} for the Sand Storm tests is a computed quantity and included in this summary of measurements only because of the lack of σ_{z1} observations during unstable conditions. The 90th percentile values of normalized exposure ($p = 0.10$ in Fig. 4.35) and the average value of Q , σ_{y1} , and $\bar{u}$ for all the tests were used to compute the average σ_{z1} values. The use of the 90th percentile values was based on the fact that the higher exposure values at each distance would be more likely to be estimates of puff-center values in situations where the puff exhibited some degree of vertical meander. The values obtained by this procedure were reduced to account for the initial vertical puff dimensions. The use of the median values of the Sand Storm exposure at each distance from the source results in a σ_{z1} curve higher by a factor of 3 to 4 with a slope more closely approaching that of neutral and stable conditions.

Measured values of normalized exposure are presented in Fig. 4.40. The numerous Högström data on puff dimensions were obtained photographically and thus do not include measured exposures. However, the approximate upper limit of normalized exposure has been computed from the appropriate values of σ_{y1} and σ_{z1} at 1000 m in Figs. 4.38 and 4.39.

The average observed value and range of the longer Dugway tests are presented along with average exposure values at 100 m for 17 shorter range tests. In these latter tests a correction was applied to the exposure data to account for the initial lateral puff width, which was frequently rather large.

The Sand Storm experiments are represented by two lines, the higher values representing the 90th percentile exposure data and the lower

Fig. 4.40—Summary diagram for normalized axial exposure data. The point representing the approximate limit of most stable data is based upon the smallest values of σ_{y1} and σ_{z1} at 1000 m observed by Högström.

line, median values. In each case an adjustment for the initial vertical puff size was applied to the observations.

The Point Arguello data show some differentiation between stable and unstable exposures, but the stable values are still considerably smaller than would be expected on the basis of the other data that have been presented. Again, this may be due to the turbulence induced by

the very rough terrain over which the experiments were conducted.

A set of suggested instantaneous-source values of σ_{y1} , σ_{z1} , and $\psi_p \bar{u}/Q$, based on the foregoing data, are presented in Table 4.23.

Editor's Note: An experimental program to study in detail the atmospheric diffusion of airborne aerosols over an isolated urban area was conducted at Fort Wayne, Ind. (Glenn R. Hilst and Norman E. Bowne, *A Study of the Diffusion of Aerosols Released from Aerial Line Sources Upwind of an Urban Complex*, Vols. I and II, Travelers Research Center, Hartford, Conn., 1966). Seventy aerial line-source releases were made in 21 separate experimental periods at night under various thermal stability conditions.

The city was expected to produce enhanced mixing because of increased surface roughness and, also, to show a heat-island effect. The tracer and meteorological sampling networks were designed to measure these effects quantitatively. Vertical tracer sampling on towers and a tethered balloon provided useful information on vertical motions around the city.

The following features of the atmospheric motion within and around an isolated city were identified:

1. In a large majority of situations, but particularly when the temperature lapse rate in the lower 61 m of the rural atmosphere is between dry adiabatic and isothermal, the axis of the tracer cloud descends toward ground level. The cloud was observed to enter the city with maximum dosages consistently at or near street level under these conditions. With inversion conditions the cloud remained at release height and diffused slowly in the vertical.
2. The enhanced surface roughness and thermal mixing caused by the city produced a 30 to 50% increase in the vertical mixing of the aerosol over the city as compared with the rural area.
3. An analysis of the mean and variance of tracer dosages at the surface sampling stations showed a random component of variability of about a factor of 2. No distinct differences of diffusion rates could be differentiated on the basis of land use within the city. These results suggest that a city of the size and structure of Fort Wayne can be considered a single-surface anomaly in predicting its effect on aerosol diffusion.

Table 4.23—SUGGESTED ESTIMATES FOR σ_{y1} , σ_{z1} , AND $\psi_p \bar{u}/Q^*$

Parameter	Conditions	100 m	4000 m	Approximate power function
σ_{y1} , m	Unstable	10.0	300	$0.14(x)^{0.92}$
	Neutral	4.0	120	$0.06(x)^{0.92}$
	Very stable	1.3	35.0	$0.02(x)^{0.89}$
σ_{z1} , m	Unstable	15.0	220	$0.53(x)^{0.73}$
	Neutral	3.8	50.0	$0.15(x)^{0.70}$
	Very stable	0.75	7.0	$0.05(x)^{0.61}$
$\psi_p \bar{u}/Q$, m^{-2}	Unstable	2.12×10^{-3}	4.81×10^{-6}	$4.20(x)^{-1.65}$
	Neutral	2.08×10^{-2}	5.30×10^{-5}	$35.5(x)^{-1.62}$
	Very stable	3.26×10^{-1}	1.30×10^{-3}	$330(x)^{-1.50}$

*The power functions are applicable in the given range of distances only.

4-11 ESTIMATES OF TRAJECTORIES AND DIFFUSION (CONSTANT-LEVEL BALLOONS)

4-11.1 Use of Constant-level Balloons for Trajectory Estimation

In the past, estimates of the trajectory and spreading of pollutant releases to the atmosphere have usually been based upon wind statistics obtained at fixed points (Eulerian networks). Fundamentally, however, atmospheric diffusion depends on the movement of individual air parcels (Lagrangian statistics). In recognition of this fact, recent developments in the field of diffusion meteorology have emphasized ways of passing from the easily obtained Eulerian statistics to the desired Lagrangian statistics. It would appear that, although Eulerian wind statistics may be suitable for diffusion estimates over small times and distances, for the longer times and distances there are important difficulties inherent in this technique. For example, as a pollutant spreads vertically, it encounters wind-direction and speed changes that cannot be measured by a surface network of anemometers and are difficult and expensive to determine by existing fixed-point vertical wind-sounding methods.

The literature is replete with ingenious techniques for estimating air trajectories from Lagrangian observations. On the microscale one might mention the photographic positioning of soap bubbles by Edinger (1952), of dandelion seed by Badgley and Fleagle (1952), and of Kleenex lint by Miller (1952). However, even these tracers possessed some fall velocity with respect to the air. If a substance with a density equal to that of the air is introduced into the atmosphere, there is little doubt that it will follow the atmospheric motions. The difficulties arise in positioning such substances. With the exception of smoke, most of these substances are not visible to the naked eye and do not act as reflectors of electromagnetic radiation. Therefore their detection at a later time involves either a complex sampling network or a rapidly moving atmospheric probe such as an aircraft.

An alternative method of obtaining air trajectories involves placing a gas lighter than air within a visible container heavier than air so that the average density of the traceable object

is equal to that of the air. A no-lift balloon satisfies this criterion, and through the years meteorologists such as Richardson and Proctor (1925), Koschmieder (1925), Gifford (1953), Lucas, Spurr, and Williams (1957), and Sakagami (1961) have made use of no-lift balloons to estimate air trajectories and atmospheric diffusion. In the following sections the use of a constant-volume balloon as a tracer of air motions, as first reported by Angell and Pack (1960), will be explored. The experiments reported are primarily those conducted by the personnel of the Environmental Science Services Administration (formerly the Weather Bureau).

The tetrahedron-shaped constant-level balloons (tetroons) are made of the nearly inelastic material, Mylar. Prior to flight, the tetroon is filled with a helium-air mixture to a pressure considerably higher than that at the expected flight (density) level. The advantage of the superpressured tetroon over expansible no-lift balloons is that the tetroon volume does not change appreciably with a change in temperature of the inflation gas. Thus there is little variation in buoyancy force, and the tetroon responds primarily to ambient density variations and to the three-dimensional wind patterns.

Since, in general, an air parcel moves vertically as well as horizontally, the fidelity with which a tetroon can trace air motions is a function of the fidelity with which the tetroon follows the vertical air motion. Inasmuch as there is always a restoring force tending to return the tetroon to its equilibrium floating surface, the amplitude of tetroon oscillations in the vertical will always be less than that of air parcels. There is, however, evidence that the three-dimensional tetroon trajectory represents a first approximation to the three-dimensional air-parcel trajectory. Thus Angell (1964) showed that at Cardington, England, in nearly calm conditions, the period of vertical oscillation of the tetroon was almost identical with the period of vertical oscillation of wind vanes attached to a barrage-balloon cable. Furthermore, at this same site the period and amplitude of the tetroon oscillations in the vertical were always greater in the afternoon when the atmosphere was relatively unstable than in the morning when the atmosphere was relatively stable, and indeed there was fair

agreement between the period observed and the period theoretically expected from a consideration of the lapse rate. Finally, at Cardington it was found that at the high-frequency end of the tetron-derived vertical-velocity spectrum, the spectral density decreased approximately as frequency to the -2 power in agreement with theoretical expectations for Lagrangian-type data.

The tetrons have generally been positioned by radar, either through the use of passive reflectors or transponders (radio beacons) attached to the tetrons. The latter technique was first reported by Pack (1962) and was exten-

sively used in the Los Angeles Basin by Pack and Angell (1963). Detailed descriptions of the various tetron-transponder systems used may be found in the various references noted in this section. With an appropriate radar, tetron positions can be obtained at intervals of a few seconds over distances well over 100 km.

A picture of the types of trajectories obtained in widely varying geographical areas is given by Figs. 4.41–4.43, which show tetron trajectories from Cardington, England (Angell, 1964), Las Vegas, Nev. (Angell and Pack, 1961), and Los Angeles, Calif. (Pack and Angell, 1963). Cardington is located amongst gently

Fig. 4.41—Tetron trajectories at Cardington, England, superimposed upon a simplified topographic map of the area. Tetron positions indicated at 5-min intervals. Flights labelled T were made when the barrage balloon (with fixed-point wind instruments) could not be flown. (From Angell, 1964.)

rolling hills in south central England. Here the tetroons were flown at heights near 800 m. Very apparent from Fig. 4.41 is the straightness of trajectories in this region and, at this height, the lack of dependence of trajectories upon terrain features. The Las Vegas flights

(Fig. 4.42) were launched from Yucca Flat and exhibited vertical height oscillations of as much as 3000 m during the daytime hours. The flights went upslope during the day and down-slope (flights 6 and 13) during the night with some evidence that the veering of the trajec-

Fig. 4.42—Tetroon trajectories at Yucca Flat near Las Vegas, Nev., superimposed on a simplified topographic map of the area. Tetroon positions indicated at 5-min intervals. Dotted segments of trajectories estimated from visual sightings. (From Angell and Pack, 1961.)

tories during the day (flights 1, 2, 3, 4, 5, and flights 9 and 10) was associated with solar heating of the mountain slopes. Numerous flights have been made from various sites within the Los Angeles Basin, and Fig. 4.43 shows the flights from Long Beach at heights of 300 m to 600 m. Note the large directional shifts along the Long Beach flights, particularly in comparison with the Cardington flights.

4-11.2 Use of Tetroons for Estimating Atmospheric Diffusion

In addition to providing an estimate of the travel direction of a pollutant, tetroons can be utilized to yield an estimate of the diffusive capabilities of the atmosphere. In this section

alternate ways in which this can be done are considered, and comparisons between the diffusion derived from tetroons and the diffusion derived by more-conventional techniques are recorded. Finally, mention is made of the use of tetroons to bridge the gap between the more easily obtained Eulerian statistics and the oftentimes desired Lagrangian statistics.

Within the atmosphere two different types of diffusion are of interest. The first type involves crosswind diffusion from a continuous point source (smoke-plume type diffusion), and the second involves so-called "relative" diffusion (smoke-puff type diffusion). Insofar as possible, both types of diffusion will be studied in both vertical and lateral dimensions.

Fig. 4.43—Tetroon trajectories of 2-hr or more duration for releases from Long Beach, Calif. Tetroon positions are indicated at 1-hr intervals. (From Pack and Angell, 1963.)

In the following sections lateral atmospheric diffusion is estimated from tetron data in three ways: (1) from successive tetron releases, (2) from the lateral distance between pairs of nonsimultaneously released tetrons, and (3) from individual tetron trajectories.

4-11.2.1 Lateral-diffusion Estimates from Successive Tetron Releases. The most common measure of lateral diffusion, the lateral standard deviation, can be obtained from successive tetron releases by evaluation at given downwind distances of the root-mean-square value of the distances between the mean trajectory and individual trajectories. Figure 4.44 shows the standard deviations so obtained for series of tetron flights within the Los Angeles Basin

and near Las Vegas, Nev. The series were selected so that a mean wind could reasonably be defined for each series. The time between the first and last tetron release in each series varied from 8 to 48 hr. For these flights in the Los Angeles Basin, the lateral standard deviations were large, averaging 50% to 75% of the downstream distance because the tetrons were being used to simulate a continuous source sampled over periods of many hours. Thus the lateral standard deviations reflect not only what might be considered turbulent diffusion but also the effect of changes in the mean wind direction with time. The strength of the diurnal wind regime in the Los Angeles Basin is well known.

Fig. 4.44—Estimates of lateral diffusion from successive tetron releases as a function of distance at Los Angeles, Calif., and Las Vegas, Nev. Dashed line gives typical values of σ_y obtained from 1-hr tracer diffusion experiments.

4-11.2.2 Lateral-diffusion Estimates from Tetroon Pairs

It has been indicated that diffusion estimates from successive tetroon releases so far available yield lateral standard deviations appropriate to a large sampling time. Also there is a certain subjectivity involved in deciding what flights should be included in a series and in defining the mean trajectory to be associated with that series. To some extent these difficulties may be circumvented by considering the lateral distance between pairs of nonsimultaneously released tetroons at various downwind distances. Panofsky and Brier (1958, p. 210) showed that the best unbiased estimate of the variance of the population (σ_y^2) is given by

$$\sigma_y^2 = (N-1)^{-1} \sum_{i=1}^N (Y_i - \bar{Y})^2 \quad (4.35)$$

where N is the number of observations, Y_i is the individual position on the y axis, and $\bar{Y}$ is the mean position on the y axis. For the case of $N = 2$,

$$\sigma_y^2 = \left(\frac{Y_1}{2} - \frac{Y_2}{2} \right)^2 + \left(\frac{Y_2}{2} - \frac{Y_1}{2} \right)^2 \quad (4.36)$$

but, since by definition the lateral distance, d , between a particle pair is $Y_1 - Y_2$, then

$$\sigma_y^2 = \frac{d^2}{2} \quad (4.37)$$

Therefore, in principle at least, the lateral variance (and hence lateral standard deviation) can be estimated from a continuous point source through evaluation of the average of the square of the distances between pairs of nonsimultaneously released tetroons at various downwind distances. Furthermore, the effect on the lateral standard deviation of various release and sampling durations can be estimated by choosing tetroon pairs having different time intervals between release. This then is a particularly suitable method for estimating a diffusion climatology for various sites under given atmospheric conditions. Accordingly, at a variety of launch sites, circles with radii of 5, 10, 15 km, etc., were drawn, and the distance between points of intersection of pairs of trajectories with these circles was evaluated. This was done for all possible pairs of flights where the time interval between tetroon releases was less than 6 hr and less than 24 hr.

Based on the above procedure with 201 observations of tetroon pairs, Fig. 4.45 shows the mean lateral standard deviation as a function of downstream distance for various tetroon launch sites and for time intervals between releases of less than 6 hr (underlined symbols) and less than 24 hr. It is assumed, then, that these standard deviations are approximations to the standard deviations that would be obtained if one released a tracer material for periods of 6 hr and 24 hr and also sampled for the same periods. Thus, included in these standard deviations are meanderings of the tracer plume as well as what might be considered changes in the mean wind direction (meanderings on a much larger time scale). The asterisks at 5-km intervals in Fig. 4.45 indicate the mean of the 24-hour series (series 1, 2, 3, and 4) in Fig. 4.44. Inasmuch as these four series all involved flights from Long Beach, the similarity in the ordinate of the asterisks and the Long Beach designators implies that, basically, the two techniques are compatible.

It is of interest from the viewpoint of diffusion climatology that, for release periods of 6 hr, the lateral diffusion from the Long Beach and Venice sites is about three times the magnitude of the lateral diffusion from Cardington. This would be expected owing to the presence of a pronounced diurnal wind regime within the Los Angeles Basin. The tetroon flights from Marineland yield relatively small values of the standard deviation because flights were made only during the daytime sea-breeze regime and because many of the flights from Marineland involved the simultaneous release of two tetroons. The relatively rapid increase of lateral standard deviation with downstream distance for Wallops Island flights (Angell and Pack, 1962) released within 6 hr of each other suggests the predominance of large-scale eddies over the water during the winter period of the flights.

The adjacent dashed and solid lines in Fig. 4.45 indicate the mean values of lateral standard deviation as a function of downstream distance for all the tetroon launch sites and for time periods of release and sampling of less than 6 hr and less than 24 hr, respectively. It is emphasized that these mean values are not universally applicable owing to the preponderance of tetroon flights within the cyclic wind

Fig. 4.45—Lateral standard deviation as a function of downstream distance based upon tetron flights from Cardington (▲), from Las Vegas (●), from Wallops Island (■), and from Marineland (△), Long Beach (○), and Venice (□) within the Los Angeles Basin. Underlined symbols indicate tetron releases within 6 hr of each other, plain symbols indicate tetron releases within 24 hr of each other. The means for all flights are given by the adjacent solid and dashed lines for time periods of less than 24 hr and 6 hr, respectively. Asterisks represent means of the 24-hr series given in Fig. 4.44. Crosses represent values obtained from transosonde releases within 24 hr of each other (multiply ordinate and abscissa values by 100). P indicates values obtained by Pasquill at Porton.

regime of the Los Angeles Basin. Nevertheless the similar behavior of flights at Las Vegas (Yucca Flat) and Los Angeles suggests that such cyclic regimes are sufficiently widespread to be of practical interest.

The slopes of the adjacent solid and dashed lines in Fig. 4.45 indicate that, over down-

stream distances of 5 to 35 km, the lateral standard deviation is proportional to downstream distance to the 0.87 power for tetron releases over 24 hr and proportional to downstream distance to the 0.84 power for tetron releases over 6 hr. For all downstream distances between 5 and 35 km, the lateral stan-

standard deviation for the 24-hr releases is almost exactly 1.4 times the lateral standard deviation for the 6-hr releases. On the basis of this tetron data, one would estimate that for a continuous point source the lateral standard deviation is proportional to sampling time to the 0.24 power. Cramer (1959) and Stewart, Gale, and Crooks (1954) have found that for sampling times of less than 30 min the concentration of a pollutant is inversely proportional to the one-fifth power. Inasmuch as concentration is inversely proportional to the product of lateral and vertical standard deviations, their results would indicate a lateral standard deviation proportional to the one-tenth power of the sampling time if both vertical and lateral dimensions are equally responsive to sampling time and a lateral standard deviation proportional to the two-tenths power of the sampling time if the vertical spread is assumed invariant with sampling time.

It is of interest to compare the tetron results obtained at Cardington with the Pasquill (1962) results obtained at Porton (lower dashed line in Fig. 4.45) since the terrain is similar in the two areas. With the assumption that the lateral standard deviation is also proportional to the 0.24 power of the sampling time for sampling times shorter than 6 hr, Pasquill's aircraft probes of the plume from a continuous point source correspond to samples taken over an 8-min period. Although a slightly shorter sampling period might be more appropriate, the data are sufficiently consistent to suggest that successive tetron pairs yield a useful approximation to the lateral diffusion to be expected over given time intervals of release and sampling. The advantage of the pair method is that even with existing radar facilities lateral diffusion can be estimated for sampling times ranging from a few minutes to many hours.

The crosses in Fig. 4.45 indicate lateral standard deviations as a function of downstream distance derived from transosondes released within 24 hr of each other. The transosondes were released from Iwakuni, Japan, for flight at about 300 mb (Angell, 1961). Note that the transosonde data refer to downstream distances and lateral standard deviations 100 times as large as the abscissa and ordinate values shown in Fig. 4.45. Thus, over downstream distances of 1000 to 4000 km, the

lateral standard deviation varies from 140 to 520 km and indicates a lateral standard deviation proportional to nearly the first power of the downstream distance. Furthermore, for the transosonde flights the ratio of lateral standard deviation to downstream distance is only about half that found for the Cardington tetron flights, the tetron flights with the smallest value of this ratio in Fig. 4.45. However, owing to the great steadiness of the winds over Japan in winter, the transosonde results cannot be considered truly representative of the results that would be obtained from most release sites.

4-11.2.3 Continuous-point-source Diffusion Estimates from a Single Trajectory. Gifford (1960a), Pasquill (1961), and others have shown that the lateral diffusion can be estimated from running means of the lateral wind fluctuations and that this is, theoretically, fully equivalent to using Taylor's (1921) original formulation. The relevant formula is

$$\sigma_y = (\overline{v'^2} t^2)^{1/2} \quad (4.38)$$

where σ_y is the lateral standard deviation after travel time t and $\overline{v'^2}$ is the variance of the lateral wind fluctuation averaged over the diffusion (or travel) time t .

The use of Eq. 4.38 for diffusion estimation has been considered by Angell (1962). First, it should be noted that a single set of lateral wind-fluctuation (v') statistics of infinite length in a stationary homogeneous turbulence field would, in theory, provide complete information on lateral diffusion. However, for a finite length of v' information in a steady homogeneous turbulence field, we should expect the σ_y value to always be less than the true value. In the case of real atmospheric data, we should also expect differences in the observed turbulence field, owing to the manipulation of the data and to observational errors, which affect the v' statistics. On the other hand, the lateral standard deviations derived in this way refer to a sampling time corresponding to the travel time, which, in turn, is comparable to the sampling time utilized by previous investigators. Thus the lateral standard deviations derived from Eq. 4.38 might be expected to more closely resemble previously obtained continuous-point-source diffusion data than the lateral standard deviations obtained by either of the two methods discussed earlier.

The solid lines in Fig. 4.46 represent lateral standard deviations as functions of downstream distance derived from individual tetron flights through the use of Eq. 4.38. In general, the tetron flights were made at heights near 600 m. For clarity the solid lines in Fig. 4.46 have been drawn as straight lines even though there was some slight tendency for the lines to be concave downward. The lateral standard deviations were computed for travel times as large as 20% of the duration of the v' statistics, but this is probably extreme, and, when longer tetron flights are available, it would be desirable to limit evaluation to 10% of the duration of the v' statistics. An obvious drawback of this method is that it requires very long

Fig. 4.46—Lateral standard deviation as a function of downstream distance as derived from running means of the lateral velocity components along individual tetron flights from Long Beach, Calif. (LB), Las Vegas, Nev. (LV), Covington, Ky. (CV), and Wallops Island, Va. (W). The dashed lines represent continuous-point-source lateral-diffusion estimates obtained by Crozier and Seely (CS), Pasquill (P), and from Project Green Glow (GG).

Fig. 4.47—Vertical standard deviation as a function of downstream distance as derived from running means of the vertical-velocity components along individual tetron flights from Las Vegas, Nev. (LV), and Wallops Island, Va. (W). The dashed lines represent continuous-point-source vertical-diffusion estimates obtained by Cramer (CR), Hilst and Simpson (HS), from Harwell (BEPO), and from the Tennessee Valley Authority (TVA).

tetron trajectories to obtain diffusion data at even moderate distances downstream.

For comparison, the dashed lines in Fig. 4.46 indicate the lateral standard deviations obtained by Crozier and Seely (1955) and other previously mentioned investigators. The variation reflects the meteorological or topographical conditions during the various flights with the Wallops Island data representing regular flow over a smooth surface, the Covington data representing regular flow over rolling hills, the Las Vegas data representing strong desert convection, and the Los Angeles data indicating the effects of the extreme longer period meander in a region of topographic complexity and light winds.

The solid lines in Fig. 4.47 represent the vertical standard deviation (σ_z) as a function of distance derived from tetron flights through the use of an equation similar to Eq. 4.38. Be-

cause of the difficulties involved in obtaining accurate tetron vertical velocities from the WSR-57 radar at Los Angeles (Long Beach flights) and Cincinnati (Covington flights), these data have been omitted from Fig. 4.47.

Figure 4.47 shows that on the basis of the tetron flights the ratio of vertical standard deviation to downstream distance varies from a value of about 0.01 for daytime flights over the sea and nighttime flights over the desert to a value of 0.1 for daytime flights over the desert near Las Vegas. As in the case of Fig. 4.46, the appropriateness of the tetron technique is indicated by the similarity in the rate of change of vertical standard deviation with downstream distance as derived from the tetron flights and from conventional means.

4-11.2.4 Relative Diffusion Estimates from Simultaneous Releases. The second basic type diffusion investigated with tetrons is relative diffusion, which involves the rate of growth of an individual cluster of particles. Basically this puff type of diffusion depends on the increase in distance between pairs of particles, and therefore tetron determinations require the use of two trajectories. Only a few cases are available for presentation. Obviously the tetrons must possess very nearly the same equilibrium floating surface, or the wind shear in the vertical will cause a misleadingly large rate of balloon separation with time.

Based upon four pairs of simultaneously released tetrons at Marineland, Calif., the lateral standard deviation was found to be proportional to $x^{0.38}$, which is less than the value derived from continuous point-source experiments. However, because of the small number of cases, this value may have little significance.

Of greater theoretical interest than the increase in separation distance between pairs of particles with respect to downstream distance is the increase in separation distance with respect to time. In particular, on the basis of the Kolmogorov similarity theory, Batchelor (1950) has predicted that at small time the square of the separation distance should be proportional to t^2 (with the assumption of negligible initial separation), and at intermediate time he has predicted that the square of the separation distance should be proportional to t^3 . Gifford (1957) has synthesized the results of several experiments and has

offered confirmation for Batchelor's hypothesis on a time scale of seconds and a few minutes.

Figure 4.48 shows the square of the distance between pairs of simultaneously released tetrons as a function of time after release of the tetrons. The numbered pairs of flights are from Marineland, Calif., the pair labeled CVG refer to flights at Covington, Ky., and the pair labeled LAX, to flights made from Los Angeles by Holzworth, Kauper, and Smith (1962). In the latter case tetron positions were determined by observers following the balloons in automobiles. Included for comparison in Fig. 4.48 are no-lift balloon data obtained near the ground by Wilkins (1958) and smoke-puff data obtained in the stratosphere by Kellogg (1956). The long line represents the median value of the square of tetron separation distances with respect to time. The median line suggests a power varying from 1.5 at a time of 10 min to a power of 2.5 at a time exceeding 100 min. However, on a few of the individual tetron flights, the tetrons actually approached one another. This is particularly true for the Cincinnati data (Covington flights) and paired flights 75 and 76 in Los Angeles.

4-11.2.5 Estimation of Lagrangian Statistics from Eulerian Statistics. The foregoing discussion has dealt with ways of estimating atmospheric diffusion from Lagrangian type data. However, since Eulerian (fixed-point) statistics are still more readily obtained than Lagrangian (air particle attached) statistics, it is desirable to determine whether there is some consistent relation that would allow one to estimate Lagrangian statistics from Eulerian statistics. Indirect estimates of Lagrangian statistics have been made in recent years by sampling mass tracers, such as fluorescent aerosols. Comparison of the lateral standard deviation of particle diffusion of such mass tracers with the standard deviation of appropriately averaged wind directions at a fixed point has suggested to Hay and Pasquill (1959) that there is a basic scale relation between Eulerian and Lagrangian statistics such that, in the mean, the predominant period of oscillation following an air parcel is about four times the predominant period of oscillation noted at a nearby fixed point. Through the work of Barad (1959) and of Panofsky (1962), however, there have been indications that this scale

Fig. 4.48—Square of the separation distance between pairs of tetroons as a function of time. Numbered pairs represent simultaneous tetroon flights from Marineland, Calif., CVG indicates flights from Covington, Ky., and LAX indicates flights made by Holzworth, Kauper, and Smith over Los Angeles. Results obtained by Wilkins (W) with no-lift pibals near the ground and by Kellogg (K) with smoke puffs in the stratosphere are shown for comparison.

factor, β , is a function of turbulence intensity, stability, and perhaps travel distance.

Gifford (1955) utilized no-lift pibals and wind vanes mounted on the Brookhaven tower to investigate the problem of Eulerian-Lagrangian

scale relations. The use of tetroons to estimate β is particularly appropriate at some distance above the ground where the erection of sampling stations for mass-tracer experiments is difficult and expensive. Consequently, during

the summer of 1962, tetrons were flown past instrumented barrage-balloon cables at Cardington, England, in an effort to obtain β values through comparison of the frequency at which the tetron-derived vertical-velocity spectral density was a maximum with the frequency at which the fixed-point vertical spectral density was a maximum (Angell, 1964). Limiting the discussion to those tetron flights which were accurately positioned by radar for at least 40 min at float altitude, an average β value of 2.4 was obtained. However, it appears from the top part of Fig. 4.49 that β tends to be relatively large when the turbulence intensity (in this case, the ratio of standard deviation of vertical velocity to mean wind speed) is relatively small, and vice versa. The bottom part of Fig. 4.49 shows the comparison between β and atmospheric stability, where the latter is estimated from the change in temperature over a 900-m depth centered on the tetron flight level. Since all tetron flights were made during the day, the variation in stability is not great, and, although there is some tendency for β to increase with increasing stability, the trend is not as striking as in the case of the turbulence intensity.

An alternative method of estimating β has been suggested by Smith and Hay (1961) and has been noted as Eq. 4.26. The average turbulence intensity indicated by the simultaneously released pairs of tetron flights from Marineland is 0.34, and consequently, through the use of the information on $d\sigma_y/dx$ derived from the Marineland flights, Eq. 4.26 yields an average β of 2.1. The similarity in β values derived by the two techniques although undoubtedly partly fortuitous is encouraging in its implication that fairly uniform results may be derived from very dissimilar methods.

4-12 RECAPITULATION

It would be most satisfying if this recapitulative section could consist of a framework in which the individual experimental series were small but distinct members. Although such an unequivocal construction cannot be presented, certain features of the current state of knowledge seem to be well documented by diffusion experiments.

The crosswind spread, σ_y , from a continuously maintained source in the first few

Fig. 4.49 — Variation of Lagrangian-Eulerian scale (β) with turbulence intensity (top) and with stability (bottom) as obtained from tetron flights past instrumented barrage-balloon cables at Cardington, England.

hundred meters above the earth's surface has been the subject of repeated study and a summary such as is presented in Fig. 4.21 has broad features that are in agreement with most experimental results, namely, a power-function distance dependency (from about $x^{0.80}$ to $x^{0.90}$), a relation to the measured value of the low-level horizontal component of turbulence, and a dependence on the time period over which the average concentration distribution is measured.

The vertical spreading of material released from a continuous source has received comparatively little attention in diffusion experiments owing primarily to the difficulty and expense of adequately documenting this feature. Common practice has been to estimate the vertical diffusion from measurements of the ground-level crosswind spread and concentration distribution, a technique prone to some degree of error because of the effects of deposition. For release within a typical radiation inversion, it can be stated with considerable assurance that the vertical spreading will cease after some short travel from the source and the diffusion process will be dominated by the lateral spreading and the as yet not fully accounted for effects of vertical gradients

of the horizontal wind. Under unstable conditions the plume will spread rapidly until some vertical lid to mixing is reached. The existence of such a lid is common as amply verified by the work of Holzworth (1964). The implications of this lid are of great importance in any assessment of medium- and long-distance diffusion within the friction layer.

The downwind concentration distribution within a plume that in the course of its travel intersects the ground is well documented by surface sampling but is subject to some uncertainty because of the complex process of deposition. A continuous scavenging mechanism, such as deposition, can result in a measured decrease of concentration with distance quite different from that which would have occurred in the absence of deposition. The curves of normalized concentration variation with distance presented in Fig. 4.24 are quite representative of diffusion of the small particulates, but the magnitude of the correction factor necessary to remove the effects of deposition is in doubt, particularly at the greater travel distances during stable conditions. The conjecture that the correction for deposition would modify the concentration curves in Fig. 4.24 so as to approach the Pasquill curves appears to be a reasonable working hypothesis until theoretical studies and field experiments, both of which are currently being pursued, offer more quantitative alternatives.

With due cognizance of the experimental data presented in this chapter, there does not seem to be any strong argument favoring any one of the models or methods of continuous-source diffusion estimation presented in this chapter over any other for practical applications. The use of the horizontal wind-direction-fluctuation data and the relabeled Pasquill curves at locations of regular terrain are adequate for rapid assessments of the magnitude of a problem. The judicious use of these curves with various forms of the generalized Gaussian diffusion

equation further broadens their utility. On the other hand, if machine processing of large amounts of data is indicated by the nature of the problem, the analytical forms of the diffusion parameters advanced by the Hanford group can be used. An attractive and useful statistical solution of the problems at a site requiring continuous diffusion estimates has been suggested by the Dry Gulch and Ocean Breeze studies. It is imperative to point out, however, that when the source and environmental characteristics point to a major pollution problem there is no alternative to the services of a diffusion meteorology specialist to assess the problem and suggest solutions.

The results of the instantaneous-source diffusion experiments summarized in Figs. 4.38, 4.39, and 4.40 and in Table 4.23 form a coherent picture despite the variety of experimental configurations. The Smith-Hay formulation (Eq. 4.27) has been used with some success (see Secs. 4-10.1.1, 4-10.1.6, and 4-10.2.1). Since the concentration or exposure from an individual puff is likely to be considerably more variable than that experienced from a continuous source, probability estimation techniques, such as developed from the Sand Storm data (Sec. 4-10.1.2), should be given serious consideration.

Finally, it should be mentioned once again that the diffusion experiments discussed in this chapter were carried out under relatively ideal conditions. When diffusion estimates are required over rugged terrain, at land-water boundaries, or during conditions of marked inhomogeneities of atmospheric structure, manipulation of the diffusion equations, as well as adjustment of parameter values, may be called for. In direct parallel to the weather-forecast problem, these procedures contain elements of both science and art, and here the inflexible guides of a handbook must yield to the acumen and imagination of a trained meteorologist.