carefully performed diffusion experiments during the 1950's and 1960's. Project Prairie Grass (Haugen, 1959) is probably the most frequently quoted diffusion experiment. The terrain was uniform, releases were from near ground level, and concentration measurements were at downwind distances less than 1 km. These experiments resulted in Pasquill's (1961) curves, which were adapted by Gifford (1961, 1968, 1976) into the forms shown in Fig. 4.4. Note that, at distances beyond 1 km, the lines are dashed (i.e., a guess). They may work under certain ideal conditions at greater distances, but there is little basis in observations.

Table 4.4 Brookhaven National Laboratory Parameter Values in the Formulas $\sigma_y = ax^b$ and $\sigma_z = cx^d$

	Parameter			
Type	a	b	c	d
B_2	0.40	0.91	0.41	0.91
B_1	0.36	0.86	0.33	0.86
C	0.32	0.78	0.22	0.78
D	0.31	0.71	0.06	0.71

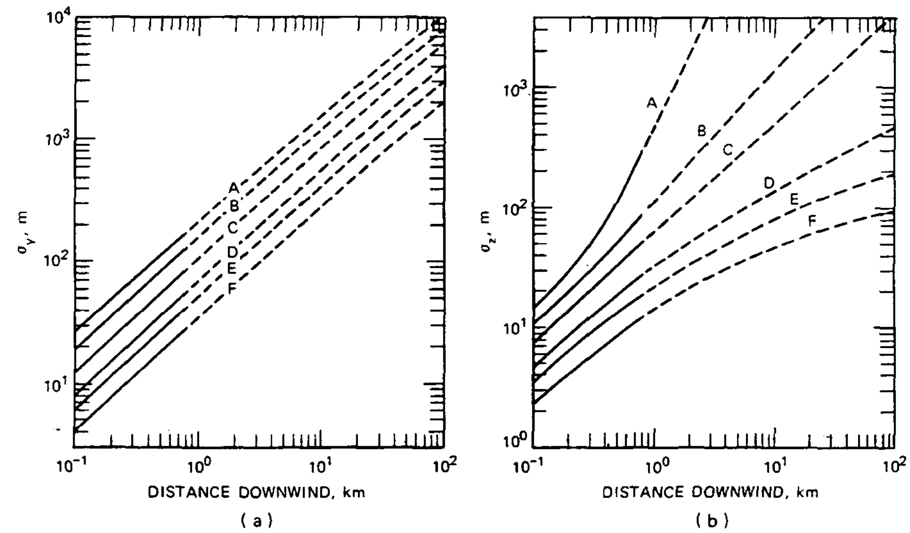

Fig. 4.4 Curves of σ_y and σ_z for turbulence types based on those reported by Pasquill (1961). [From F. A. Gifford, Turbulent Diffusion-Typing Schemes: A Review, *Nucl. Saf.*, 17(1): 71 (1976).]

Because calculators and computers are in such widespread use at present, most people would rather have a formula than a graph or table. Several researchers have worked out analytical power-law formulas for σ_y and σ_z. One of the early suggestions was by M. E. Smith (1968). He summarized the BNL formulas, which are based on hourly average measurements out to about 10 km of diffusion of a nonbuoyant plume released from a height of 108 m:

$$\sigma_y = ax^b \qquad \sigma_z = cx^d \qquad \text{(x in meters)} \qquad (4.2)$$

Values of the parameters a, b, c, and d are given in Table 4.4.

Briggs (1973) combined the Pasquill, BNL, and TVA curves (observations out to x = 10 km), using theoretical concepts regarding asymptotic limits of the formulas, to produce the widely used set of formulas given in Table 4.5. Initial plume spread at all stabilities is proportional to x, the proportionality factor being σ_θ (in radians). At large distances, σ_y is proportional to $x^{1/2}$, as predicted by the Fickian and Taylor theories of diffusion. Note that σ_y and σ_z are independent of release height and roughness in these formulas. There are too few experimental data to support more complex formulations including these two variables.

The Prairie Grass experiments were carried out over terrain with roughness z_0 of 3 cm. F. B. Smith (1972) and Pasquill (1975, p. 19) have found that σ_z varies as z_0^p, where p lies in the range 0.10 to 0.25. A technique for incorporating Smith's (1972) recommendations into analytical forms for σ_z in each of the P–G categories was given by Hosker (1973). The larger values of the exponent p are applicable to shorter distances and rougher surfaces. Over rough urban surfaces, especially under the influence of the nighttime urban heat island, the increased roughness should be taken into account. McElroy and Pooler's (1968) diffusion experiment in St. Louis was used by Briggs (1973) to develop the formulas given in Table 4.5. Other people make the assumption that urban σ_y and σ_z should be moved up one stability class (e.g., C to B) to account for increased dispersion over urban areas.

Table 4.5 Formulas Recommended by Briggs (1973) for $\sigma_y(x)$ and $\sigma_z(x)$ ($10^2 < x < 10^4$ m)

Pasquill type	σ_y, m	σ_z, m
	Open-Country Conditions	
A	$0.22x(1 + 0.0001x)^{-1/2}$	$0.20x$
B	$0.16x(1 + 0.0001x)^{-1/2}$	$0.12x$
C	$0.11x(1 + 0.0001x)^{-1/2}$	$0.08x(1 + 0.0002x)^{-1/2}$
D	$0.08x(1 + 0.0001x)^{-1/2}$	$0.06x(1 + 0.0015x)^{-1/2}$
E	$0.06x(1 + 0.0001x)^{-1/2}$	$0.03x(1 + 0.0003x)^{-1}$
F	$0.04x(1 + 0.0001x)^{-1/2}$	$0.016x(1 + 0.0003x)^{-1}$
	Urban Conditions	
A–B	$0.32x(1 + 0.0004x)^{-1/2}$	$0.24x(1 + 0.001x)^{1/2}$
C	$0.22x(1 + 0.0004x)^{-1/2}$	$0.20x$
D	$0.16x(1 + 0.0004x)^{-1/2}$	$0.14x(1 + 0.0003x)^{-1/2}$
E–F	$0.11x(1 + 0.0004x)^{-1/2}$	$0.08x(1 + 0.00015x)^{-1/2}$

Recent diffusion experiments under clear, nearly calm nighttime conditions (so-called category G) suggest that horizontal diffusion is actually greater during these conditions than under conditions associated with category F (Sagendorf and Dickson, 1974) because the plume often meanders during G conditions, which results in σ_θ equal to 20° or more and relatively low hourly average ground concentrations at a given point. Van der Hoven (1976) analyzed several category G diffusion experiments and found that observed σ_y values corresponded to anything between categories A and F. Thus diffusion in terms of tabulated dispersion parameters is indeterminate when category G stability is found. Of course, diffusion can still be estimated on the basis of actual measurements of σ_θ.

With the use of stability classes in complex terrain situations, σ's are also difficult to determine. The diffusion experiments summarized in Chap. 12 generally show that σ_y and σ_z in complex terrain are a factor of 2 to 10 greater than that predicted from the Pasquill curves. Again, measurements of σ_θ and σ_e are the best solution to this uncertainty.

4-4.2 The σ_θ and σ_e Method

Much research concerning the best way to relate σ_y and σ_z to σ_θ and σ_e is being done. In perhaps 5 years the subject will reach a stage where definitive conclusions can be drawn. The recommendations in this section are based on the latest available research. The idea behind this research is to remove a layer of empiricism (the Pasquill–Gifford curves) from diffusion calculations by developing a technique that relates diffusion directly to turbulence. Taylor's (1921) work suggests the formulas:

$$\sigma_y = \sigma_v t\, f_y \left(\frac{t}{T_y}\right) \tag{4.3}$$

$$\sigma_z = \sigma_w t\, f_z \left(\frac{t}{T_z}\right) \tag{4.4}$$

where f_y and f_z are universal functions and T_y and T_z are turbulence time scales in the y and z directions. The fact that averaging times for all variables are equal and that turbulence parameters are measured or estimated near the release height is implicit. Since diffusion calculations are generally made in practice for downwind distances (x) rather than times (t), the following forms of writing Eqs. 4.3 and 4.4 are desirable:

$$\sigma_y = \sigma_\theta x\, f_y \left(\frac{x}{uT_y}\right) \tag{4.5}$$