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# WHAT WERE PASQUILL AND GIFFORD THINKING?

*Steven Hanna*

Hanna Consultants, Kennebunkport Maine USA

**Abstract**: The Pasquill-Gifford (PG) sigma curves ($\sigma_y$ and $\sigma_z$) have been used to calculate dispersion in the atmosphere for about 60 years. In the early years, harmonization occurred in use of PG sigma curves in operational transport and dispersion models. Some operational models still make use of the curves. This paper provides some historical background, including justifications by Pasquill and Gifford for distributing their $\sigma_y$ and $\sigma_z$ nomograms. I worked with both of them in the 1970s and 1980s. First, it is important to point out that both Pasquill and Gifford were leading international experts on the basic physics of atmospheric boundary layer turbulence and diffusion, as shown by their seminal books and journal articles. Frank Pasquill always pointed out that it was best to use either observations or models of turbulence components (e.g., $\sigma_u$, $\sigma_v$, and $\sigma_w$) and Lagrangian time or distance scales in atmospheric diffusion models. But, he said, if you don't have that information, here is an alternative simple method that uses nomograms to estimate plume width and depth. Gifford later added his own interpretations, converted plume width and depth to $\sigma_y$ and $\sigma_z$, and added more data. The PG curves are basically lines drawn through observations of variations of $\sigma_y$ and $\sigma_z$, for five stability classes (A through E) with distance from all available field data that they could find at the time. The lines intentionally followed certain theoretically-justified slopes at asymptotes (e.g., linear at small distances). The user could, given the stability class and downwind distance, estimate $\sigma_y$ and $\sigma_z$ by eye.

***Key words:*** *Pasquill-Gifford curves, dispersion modeling*

## INTRODUCTION

This paper summarizes the rationale for development of simple dispersion nomograms by Frank Pasquill and Frank Gifford in the 1960s.

Frank Pasquill's early work history:

- He worked from 1937 to 1943 at the Chemical Defence Establishment of the Meteorological Office at Porton Down. He modified O.G. Sutton's equations based on these experiments and the results are now known as the Sutton-Pasquill model of evaporation.
- From 1943 to 1946, he worked in Queensland, Australia on classified work on the dispersion of toxic agents. In 1946, he returned to head a new unit of the Meteorological Office at Cambridge.
- In 1950, he was assigned to the Atomic Energy Research Establishment at Harwell. He worked with N.G. Stewart on the dispersion of radionuclides from nuclear plants and from the atomic testing.
- In 1954, he returned to Porton Down to conduct field measurements on the structure of atmospheric turbulence and the dispersion of pollutants. He developed a simple method for assessing atmospheric stability based on wind speed, solar radiation, cloud cover, and time of day. This resulted in the Pasquill stability classes A (very unstable) through F (very stable). In addition, he developed curves that are now interpreted as the vertical and horizontal dispersion coefficients
- He wrote the first edition of his book Atmospheric Diffusion in 1961, and the second edition in 1974. A subsequent issue was coauthored by F.B. Smith.
- Was Chief of the Boundary Layer Branch of the UK Met Office for several decades.

Frank Gifford's early work history

- He was a weather forecaster with the US Air Force during WWII, and contributed to the D-Day forecast.
- He received a PhD in Meteorology from Penn State, under Hans Panofsky.
- He was Director of NOAA's Atmospheric Turbulence and Diffusion Laboratory in Oak Ridge TN for about 25 years
- He initially studied local and mesoscale meteorology at Oak Ridge area. He then developed basic turbulence and dispersion theories for use by the AEC and DOE. He was on many international committees with Von Karman, Pasquill etc.
- Chief author of chapter on Turbulence and Diffusion in DOE M&AE 1968

## RESEARCH INTERESTS IN 1950s AND 1960s

The atmospheric turbulence and diffusion topic was of great interest in the years following WWII, mainly because of the need to understand the spread and deposition of materials from nuclear explosions and from releases of chemical and biological agents in warfare. The top international fluid dynamicists were involved in fundamental research on the topic. Frank Pasquill and Frank Gifford were part of this set of experts. I recall Frank Gifford describing his meetings with Von Karman, Batchelor, Corrsin, Frenkiel, Inoue, Kolmogorov, Monin, Priestley and Obukhov.

Both Pasquill and Gifford developed advanced versions of Taylor's (1921) theory, which says that turbulent dispersion is the result of the effects of turbulent velocity fluctuations over the duration of travel of the pollutant cloud (see Pasquill 1974 and Gifford 1968, which contain comprehensive summaries of their rationale). For example, assume that $\sigma_y(t)$ is the standard deviation of the lateral distribution of pollutant in a cloud at a time, t, after the cloud is released from a source location. In Taylor's theory, it is assumed that $\sigma_y$ depends on $\sigma_v$, $T_v$, and t, which are the standard deviation of the lateral turbulent speed fluctuations, the integral time scale of these fluctuations, and the time of travel from the source to the location of interest, respectively.

For continuous plumes, Pasquill converts Taylor's equation to an integral over the energy spectrum for lateral turbulence. He shows that the travel time and the sampling time act as high-pass filter (i.e., only eddies with frequencies higher less than the inverse of the travel time and/or sampling time can be "felt" by the dispersion process). For example, for a sampling time of 10 minutes, any eddies with time scales much greater than 10 minutes cannot influence the dispersion. Similarly, the averaging time (or resolution) of the turbulent speed measurements acts as a low pass filter. For example, for a sampler time resolution of 1 minute, any eddies with time scales much less than 1 minute cannot influence the observed dispersion.

Furthermore, Pasquill points out that the turbulence time scales felt by a fixed anemometer ($T_E$ for Eulerian) are likely smaller than those felt by the cloud ($T_L$ for Lagrangian), which is moving with the wind. The variable $\beta$ is defined as $T_L/T_E$ and is found to have a typical value of about 4.

So, the bulk of the research by Pasquill and Gifford was directed towards using observations or parameterizations of $\sigma_y$ and $T_v$ to calculate cloud dispersion. The theory was extended to handle instantaneous or time variable sources.

It is assumed that the cross-wind distributions of concentration in a plume are Gaussian. For a continuous plume, $\sigma_y$ is the lateral direction and $\sigma_z$ is the vertical direction. For an instantaneous release, the along wind dispersion, $\sigma_x$, is also important.

## DEVELOPMENT OF P-G NOMOGRAMS

Although both Pasquill and Gifford recommended use of the above basic science concepts along with observations of turbulence fluctuations to calculate transport and dispersion, they recognized that, for operational purposes, detailed local turbulence observations are seldom available. As a simpler alternative method, Pasquill suggested a way to estimate lateral and vertical cloud dispersion based on nomograms. These could be used quickly and with minimal knowledge of the weather conditions. It is assumed that there is flat open terrain with grass or other some other surface with similar roughness. A continuous non-buoyant point source is assumed, at an elevation within the surface boundary layer (usually a height less than 100 m).

Buckingham's pi theorem was used, which suggests that dispersion expressed as $\sigma_y$ or $\sigma_z$ is dependent on downwind distance, x, and a measure of stability class, which can be defined knowing time of day, wind speed U, and insolation or heat flux from surface (see Figure 1). Pasquill collected many sets of field observations of $\sigma_y$ and $\sigma_z$ and plotted the data versus x for each stability class. The reason why distance, x, is used rather than travel time, t, is that most available field experiments make use of a spatial network of samplers. The simple relation, $x = Ut$, is assumed. A line was fitted to the observations by eye and assuming certain asymptotic behavior (such as the fact that $\sigma_y$ or $\sigma_z$ are known to be linearly related to x at small x). The resulting $\sigma_y$ and $\sigma_z$ nomograms are in Figure 2, from Gifford (1976).

The appendices to reports by Pasquill include plots of the actual observations used for developing the best-fit lines. For example, there is a separate plot for $\sigma_y$ for stability class D. As found for most atmospheric observations, there is significant scatter of about plus and minus a factor of about two, with occasional larger differences. We find this amount of scatter with current field studies, too.

Later, Bruce Turner (at the EPA) and Gary Briggs (at Frank Gifford's ATDL in Oak Ridge) fit simple one-line analytical formulas to the PG nomograms, for use in numerical models. Briggs' formulas conformed to known theoretical formulas at the large and small distance asymptotes. Briggs also suggested separate formulas for rural and urban land use (see Briggs (1972) and Hanna, Briggs, and Hosker (1982)). Golder (1972) suggested modifications for accommodating alternate metrics for stability such as the Obukhov length, L. Frank Pasquill's associate director of the Boundary Layer Branch, F.B. Smith, developed methods to correct the nomograms to account for a full range of surface roughnesses.

## FURTHER COMMENTS

Note that the $\sigma_z$ curves in Figure 2 for the most unstable stability classes (A and B) swoop upwards at large distances. For example, at the top of the figure, the $\sigma_z$ curve "leaves the figure" at x = 3 km, where $\sigma_z$ is approximately equal to distance travelled. As Pasquill points out, there are not adequate samplers to determine $\sigma_z$ from a vertical profile, so it is calculated, in practice, from the Gaussian formula, assuming knowledge of $\sigma_y$, cloud centerline concentration C, source emission rate Q, and wind speed U:

$$\sigma_z = (Q/C)/(\pi U \sigma_y) \tag{1}$$

We now know, from convective scaling analysis and further laboratory and field studies (Weil. 1988), that, for near-surface releases, the height where maximum concentration occurs increases with distance and approaches $z_i/2$, where $z_i$ is the mixing depth (usually about 1 or 2 km) on sunny summer days with light winds. As a result, ground level cloud centerline C is smaller (by a factor of 2 or 3) than it is at a height of $z_i/2$, and, hence, $\sigma_z$ is overestimated by eq. (1). State-of-the-art modeling systems such as AERMOD (Cimorelli et al., 2004) use new convective scaling formulas for very unstable conditions.

I advise today's model developers that any new formulas had better follow the PG curves fairly closely, especially for stabilities close to neutral (classes C and D and E) since the PG curves are based on many observations, including the widely-used Prairie Grass data. This robust nature of the Gaussian plume formula applications with $\sigma_y$ and $\sigma_z$ from the PG curves also leads to it being relatively unbiased when included in multi-model comparison exercises involving new field observations of dispersion (e.g., Hanna et al., 2019).

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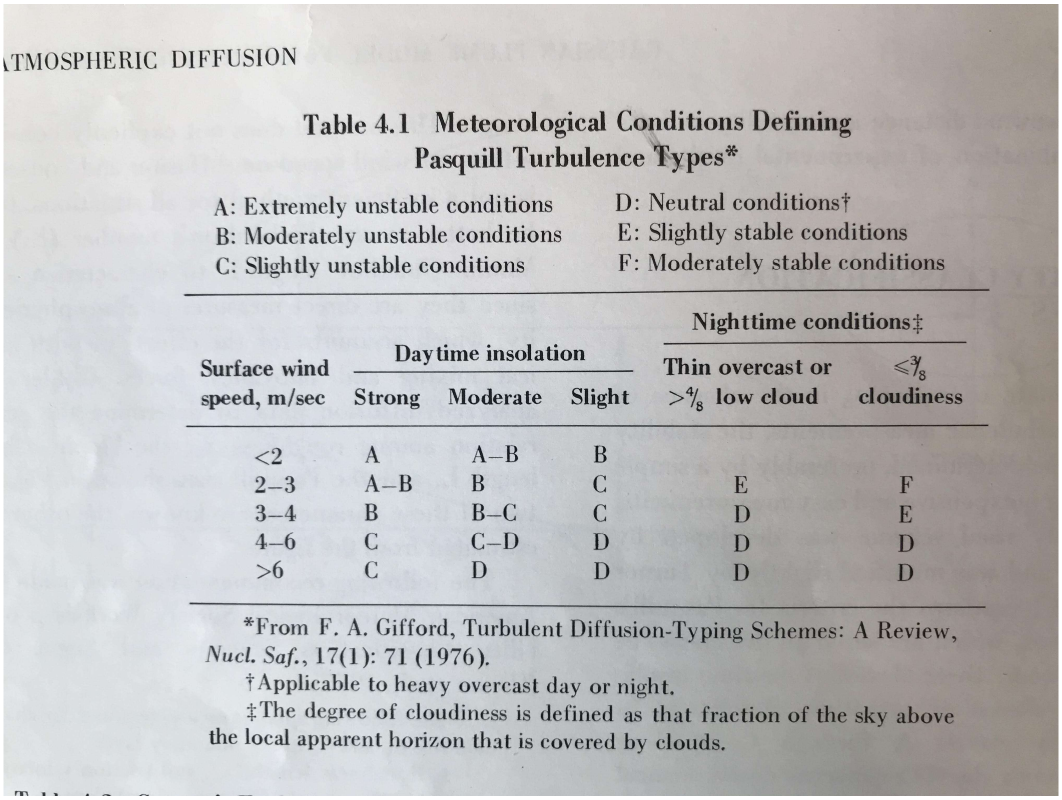

TMOSPHERIC DIFFUSION

**Table 4.1 Meteorological Conditions Defining Pasquill Turbulence Types***

A: Extremely unstable conditions
B: Moderately unstable conditions
C: Slightly unstable conditions
D: Neutral conditions†
E: Slightly stable conditions
F: Moderately stable conditions

| Surface wind speed, m/sec | Daytime insolation | | | Nighttime conditions‡ | |
|---|---|---|---|---|---|
| | Strong | Moderate | Slight | Thin overcast or $>4/8$ low cloud | $\leq 3/8$ cloudiness |
| <2 | A | A–B | B | | |
| 2–3 | A–B | B | C | E | F |
| 3–4 | B | B–C | C | D | E |
| 4–6 | C | C–D | D | D | D |
| >6 | C | D | D | D | D |

*From F. A. Gifford, Turbulent Diffusion-Typing Schemes: A Review, *Nucl. Saf.*, 17(1): 71 (1976).

†Applicable to heavy overcast day or night.

‡The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

**Figure 1.** Pasquill method for estimating stability class (from Hanna et al. 1982 and originally published by Gifford, 1976)

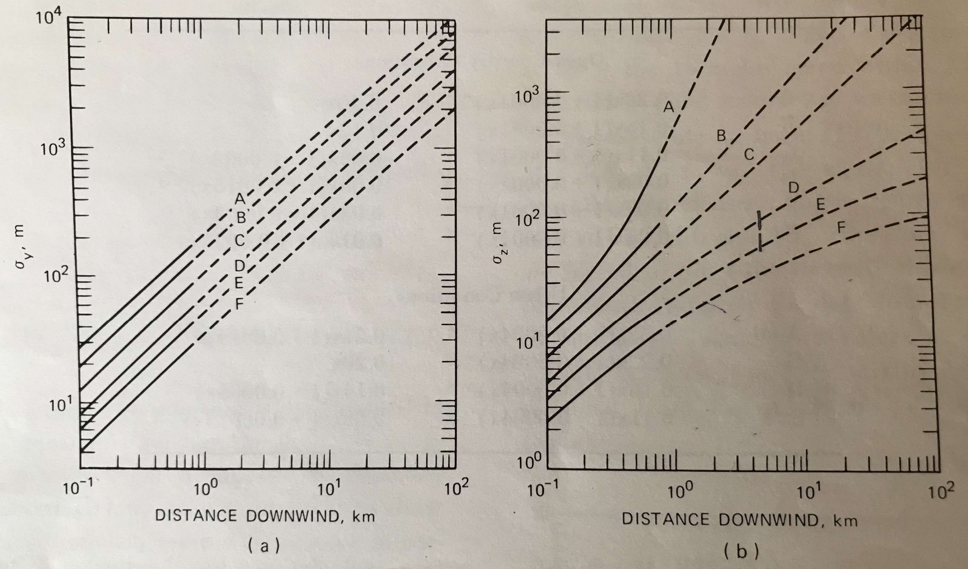

**Fig. 4.4 Curves of $\sigma_y$ and $\sigma_z$ for turbulence types based on those reported by Pasquill (1961). [From F. A. Gifford, Turbulent Diffusion-Typing Schemes: A Review, *Nucl. Saf.*, 17(1): 71 (1976).]**

**Figure 2.** Pasquill-Gifford nomograms for $\sigma_y$ and $\sigma_z$, as a function of downwind distance and stability class (from Hanna et al. 1982 and originally published by Gifford, 1976)