EPA-600/4-76-030a
July 1976

ATMOSPHERIC DISPERSION PARAMETERS IN GAUSSIAN PLUME MODELING
Part I. Review of Current Systems and Possible Future Developments

by

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ABSTRACT

A recapitulation of the Gaussian plume model is presented and Pasquill's technique of assessing the sensitivity of this model is given. A number of methods for determining dispersion parameters in the Gaussian plume model are reviewed. Comparisons are made with the Pasquill-Gifford curves presently used in the Turner Workbook. Improved methods resulting from recent investigations are discussed, in an introductory way for Part II of this report.

PREFACE

The increasing concern of the last decade in environmental issues, and the fuller appreciation that air quality simulation modeling may provide a unique basis for the objective management of air quality, has generated an unprecedented interest in the development of techniques for relating air quality and pollutant emissions through appropriate modeling of the atmospheric transport and dispersion processes that are involved. A multitude of recent publications in the U.S.A. and elsewhere points to the wide interest at many different levels of local, state, regional and national planning, and testifies to the widespread acceptance of meteorological type air quality modeling as an important rational basis for air quality management. This point of view is now internationally recognized in most industrial countries.

Earlier attitudes towards the quantitative estimation of atmospheric dispersion of windborne material from industrial and other sources were strongly influenced by a system introduced in 1958, and published in 1961, by Dr. F. Pasquill of the Meteorological Office, United Kingdom. This was followed in 1962 by the publication of his definitive textbook on "Atmospheric Diffusion," which includes detailed consideration of the well-known simple "Gaussian-plume" model for the average concentration distribution in space from an elevated continuous point-source under steady conditions. The unique feature, however, of the Pasquill system is the method by which the critical parameters expressing the downwind spread of the plume might be estimated in terms of the ambient meteorological conditions. These estimates were later expressed in slightly more convenient, although exactly equivalent form, by Dr. F. Gifford, and this so-called Pasquill-Gifford system for dispersion estimates has been widely used ever since. It was early given some general endorsement as a valuable practical scheme by the Public Health Service of the U. S. Department of Health, Education, and Welfare, by the publication in 1967 of the "Workbook of Atmospheric Dispersion Estimates" (Public Health Service Publication No. 999-AP-26) by D. B. Turner, that exclusively utilized this system of Gaussian-plume dispersion parameters.

In spite of the gradual appearance in recent years of air quality models based on more sophisticated formulations of the atmospheric processes, e.g., through fluid-dynamical equations assumed to govern the physical processes of transport and turbulent diffusion, great use continues to be made of the simpler Gaussian-plume models. However, a direct consequence of the unprecedented interest in the subject has been the publication of many attempts to confirm or improve the realism of the dispersion estimates. These and other matters relating to the substantial progress made in recent years in understanding atmospheric dispersion, are discussed in a much revised 2nd Edition of the Pasquill book, that was published late in 1974. Under these circumstances it seemed desirable to examine critically the possible requirements for change in the Turner Workbook values for dispersion, that have been so widely used since 1967. The present two-part report was prepared to meet this need.

It was extremely fortunate that Dr. Pasquill was available for detailed discussions during its preparation (1975-76), both while he was a Visiting Professor at the North Carolina State University and also the Pennsylvania State University (under research grant support of the EPA), and also as a Visiting Scientist to the Meteorology and Assessment Division of the E.P.A., Research Triangle Park, N. C. Even more fortunate has been Dr. Pasquill's willingness to assume responsibility for preparation of the second part of the report, which critically examines the possible requirements for change of the Turner Workbook values. The first part was prepared by Dr. Allen Weber of the Department of Geosciences at North Carolina State University, in consultation with Dr. Pasquill and the undersigned. It provides a reasonably comprehensive review of current systems and possible future developments, and is a necessary input for the critical examination of the second part. It is perhaps unnecessary to emphasize that there are still many problems of dispersion that are unlikely to be resolved satisfactorily in terms of simple Gaussian-plume models. However, it is hoped that the present publication will provide a more up-to-date basis for continuing the successful treatment of the many important practical problems that can be analyzed by this simple approach.

Research Triangle Park
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March 1976

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ACKNOWLEDGEMENTS

It has been the author's good fortune to have close contact with Dr. Frank Pasquill for several weeks while writing this review. Dr. Pasquill's insight on the problem of turbulent dispersion has been extremely valuable. Mr. Kenneth Calder provided extremely good information and guidance in pointing out important studies of atmospheric diffusion bearing on this study.

During the course of the work the author received valuable assistance from several individuals on the telephone and otherwise. Dr. Frank Gifford was especially helpful in this way in clarifying important issues. Mr. Jui-Long Hung and Mr. Richard D'Amato were very helpful in preparing figures in this report.

The author would like to thank Mr. Larry Niemeyer for providing two months support under the Intergovernmental Personnel Act to conduct this study.

SECTION 1

INTRODUCTION

For purposes of simplicity this review will be restricted to a discussion of the single source dispersion problem (e.g. an isolated stack) either as a problem in its own right or as an element of an "area" source. The dispersing material is assumed to be passive i.e. the material does not react chemically, decay by radioactivity, undergo washout by precipitation, deposit on the surface of the earth, or react in any other way to violate the law of conservation of matter. Furthermore, there will be no discussion of buoyant plume behaviour since a recent comprehensive review and summary of this problem has been given by Briggs (1969, 1975).

Discussion of dispersion will be in terms of the so-called Gaussian plume dispersion model (defined in Section 2). This basic model follows directly from some of the theoretical models of dispersion. It is also known that a great deal of the experimental dispersion data now available for single sources in steady conditions, seems to be reasonably well described by the Gaussian shape of the spatial distribution pattern, when properly time-averaged. Gifford (1975, 1976) provided a brief survey and review of the Gaussian-model methodology as well as clearly specifying the kinds of situations when the simple Gaussian form is inappropriate.

SECTION 2

THE GAUSSIAN PLUME MODEL

The Gaussian plume diffusion model* for an elevated point source (assuming reflection at the ground) is represented by the equation

$$C(x,y,z;H) = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}} \exp\left\{-\frac{y^2}{2\sigma_y^2}\right\}\left[\exp\left\{-\frac{(H-z)^2}{2\sigma_z^2}\right\} + \exp\left\{-\frac{(H+z)^2}{2\sigma_z^2}\right\}\right] \quad (1)$$

where**

C is the time averaged concentration of pollutant;

x, y, and z are the distances downwind, crosswind, and vertically upward, respectively;

H is the effective source height above ground level (H is equal to the sum of the physical stack height h_s and the plume rise ΔH);

Q is the source strength;

σ_y is the standard deviation of the time-averaged plume concentration distribution in the crosswind direction;

σ_z is the standard deviation of the time-averaged plume concentration distribution in the vertical direction;

$\bar{u}$ is the time-averaged wind speed at the level H.

The sampling time used in the definitions above is normally chosen to be about one hour because such a time period admits most of the turbulent fluctuations and defines time-mean values that are

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* The historical basis of the Guassian plume model is not of crucial importance here, although, the interested reader will be able to intersect the line of development of this model at a significant stage by referring to Gifford (1960).

** Mathematical symbols will be defined after their first appearance in the text and in a special list in the Appendix quasi-steady. It is also a very convenient time interval to describe air pollutant concentrations.

It is assumed in the use of the Gaussian plume model that there is a uniform rate of emission of pollutant during the one hour period. It is also assumed that diffusion in the x direction is negligible. This would be literally true if the release were continuous and effectively so if the time of release is equal to or greater than the travel time $x/\bar{u}$ from the source to the location of interest.

The range of application of Eqn. 1 is restricted to within the downwind distance x where the plume first encounters the top of the mixing layer*. The top of the mixing layer is of the order of one kilometer, but it can extend anywhere from a few hundred meters to several kilometers depending on several factors including synoptic scale features of the weather. The top of the mixing layer can be estimated from the results of Holzworth's (1972) extensive survey or by direct measurement, e.g. with an acoustic sounder.

The distance downwind where the top of the plume intersects this "lid" (as it is often called) is quite variable. Similarly the point downwind where the plume from an elevated source reaches its maximum ground-level concentration will depend on several factors. Often the point of maximum ground-level concentration will be closer to the source than the distance to the plume's reflection from the lid. Since it is often desired to know what the maximum concentration will be, the complication of the restrictive lid will (under many circumstances) be

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* By considering reflections of the pollutant from the top of the mixing layer and the ground, the range of the Gaussian plume model can be extended. Another simpler method of obtaining concentration beyond the distance where the plume is trapped under the top of the mixing layer is provided in Turner (1969).

of no consequence. On the other hand, there are circumstances where the mixing depth will be critically important so this concept must be borne in mind when doing diffusion calculations.

There are two additional aspects relating to time-averaging that are of special significance. The first is that the time-average of σ_y is not usually stationary, i.e. the longer the time average the larger σ_y tends to become. Therefore, all graphs and tables of this parameter should make clear the duration of the average.

An attempt has been made (based on experimental studies) to predict the effect of limited sampling time on the value of σ_y. Several authors, whose results were summarized by Gifford (1975), suggest

$$\frac{\sigma_{yA}}{\sigma_{yB}} = \left[\frac{t_A}{t_B}\right]^q \qquad (2)$$

where σ_{yB} is the standard deviation of concentration averaged over some reference period t_B, e.g. one hour, and σ_{yA} is the standard deviation of the concentration over the time period of interest, t_A. The value of q advocated by Gifford is 0.25 to 0.30 which seems to hold for 1 hr. $< t_A <$ 100 hrs. By considering this same problem from a (limited) theoretical viewpoint, it is likely that the effect will be a complex function of the spectral shape and distance downwind (see Pasquill, 1974).

Similar considerations apply to σ_z from an elevated source, although recognition of the important differences between the spectra of vertical and horizontal components should make it clear that the increase of σ_z with sampling time may be expected to be terminated much more decisively at sampling times of 10 minutes or so. Further considerations along the same lines make it clear that for a ground level source a sampling time of a few minutes (3 to 5) will yield steady values of σ_z (See also Pasquill's comments on this point in Part II of this report).

Further simpler forms of the concentration from Eqn. 1 are obtainded at special locations. The following formulae and other related formulae are found in Gifford (1960) and Pasquill (1974). The concentration at ground level is

$$C(x,y,0;H) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{H^2}{2\sigma_z^2}\right)\right]. \qquad (3)$$

Along the axis of the plume at ground level the concentration is

$$C(x,0,0;H) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{H^2}{2\sigma_z^2}\right). \qquad (4)$$

If one assumes simple power-law forms for the crosswind and vertical spread, i.e.,

$$\sigma_y = \sigma_y(x_1)\left(\frac{x}{x_1}\right)^p \quad \text{and} \quad \sigma_z = \sigma_z(x_1)\left(\frac{x}{x_1}\right)^q \qquad (5\ a\ \&\ b)$$

(where x_1 is a reference distance downwind)

then, by differentiation the position along the axis where the maximum occurs is

$$x_m = \left[\frac{qH^2}{\left[\frac{\sigma_z(x_1)}{x_1^{\,q}}\right]^2 (p+q)}\right]^{1/2q}, \qquad (6)$$

or alternatively, the distance x equals x_m when

$$\frac{H^2}{\sigma_z^2(x)} = 1 + \frac{p}{q} \equiv j \ . \tag{7}$$

The magnitude of the maximum concentration is

$$C_m = j^{j/2} \exp\left(-\frac{j}{2}\right) \frac{Q}{\pi \bar{u}} \frac{\sigma_z^{j-1}(x_m)}{\sigma_y(x_m)} \frac{1}{H^j} \ . \tag{8}$$

If p = q the maximum concentration reduces to

$$C_m = \frac{2Q}{e\pi\bar{u}H^2} \left(\frac{\sigma_z}{\sigma_y}\right) \tag{9}$$

and $\sigma_z/\sigma_y = a_o$, a constant independent of x.

With p = q the distance x to the maximum is

$$x_m = \left[\frac{H^2}{2\left[\frac{\sigma_z(x_1)}{x_1^q}\right]^2}\right]^{1/2q} \tag{10}$$

or $x = x_m$ when $H/\sigma_z = 2^{1/2}$

The crosswind integrated concentration at ground level is

$$C_{CWI} = \int_{-\infty}^{\infty} C(x,y,0;H)dy = \sqrt{\frac{2}{\pi}} \frac{Q}{\sigma_z \bar{u}} \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \ . \tag{11}$$

The above formulas now form the basis of a widely used methodology (Pasquill, 1974 and Slade, 1968) of describing atmospheric dispersion in many contexts, e.g. diffusion from ground sources, tall stacks, automobiles, rockets, etc. The method requires additional special interpretation when the terrain is complicated, e.g., shorelines, mountain-valley systems, hills, forests broken by cultivated land, etc. Gifford (1976) and Egan (1975) have attempted to treat some of these "special" diffusion problems insofar as this is possible at this time. For the purpose of this study we will not concern ourselves with these exceptional flows but rather confine ourselves to the cases where the simple Gaussian plume model is clearly appropriate.

The critical parameters in the Gaussian model are the effective source height H and the dispersion parameters σ_y and σ_z. The effective stack height is composed of the physical stack height h_s plus the plume rise due to buoyancy and inertia ΔH. As stated earlier in the review the formulae by Briggs (1969, 1975) are pertinent to determine ΔH. This study will be concerned with the specification of the dispersion parameters σ_y and σ_z and with related matters affecting dispersion.

SECTION 3

SENSITIVITY OF THE GAUSSIAN PLUME MODEL

The sensitivity of a model is loosely defined as any measure of the changes of the dependent variable caused by changes in the parameters of independent variables of the model.

It is desirable to have some feel for the sensitivity of the Gaussian plume model and this can be done in a reasonably satisfactory manner by graphical means. Figure 1 shows the idealized distribution of concentration at ground level from an elevated source. (This figure is taken from Pasquill, 1974, Fig. 5-17.) In drawing the isopleths it has been assumed that $\sigma_y/\sigma_z = a_o$, a constant irrespective of distance, and that $\sigma_z \propto x^q$. The isopleths are labeled according to values of $C(x,y,0)/C_m$. The downwind distance is in terms of x' a nondimensional coordinate which uses units of distance that from the source to the point of maximum concentration. Thus, the value 5 corresponds to a downwind distance of 5 times the distance from the source to the maximum concentration. The crosswind distance is in terms of the non-dimensional coordinate $y' = y/(a_o H)$. A typical value of a_o is two. If the parameter q = 1 and $x_m/H = 10$ the relative crosswind and downwind stretching of the isopleths shown in the Figure is correct.

Now by observing Figure 1, one can conclude the following.

(1) Upwind from the point of maximum concentration the concentration values fall off very rapidly with distance being almost two orders of magnitude smaller at $x' \simeq 1/2$ than at $x' = 1$.

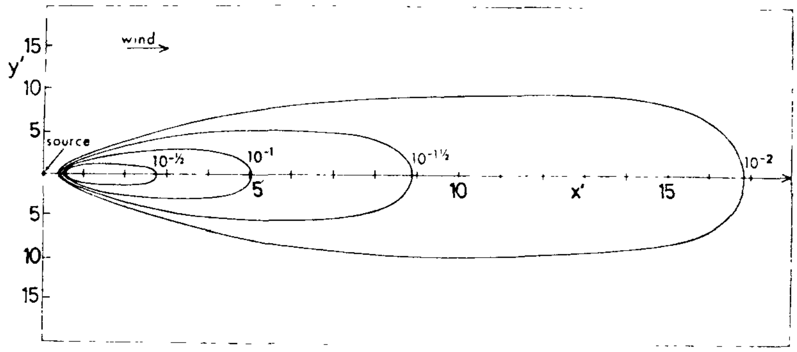

Figure 1. Idealized distribution of concentration at ground level from an elevated source. (From Figure 5-17 Pasquill, 1974)

(2) Downwind from the point x_m the fall-off of concentration is much more gradual having decreased one order of magnitude at $x' = 5$.

(3) The lateral concentration pattern varies rapidly with y', especially so in the vicinity of the point of maximum concentration.

Now, in order to evaluate the effect of changes in physical parameters at the sensitive locations (1) and (3) above, it can be seen that changes in wind direction will have a dramatic effect on the location of the areas (1) and (3). Also, given the wind direction, a change in H or σ_z will produce fairly dramatic results.

Pasquill (1974) has analyzed several cases of changes in C caused by changes in σ_z/H and wind direction at the "most sensitive position" i.e. where $dC/d(\sigma_z/H)$ is maximum. The amount of the change in C ranges between +75% (for a 20% change in σ_z) to -91% (for a 10° wind direction change and a 20% change in H). These results indicate the extreme variation in concentration one can expect for a given sensor location downwind and relatively close to a stack.

As a further step in demonstrating the sensitivity of the Gaussian plume model, Pasquill (1974) estimated errors in C_m caused by errors in the dispersion parameters for an elevated source. He considered the expression for maximum concentration (Eqn. 8). Note that maximum concentration depends on source strength Q, wind speed $\bar{u}$, the dispersion parameters σ_y and σ_z, as well as the distance at which the maximum occurs x_m. Now for simplicity Pasquill assumed that the wind speed and source strength are accurately known. He also assumed that H has 15% error and that the σ_y or σ_z vs x relationships have errors of 15%. Then, it follows from Eqn. 8

$$C_m \propto \frac{1}{H\sigma_y(x_m)} .$$

Pasquill's argument is as follows:

(1) A reasonable estimate of the r.m.s. (root mean square) error in H is about 15% (as given above).

(2) σ_z and H are related according to Eqn. (7). The r.m.s. error in σ_z implied by errors in H is therefore 15%.

(3) In addition to (2) there is an error in σ_z based on the fact that we do not know the precise values of p and q to be used in Eqn. (7). Since most likely $1 < p/q < 2$ the contribution of this error to σ_z is about 8%. (This is found by assuming the range between $\sqrt{2}$ and $\sqrt{3}$ is spanned by four standard deviations and the distribution of departure over this range is normally distributed.)

(4) By assuming no interrelationships in the errors of (2) and (3) above the net error in σ_z can be obtained by taking the square root of the squares of 15 and 8 which is 17%.

(5) There is now a need to know the error in the distance to the maximum concentration x_m since σ_y is evaluated at this distance (in the expression for C_m). If $x_m \propto \sigma_z^2(x_m)$, then the error in x_m is found by doubling the error in σ_z. From step (4) this results in an error of 34% in x_m.

(6) Since the exact form of the relationship $x_m \propto \sigma_z^2(x_m)$ is not known, Pasquill made the reasonable assumption that this error is about 15%.

(7) The net error in x_m is found by taking the square root of the sum of the squares of (5) and (6) yielding 45%.

(8) Now, assuming that $\sigma_y \propto x$ and given the results of (7) above the r.m.s. error in σ_y at x_m implied by (7) is 45%. Since again the exact form of the relationship between σ_y and x is unknown, Pasquill makes the reasonable estimate of 15% error.

(9) The net r.m.s. error in σ_y from (8) and (9) above is found by taking the square root of the sum of squares. This yields 47%.

(10) The total error in the product $H\sigma_y(x_m)$ is found by taking the square root of the sum of the squares of 47 and 15. This gives a net r.m.s. error in C_m of 49%.*

Thus in the case of a power station plume even knowing the wind speed and source strength exactly, one can do no better than about 50% error for an individual case even if the errors in σ_z, σ_y, and H are quite modest.

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* Moore (1973) has analyzed data collected for the Tilbury and Northfleet power stations. His results show that the uncertainties are broadley consistent with those of Pasquill demonstrated above.

SECTION 4

REVIEW OF σ-SYSTEMS AVAILABLE FOR USE

PREDICTIONS FROM THEORETICAL BASES

There are three current working theories of atmospheric diffusion; these are statistical theory, gradient transfer theory, and similarity theory. Pasquill (1974) has explored the many facets of these theories and their underlying bases. Table 1 of this report summarizes the important aspects of each theory with regard to the dispersion parameters σ_y and σ_z. For homogeneous turbulence the statistical theory is valid and σ_y can be predicted for an elevated or ground source. The dispersion parameter σ_z can be predicted by one or another of the theories but take special notice that none of the theories listed can be used to predict σ_z for intermediate range from an elevated source.

A valuable practical result comes from the Hay-Pasquill (1959) version of the statistical theory. The statistical theory applies as long as the plume is under the influence of homogeneous turbulence and would therefore not apply to calculations of σ_z except for short range from an elevated plume, while σ_z is small compared with the height of release. The Hay-Pasquill result is much easier to apply than Taylor's (1921) original theory because it requires only running averages rather than power spectra or correlations. It does involve a simplifying assumption; the ramifications of this can be found in Pasquill (1974) and Gifford (1968). The Hay-Pasquill result states that for an elevated or ground level source, irrespective of distance and irrespective of thermal stratification, the value of σ_y can be predicted

Table 1. APPLICABILITY OF CURRENT WORKING THEORIES OF DISPERSION

Theory →	Statistical	Gradient-transfer	Similarity
Dispersion property predicted	σ_y (elevated or ground source) σ_z (elevated source at short range)	σ_z (ground source) σ_z (elevated source at long range)	σ_z (ground source at short range)
Limitations	Homogeneous turbulence	Dispersive mechanism must be small scale eddies (no meandering)	Surface stress layer, near ground level sources

from

$$\sigma_y = \left[(\sigma_\theta)_{\tau,\ x/\beta\bar{u}}\right] x \tag{12}$$

where the parameter σ_θ is the standard deviation of wind direction measured in radians. The first subscript τ refers to the total sampling period and the second subscript refers to a running average of interval $x/\beta\bar{u}$. Pasquill (1974) summarizes several investigations on the parameter β; the currently suggested value being

$$\beta \simeq 0.44/i$$

where i is the intensity of turbulence.

The Hay-Pasquill result for σ_z (assuming an elevated source) is

$$\sigma_z = \left[(\sigma_\phi)_{\tau,\ x/\beta\bar{u}}\right] x \tag{13}$$

where σ_ϕ is the standard deviation of the elevation angle of the wind measured in radians. Note that this equation appears to be a reasonable approximation for an elevated source within the distance downwind to the point where significant interaction of the plume with the underlying surface has occurred. The main practical problem in using the above equations is that the required information on wind fluctuations is seldom readily available.

Although the concept of gradient transfer continues to be challenged in various ways, there are strong indications that the method is capable of providing realistic estimates of vertical spread from a surface release (or more generally even for an elevated release at height H where $\sigma_z > H$) given flow conditions not departing markedly from neutral stratification. Although the approach does not lead to any simple general result as in the application of statistical theory, values of the vertical distribution of concentration (hence σ_z) may be obtained from solutions (numerical if necessary) of the two-dimensional diffusion equation with plausible forms of K consistent with experience on the turbulent structure of the atmospheric boundary layer. These methods were used by F.E. Smith (1973) and will be given more attention in Section 5 of this report.

The similarity theory is presently limited in its application to predictions of σ_z in regions of the boundary layer where u_* (friction velocity) and H_F (the heat flux) are effectively constant. It is also restricted in that the height of release cannot be more than a few meters (see Pasquill, 1974). Since σ_y does not scale with Monin-Obukhov length L (see Appendix 2) there is no way at present to predict the crosswind dispersion on such a similarity basis (Calder, 1966).

Other significant results relating to the prediction of σ_z based on the working theories will be found later in this report under Section 5 entitled Improved Methods for Estimating Dispersion Parameters.

EMPIRICAL SYSTEMS OF SPECIFYING DISPERSION PARAMETERS

None of the working theories mentioned above is universally applicable over a wide range in x because of various limitations, either theoretical or practical. Because of this, several empirical systems have come into widespread use. Gifford (1976) recently summarized many of these systems.

We will briefly cover the systems mentioned by Gifford and add some recent ones that have been brought to our attention. The bases of most of these estimates are measurements of ground level concentration of some tracer at various distances downwind.

Often the basis of the σ determination was the application of some form of the Gaussian plume model, e.g., Eqn. 11 with regard to σ_z, together with a statement of the continuity equation. It is apparent that any particular observational study cannot be adopted without question as a valid generalization, since there will come into play local climatological influences and peculiarities of measurement systems which will not apply at other locations.

Some of the systems can be related in a loose sense to the statistical theory, while others are purely empirical. For convenient practical application, the values of σ_y or σ_z are presented in relation to meteorological data of a routine nature, and one of the crucial requirements is that of insuring a realistic representation of the effects of thermal stratification in terms of such data.

The British Meteorological Office 1958 System

In 1961 Pasquill published a method of determining the dispersion parameters, on the basis of making simple subjective estimates of the structure of turbulence of the atmospheric boundary layer from routine meteorological data, comprised of wind speed, insolation, and cloudiness. These three meteorological parameters were used to determine a stability category A through F (A corresponding to very unstable conditions and F to very stable conditions, D being neutral). Given the stability category and downwind distance, one could determine the corresponding value of the dispersion parameter. Because Pasquill wanted to make the identification with physical spreading easy for engineers and other non-meteorologists (principally interested in making quick estimates of the plume spread) he used an angle θ to measure "total" crosswind spread and a height h to measure "total" vertical spread. The relation of these parameters to σ_y and σ_z is

$$\theta = 4.30\ \sigma_y/x, \tag{14}$$

and

$$h = 2.15\ \sigma_z \tag{15}$$

A more precise way of measuring atmospheric turbulence is through the Richardson number Ri (which will be defined later in Appendix 2) and a qualitative correspondence exists between Pasquill categories and Ri. The large positive values of Ri correspond to stable conditions F and large negative values correspond to unstable conditions A, as pointed out by Islitzer (1965).

In Pasquill's original system no attempt was made to allow for any special dependence of σ_z growth on elevation of the source, because at that time the state of knowledge was such that there was no basis on which to make such a differentiation.

The estimates of vertical dispersion in the Pasquill system are based on the following: (See also Table 1, Part II of this report by Pasquill)

(1) Data collected at short range, less than 1 km, during neutral conditions and consolidated by Calder's (1949) semi-theoretical treatment. The roughness length implicit in the Calder treatment was 3 cm.

(2) Data collected at short range during non-neutral conditions, obtained from measurements in Project Prarie Grass[*] (Barad, 1958).

(3) Data collected in the range 1 km to 100 km during unstable conditions, and calculations based on vertical gustiness. ($z_o \approx 30$ cm)

(4) Data representing stable conditions in the range 1 km to 100 km were essentially speculative extrapolations from the more reliable data. ($z_o \approx 30$ cm)

Estimates of the crosswind spread were emphasized by Pasquill to be valid for release times of only a few minutes. If suitable wind direction fluctuation data were available, Pasquill recommended the values of the crosswind dispersion parameter to be calculated by Eqn. 12. When fine-structure data were not available θ could be calculated from the difference of the extreme maximum and minimum of the trace and setting this equal to θ, provided the distance to the point of interest is less than 0.1 km on the axis of the plume. For distances downwind of the order of 100 km, Pasquill modified this procedure to be the difference between the maximum and minimum "15 minute averages" of wind direction.

For a ground level source the σ_z values can be considered independent of sampling time up to periods of 1 hr. or so. For an elevated source (of about 100 m) the estimates should be taken to

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* Project Prarie Grass was conducted near O'Neill, Nebraska in 1956. The objective was to determine the rate of diffusion of a tracer gas as a function of meteorological conditions. The range of experiments was from 0 to 800 meters and a total of 70 experiments were performed. The release time for the tracer gas was 10 minutes.

apply for 10 min. or more of sampling time.

Giffords (1961) recasting of the Pasquill System

Gifford converted the plume spreading parameters θ and h of the Pasquill system to values of σ_y and σ_z by means of Eqn. (14) and (15). He did this feeling that it was less arbitrary and more generally understood by people making applications, to use standard deviations rather than the 10% points of Eqns. 14 and 15. The data used were exactly those of the Pasquill system mentioned above. The resulting set of curves are generally known in this country as the Pasquill-Gifford curves (PG curves) (See Fig. (2)).*

Turner's (1961, 1964) adaptation of Pasquill's Stability Scheme

Turner adapted the Pasquill stability scheme but added a qualitative specification of insolation in terms of solar altitude rather than a subjective determination. By specifically allowing for solar elevation he provided a basis for applying Pasquill's scheme elsewhere than in the latitude of Britain. This objective system of determining the stability categories also provided a means of using archived meteorological data to determine what the stability categories had been at a particular location. Thus the computer could be used with ease to produce a diffusion climatology for a region for use with the Gaussian model. The

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* Three slightly differing versions of the Pasquill-Gifford curves exist; Pasquill (1961) (which is the same as the version appearing in Turner, 1969), Gifford (1961), and Slade (ed.) (1968). This has led to a small amount of confusion in the published literature, however, the differences between versions are only in the unstable categories A, B, and C. The version under consideration here is identical to that of Turner (1969).

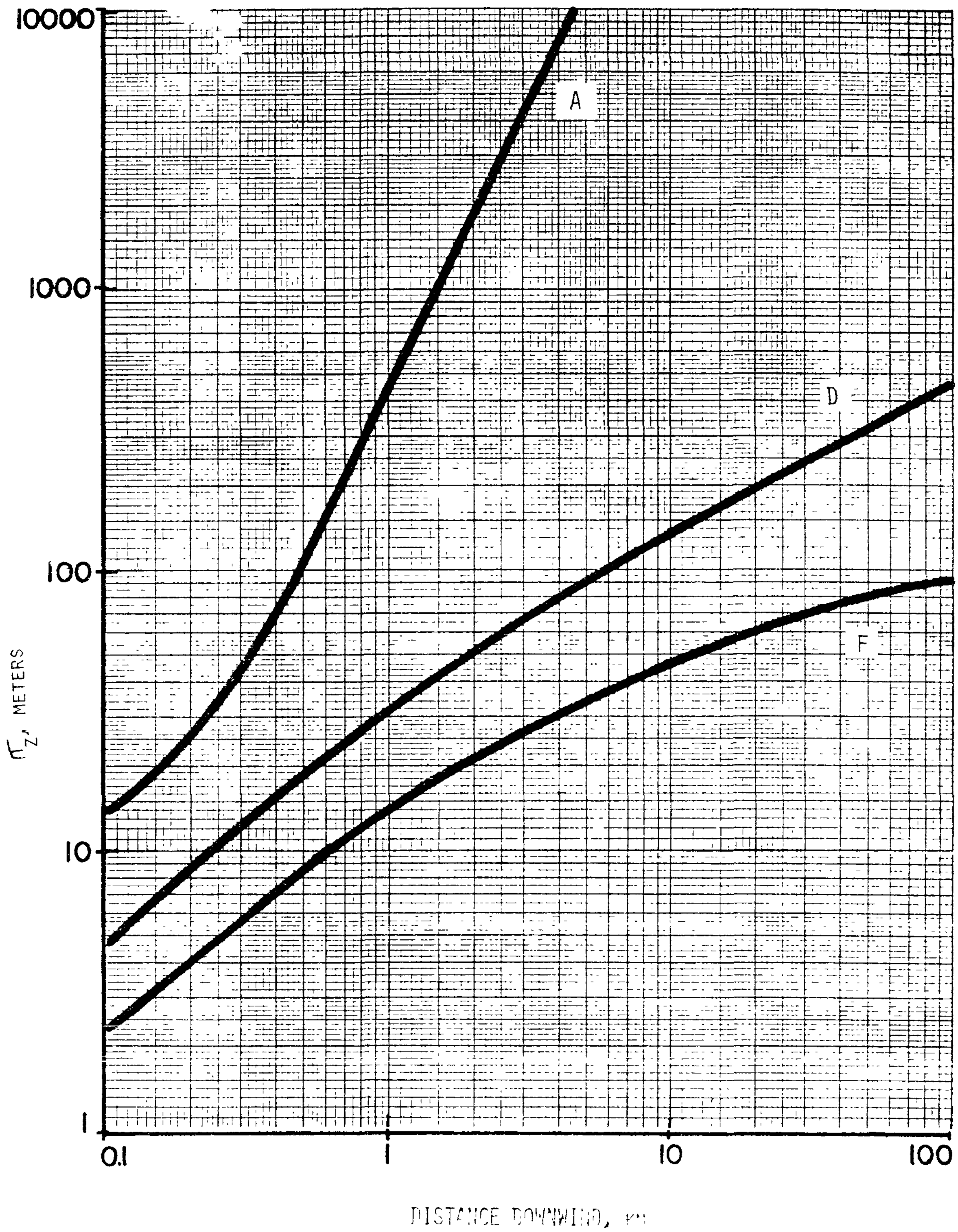

Figure 2. The Pasquill-Gifford curves for σ_z versus downwind distance x (From Turner, 1969)

σ_y's and σ_z's published in the widely used EPA workbook by Turner (1969) are exactly those of the so-called PG curves.

Klug's (1969) stability scheme

Klug (1969) developed a highly detailed set of rules to determine diffusion classes I through V (I corresponding to stable and V to unstable). The scheme was quite similar to Pasquill's except that it was more detailed and could handle more complex situations, e.g. the transition from night to morning when the boundary layer is rapidly evolving. For dispersion parameters Klug used σ_y and σ_z measurements from Project Prarie Grass (Barad, 1958).

The Brookhaven National Laboratory (BNL) System by Singer and Smith

Singer and Smith (1966) set forth a stability category system and data relating to dispersion parameters, based on a variety of data taken over a 15 year period at the BNL site. These data are noteworthy in that the plumes were released at 108 m (quite high compared to previous studies). The stability system recommended was based on wind direction traces. Singer and Smith gave the stability categories letter designations, corresponding to a turbulence type indicated on the wind direction trace. The letters are A, B_2, B_1, C, and D (A representing very unstable and D representing very stable). Each of the letter designations corresponds to a range of wind direction fluctuation in degrees taken over a one hour period with a Bendix-Friez Aerovane located at source height. The BNL categories are often referred to as "gustiness classes".

Sources of dispersion data used in the Singer-Smith system were from tracer experiments using uranine dye, oil fog, and Argon 41 (a radioactive isotope), the most important single source of data coming from the oil fog studies. Concentration measurements were obtained in three ways; photometric densitometers, fluorescence of the oil droplets, and visual estimates of the dimensions of the plume. The radioactive argon emissions allowed following the dispersing plume up to distances of more than 50 km. The uranine dye was used at short range, and in contrast with the rest of the experiments was released at 2 meter source height. The σ_z values were not measured directly but were calculated through measurement of σ_y, C, and $\bar{u}$.

The sampling times for the dispersion parameters were of the order of one hour. The dispersion curves in the ASME (American Society of Mechanical Engineers) Recommended Guide for the Prediction of the Dispersion of Airborne Effluents: Smith, 1968) are based on the Singer-Smith formulation and the recommended dispersion parameters are exactly the same.

One point worth noting with regard to the BNL system is that the σ_y and σ_z variations with distance downwind are identical.

The TVA (Tennessee Valley Authority) System

Carpenter, et al. (1971) summarized dispersion data representing helicopter sampling of SO_2 emitted from stacks of the TVA system. This study was the first dealing with dispersion data from large buoyant plumes. The stacks operational in the TVA system at the time of the experiments covered a fairly wide range of height between approximately 75 and 150 meters.

The flight paths used by the helicopters were of two basic types: lateral and vertical cross sections. The lateral cross sections were made by flying through the plume at about 30 m increments in elevation.

A typical number of passes at a given downwind distance would be six or so. This procedure would be repeated at different downwind distances; typically these distances were 0.8 km, 6 km, and again at between 16 and 32 km. Vertical traverses were made with the helicopter to determine the distribution of concentration using the sampler. Then assuming a Gaussian distribution in the horizontal and vertical, the curves were integrated by approximating the area under the curve with a rectangle, and using the relation

$$\sigma_y \text{ or } \sigma_z = \frac{\text{Area}}{C_{max}\sqrt{2\pi}} \qquad \text{(where } C_{max} \text{ is the maximum measured concentration for the transect.)} \qquad (16)$$

The sampling time involved in the TVA study was basically the time which it took the helicopter to pass through the plume, i.e. a few minutes. Shorter times were required to traverse the plume during stable conditions (the plume width being smaller). Temperature profiles were determined at the beginning of the sampling period by the helicopter temperature probe. The temperature gradients characterizing the stability category for the published curves are meant to apply at plume height. Wind speeds were measured with the pilot balloon technique.

These data were collected over a very long time period (5 to 10 years) so that dispersion values represent a large number of individual cases in the final averages. The number of individual stacks represented is of the order of 10 or so.

Some differences relating to the TVA published σ-values are apparent. Since the temperature gradient was measured at plume height the data show no super-adiabatic temperature gradients, although there is an extremely high probability that these often existed near the ground. The reason is that a large portion of the data were collected during midday hours and during the summer season. It can be concluded that unstable cases exist in "masked" form amongst the neutral and slightly stable cases. The tendency for temperature lapse rate to approach closely the dry adiabatic rate during convective conditions is well known and can be demonstrated from tall tower temperature measurements.

Another difference of the TVA data is the relatively short sampling times, especially with respect to σ_y.

The McElroy and Pooler (1968) Dispersion Curves for Urban Areas

McElroy and Pooler (1968) studied diffusion of tracer clouds over St. Louis specifically to obtain dispersion data over urban areas. This series of experiments consisted of releases of flourescent zinc-cadmimum sulfide particles. Twenty six daytime and sixteen evening experiments were conducted over a two-year period. The samplers were located on three circular arcs at distances between 0.8 and 16 km. from the dissemination point. Winds were measured by several methods, including tracking transponder equipped tetroons by radar and using the single theodolite technique.

The tracer material was released from near ground level. Sampling times were usually one hour. Determination of σ_y was by direct means whereas σ_z was inferred through the crosswind integrated formula (Eqn. 11).

A number of different systems were used to describe the turbulence representative of the various experiments. A "modified gustiness class" similar to the Brookhaven gustiness class was used (different ranges of wind direction fluctuations were adopted since the wind direction sensor was located nearer the ground than at Brookhaven). Also used to differentiate stability were the Pasquill scheme, σ_θ, and Ri (Richardson number) values (See Appendix 2). The Richardson number was based on temperature and wind measurements at the 38 and 138 meter levels of a television tower.

Markee's Dispersion Curves

Sigma curves derived by Markee (Yanskey et.al., 1966) from tracer experiments at the National Reactor Testing Station (Idaho Falls, Idaho) are available. The diffusion experiments were carried out by Islitzer and Dumbauld (1963) using uranine dye as a tracer. Releases were made at ground level with sampling arcs at 100, 200, 400, 800, 1600, and 3200 meters. Sigma y's were determined directly, and sigma z's were calculated by knowing the maximum of the crosswind distribution for a ground-level source.

The roughness appropriate to this site is about 3 cm. The release period and sampling time was 30 minutes. Other data were considered in Markee's curves, namely those from Project Green Glow (Fuquay et.al., 1964).

The stability system used by Markee is the same as Pasquill's although different systems could be incorporated since the original experiments contained measurements of σ_θ, Ri, $\bar{u}$, and $\Delta T/\Delta z$.

Bultynck and Malet's (1972) Stability System and Dispersion Data

This system was developed for use at a reactor site in Belgium (the Mol site); it differs from others in that it uses a stability parameter S defined as

$$S = \frac{\partial\theta/\partial z}{\bar{u}_{69}^{2}} \qquad (17)$$

The symbol $\bar{u}_{69}$ stands for the wind speed measured at 69 meters height. This parameter (whose dimensions are °C sec^2/m^3) is similar to a Richardson number. The measurement height of wind is not critical so long as it is confined to the height interval between 24 and 120 meters. Sixty-nine meters is the height of reactor stacks at the Mol site.

Turbulence data were used to evaluate the Hay-Pasquill (1959) form of the Taylor statistical theory (see Eqns. 12 and 13). The parameter β was determined from the expressions of Wandel and Kofoed-Hansen (1962)

$$\beta_y = \frac{\sqrt{\pi}}{4}\ \bar{u}\ /\ (\overline{v'^2})^{1/2} \qquad (18)$$

$$\beta_z = \frac{\sqrt{\pi}}{4}\ \bar{u}\ /\ (\overline{w'^2})^{1/2} \qquad (19)$$

The sampling time was one hour in all tests. Two years of data were used to form the dispersion curves (Jan. 1966 to July 1968) representing 280 hourly observations.

Comparisons of these results with the BNL curves showed favorable agreement. Dispersion data from experiments at the Mol site also compared very favorably with the predicted values of σ_y. Apparently no comparisons of σ_z were made. A total of fifteen tracer experiments were done.

TRC (The Research Corporation of New England) Curves for Rough and Inhomogeneous Terrain

Bowne (1974) proposed a new set of dispersion curves based on previously published data including McElroy and Pooler (1968), Hilst and Bowne (1971), Bowne, Smith and Entrekin (1969), McMullen and Perkins (1963), Smith and Wolf (1963), McCready et.al., (1961), Hamilton (1963), Haugen and Fuquay (1963), Towrin and Shen (1969), Church et.al., (1970), Kangos et.al., (1969), and Taylor (1965), primarily to solve dispersion problems in urban and suburban areas. Bowne proposed three sets of curves appropriate for rural, suburban, and urban terrain.

The rural dispersion curves are the same as the PG curves with the following modifications; first the curves were extrapolated back towards the source from 100 m to 1 m. There were no measurements of σ_z or σ_y in this range for rural settings. However, this extrapolation was thought to be appropriate in order to provide some information, however crude, in predicting concentrations near highways where concentrations in the first 100 m or so are very important. Second, the PG σ_z curves were modified at distances of 3 to 20 km in unstable conditions to account for the likely occurrence of limited vertical mixing due to the presence of an elevated inversion layer (finite mixing depth as mentioned earlier).

The suburban dispersion curves are based on previously published studies, including experiments at Dugway Proving Ground. The roughness corresponding to sage covered deserts is comparable to "typical suburban" areas with trees and bushes. Data were available as close as 50 m from the source, in contrast to the rural curves. No σ_y curves are published since Bowne felt that there was no significant difference between rural and suburban areas in this respect. The σ_z values show an extension back towards the source (or x = 0) with all stability categories approaching the same σ_z value (5m). Bowne anticipated the effect of the mixing height on the plume by again showing constant, or flattened-off, dispersion parameters for the unstable cases.

The vertical dispersion rates proposed by Bowne for large cities are based on data obtained from the St. Louis study (McElroy and Pooler, 1968), Ft. Wayne (Csanady, et.al., 1967), and Johnstowne studies (Smith, 1967).

Briggs' Interpolation Formulas

Briggs (1973) proposed a series of interpolation formulas for the dispersion parameters, using as a basis previously collected dispersion data. His rationale in forming these curves was to aid in predicting maximum ground-level concentrations from an elevated source. He felt that the PG curves were most accurate at the short ranges and BNL curves were probably more appropriate at intermediate and longer distances. At extremely long distances he utilized TVA data.

The transition between the PG curves and the BNL curves was made when the value of σ_z approached the value of the source height of the BNL studies, i.e. between 50 and 100 m. When σ_z approached 300 m, or so, the TVA curves were given the most weight.

Briggs also attempted, as best he could under the circumstances, to fit the theoretical variation of σ_y with distance predicted by the Taylor statistical theory, i.e. $\sigma_y \propto x$ at short distance and $\sigma_y \propto x^{1/2}$ at long range. Briggs produced a separate set of interpolation formulas for urban conditions based on the St. Louis experiment. Briggs' dispersion parameters were presented as convenient numerical formulae as well as the usual dispersion curves.

Dispersion Data for σ_y in Terms of Travel Time

Fuquay, Simpson, and Hinds (1964) analyzed 46 diffusion experiments from a ground level source at the Hanford Laboratories near Richland, Washington. They expressed the crosswind dispersion parameter σ_y in terms of travel time $(x/\bar{u})$, instead of downwind distance x as is usually the case. Their dispersion curves are parameterized in terms of $\sigma_\theta \bar{u}$ (which is very nearly equal to σ_v). Part II of this report has much additional information regarding crosswind dispersion.

At the conclusion of this section it is recognized that many other versions of dispersion parameters exist which rely on experimental work or models that have not been summarized here. Many of these differ in a quite insignificant way from the "original" Pasquill-Gifford curves. Others, while having novel features, are site specific and thus their value is somewhat limited. (This is recognized to be true of the Mol data described earlier.) According to Gifford (private communication) at least 30 additional sets of curves exist that would fall into these categories. Obviously it would be of little use here to describe all of these variations.

Comparative curves showing the vertical dispersion coefficient from a few empirical methods are presented in Figures 3 through 8. Since the PG curves are the most widely used they are the ones against which each comparison is made.

Over rural areas during unstable conditions, and for distances downwind greater than 1 km, the PG curves are consistently high compared with all others in the group under consideration. (At short ranges for unstable conditions only the Markee curves show σ_z less than the PG curves.) For the case of neutral and stable conditions, experimental data for rural sites tend to lie on both sides of the PG curves, indicating no systematic disagreement.

In comparing the PG curves with others mentioned in this report, one needs to be reminded of the fact that there has been no comprehensive definitive set of data or method amongst those considered, which could be used as a bench mark. Also, it is difficult to assess all the factors which could have contributed to differences in data sets that ought to be similar.

Because of the earlier discussion on the effect of sampling time on σ_y, no comparison of these values will be made but some discussion of the relation between σ_y and σ_θ is included in Part II.

The BNL diffusion data (Figure 3, representing an elevated release, and indirect measurements of σ_z at generally greater distances than were represented by the basic data of the PG curves) show mostly lower values of σ_z than the PG curves, except for neutral stability. The slope of the BNL curves (with the exception of very unstable cases) is not drastically different from the PG curves over the range 0.1 to about 4 km.

The TVA curves show the greatest difference from the PG curves. Recalling that there are probably many cases of unstable data among the TVA "neutral" cases, this is not surprising.

The McElroy-Pooler data for urban areas (Figure 5) show greater values of σ_z than the PG curves for the range of measurement. No A category is listed but the B category is higher for McElroy-Pooler than the PG B category (not shown in Figure 5). There is undoubtedly an effect of the urban heat flux and greater roughness values, which will be discussed in Part II of this report. The slope of the curves is again less than the corresponding PG curves.

The curves proposed by Markee (Figure 6) are somewhat similar to the PG curves, but are lower in σ_z values (except for neutral conditions) at almost all downwind distances. The slope of Markee's unstable curve is less than the PG curves.

Bowne's curves (Figure 7) weight the PG curves heavily at short, intermediate and long ranges, for rural conditions. The effect of the "lid" is dominant in the unstable case.

Briggs' interpolation curves (Figure 8) for σ_z are designed to follow the PG curves at short distances and therefore, the agreement is good. It is obvious from the earlier description of Briggs' system that it will resemble BNL and TVA curves at longer ranges.

As noted earlier, an interesting aspect of these sets of data is that all but one show disagreement with the PG curves for very unstable conditions A (in that the downwind derivative of $d\sigma_z/dx$ is positive).

This seems to mean that the free convection regime studied by Deardorff and Willis is somewhat elusive. Pasquill has made a detailed examination of the model of Deardorff and Willis (1974a,b) showing comparisons with other theories in Part II of this report.

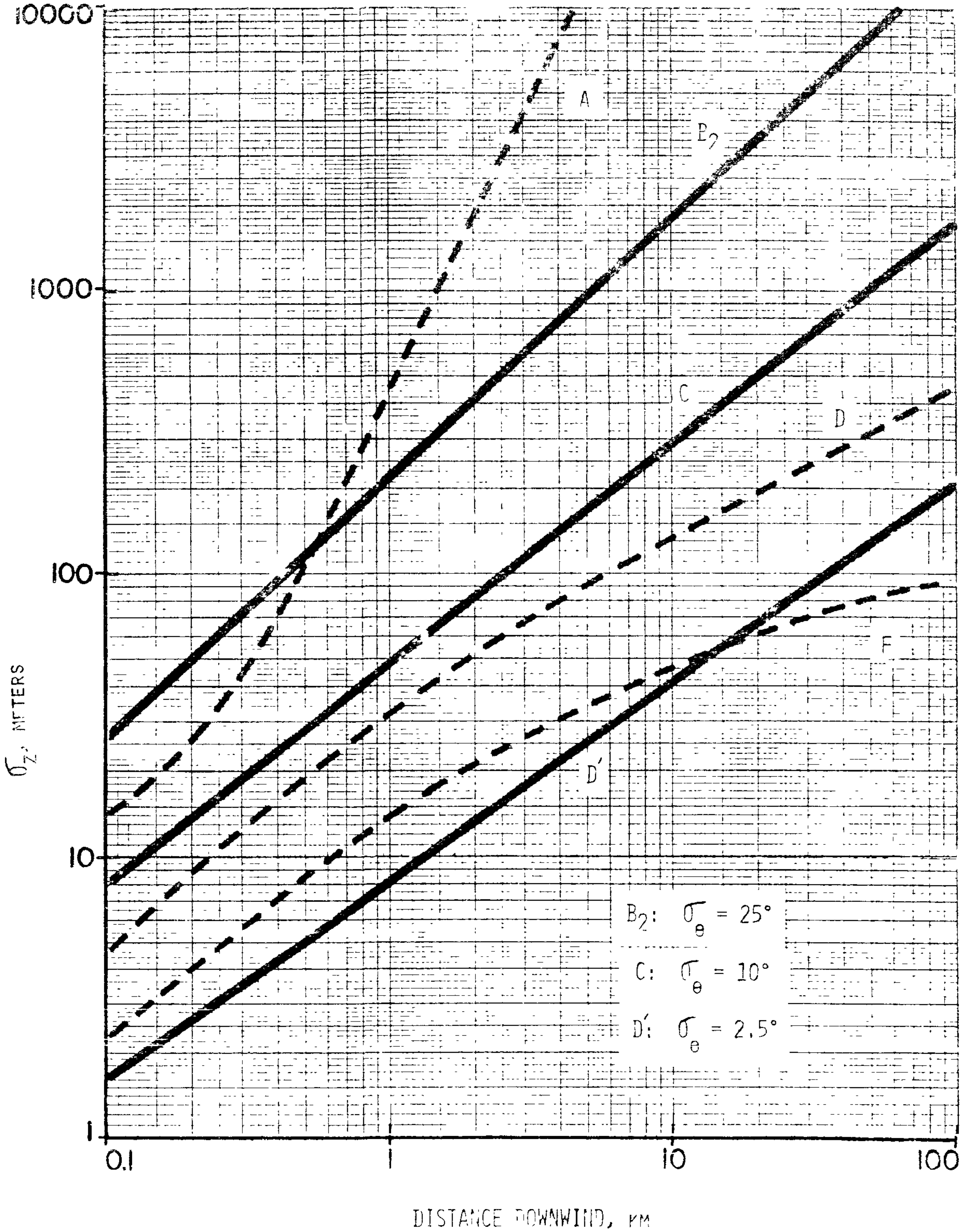

Figure 3. The dispersion curves of Singer and Smith (Smith, 1968) (solid lines) and the PG curves (dashed lines).

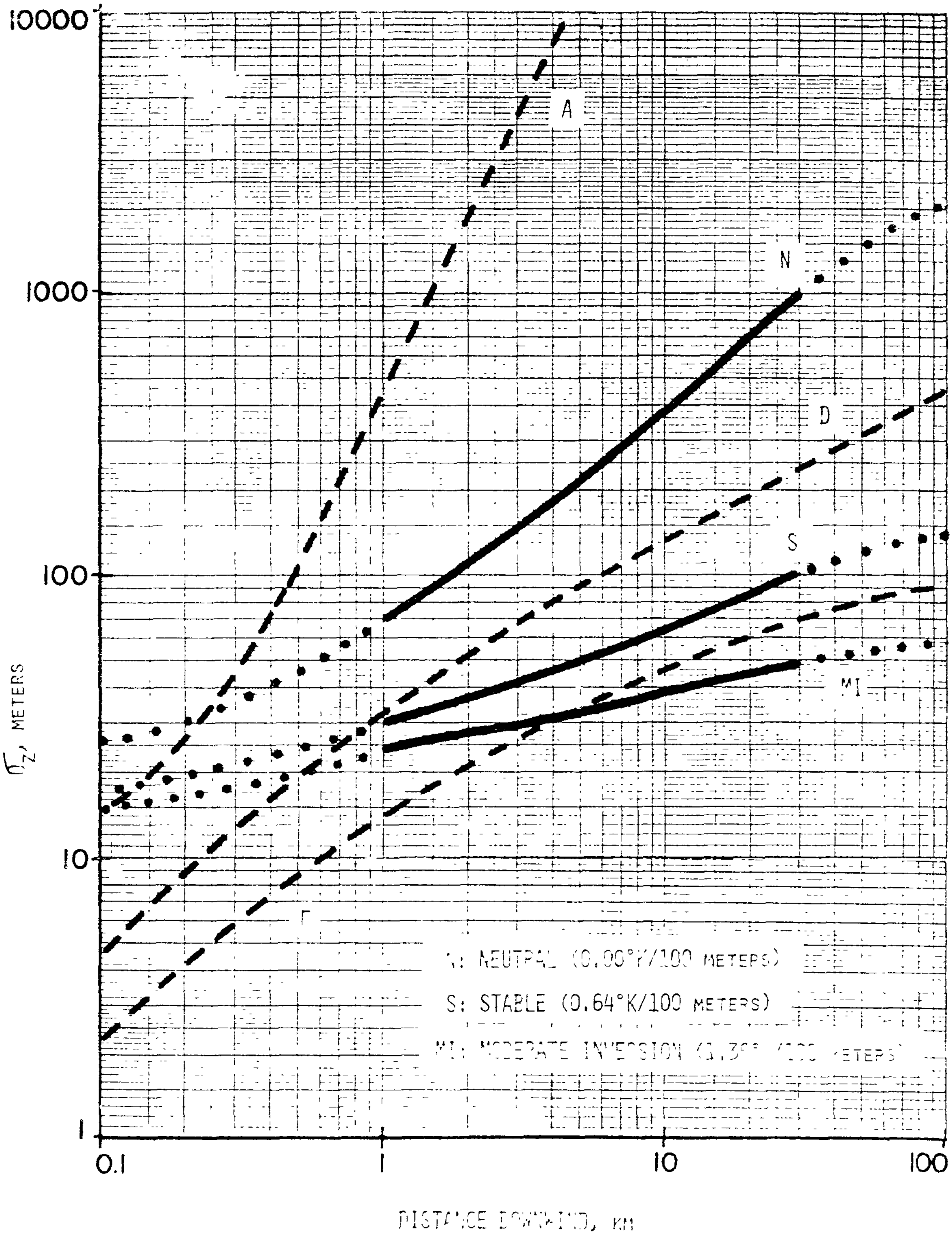

Figure 4. The TVA dispersion curves (Carpenter, et. al., 1971) (solid lines) and the PG curves (dashed lines).

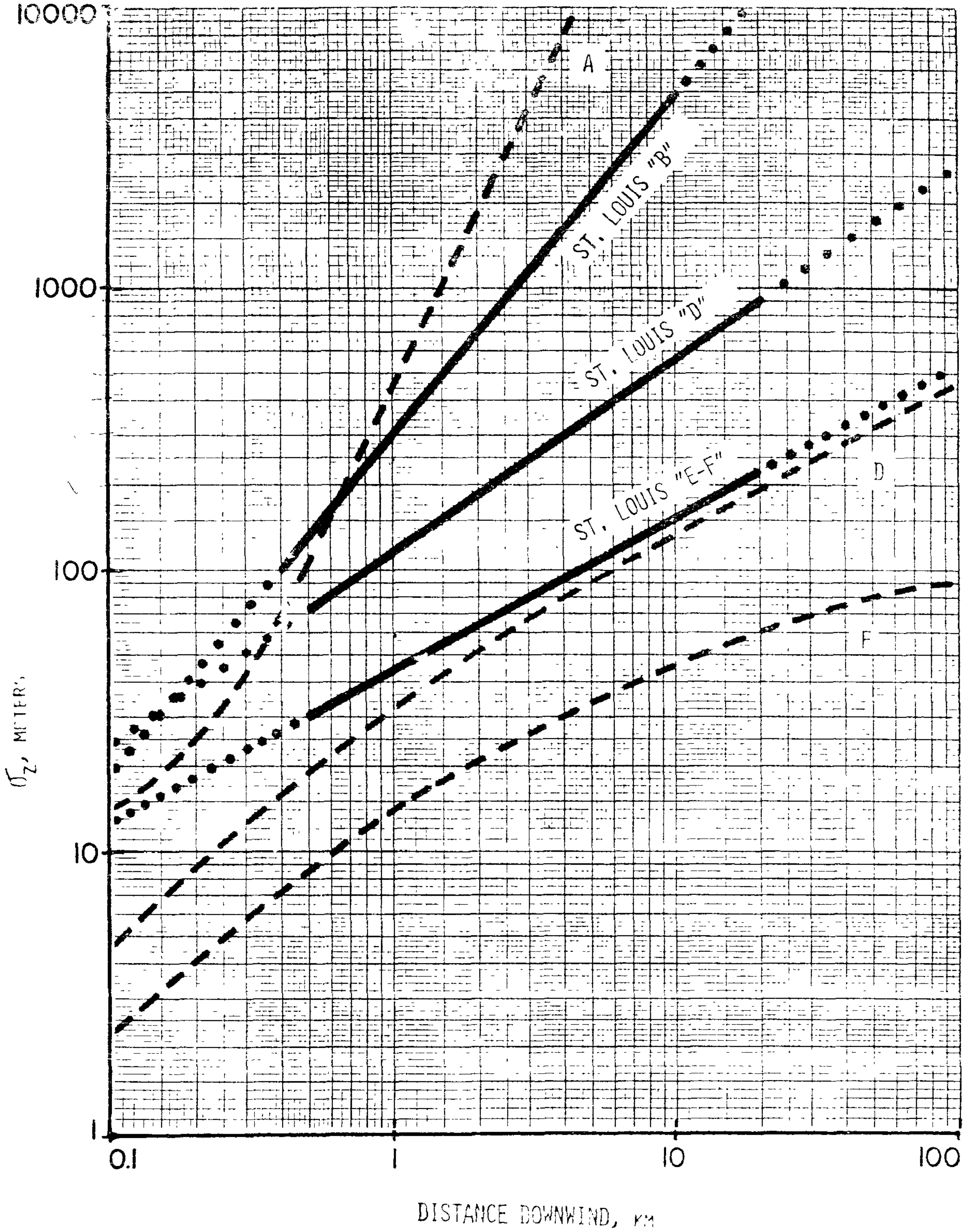

Figure 5. The St. Louis dispersion curves (McElroy and Pooler, 1968) (solid lines) and the PG curves (dashed lines).

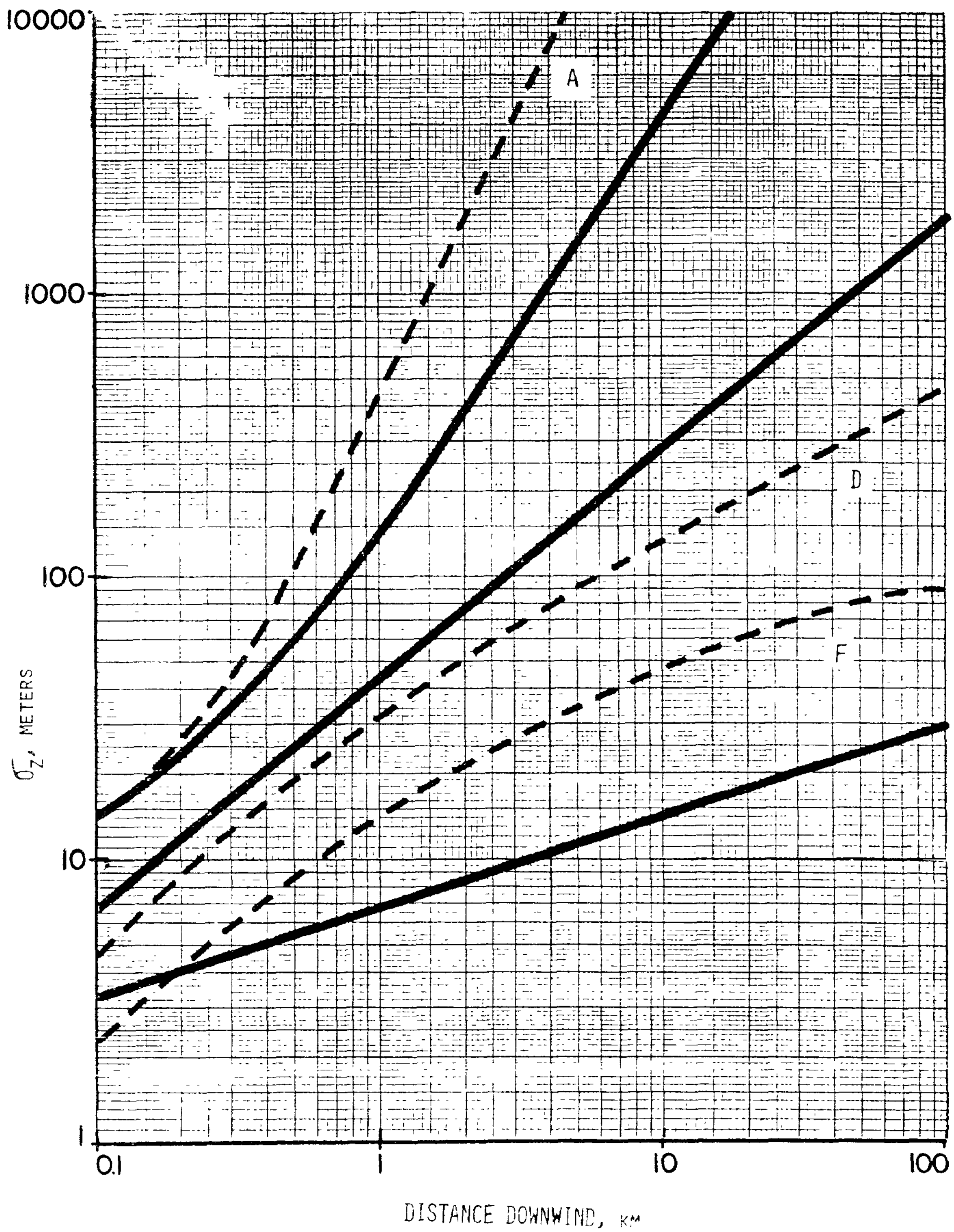

Figure 6. Markee's dispersion curves (Yanskey, et. al., 1966) (solid lines) and the PG curves (dashed lines).

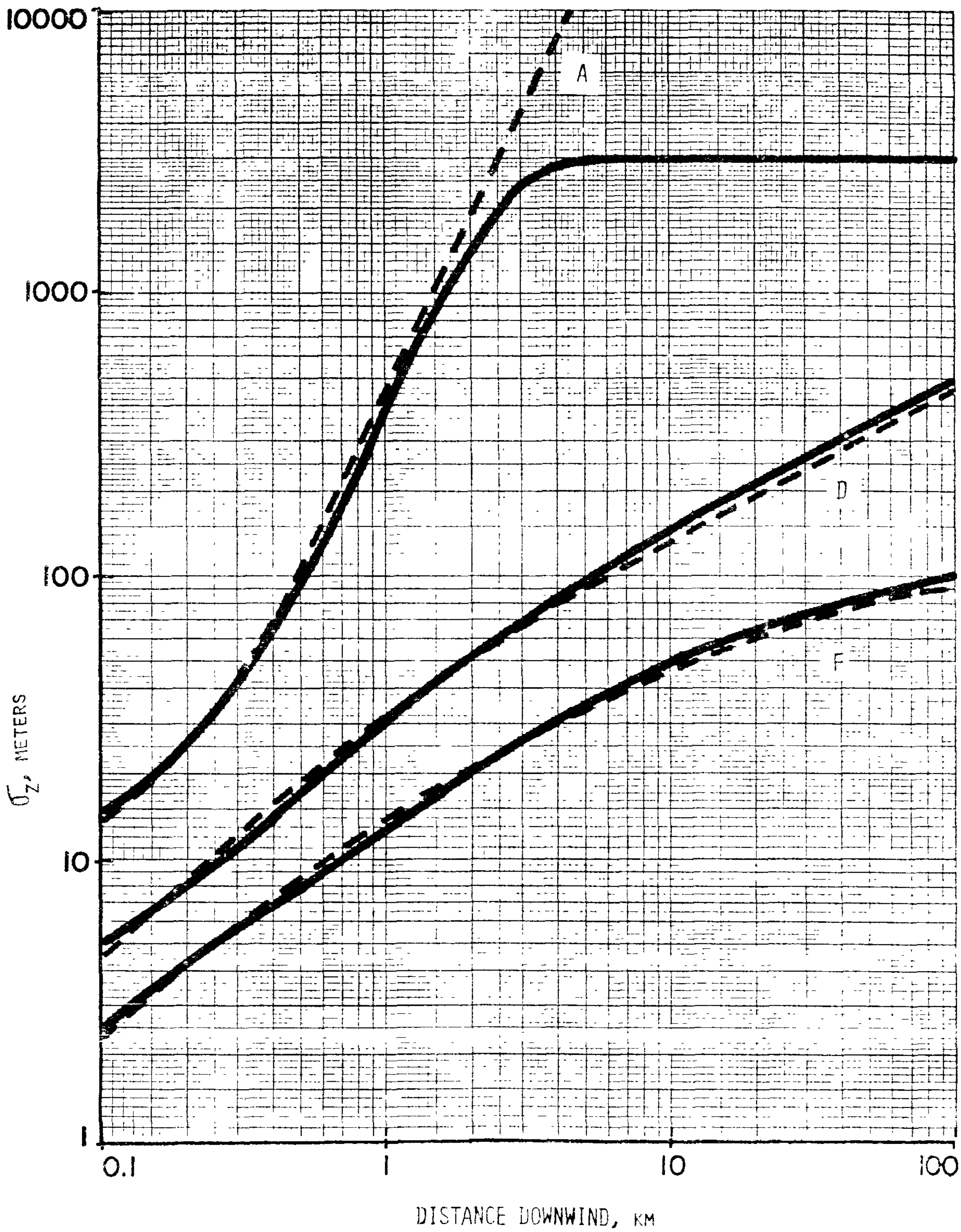

Figure 7. TRC rural dispersion curves (Bowne, 1974) (solid lines) and the PG curves (dashed lines).

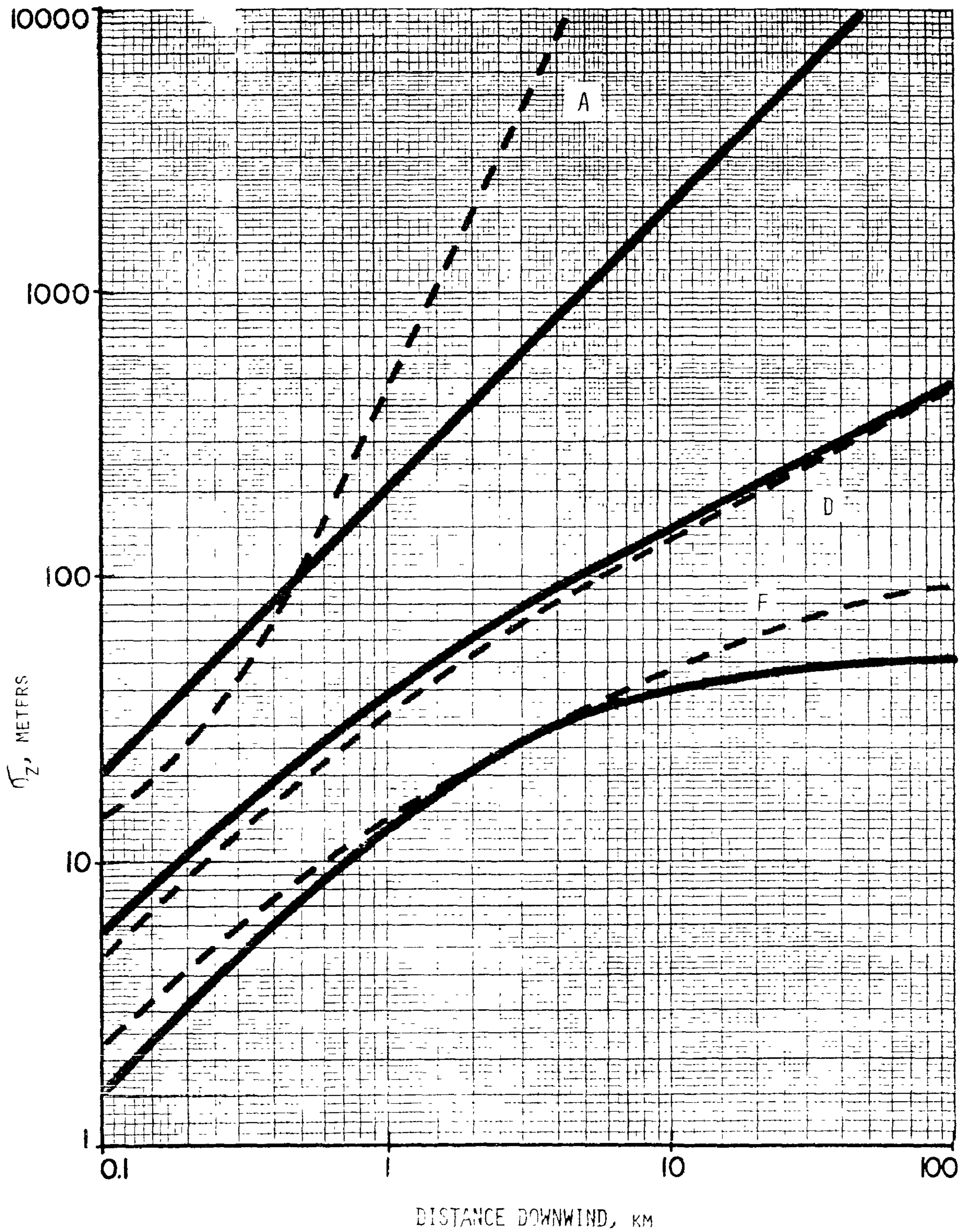

Figure 8. Briggs' rural dispersion curves (Briggs, 1973) (solid lines) and the PG curves (dashed lines).

SECTION 5

IMPROVED METHODS OF ESTIMATING DISPERSION PARAMETERS

In this section we will examine some new approaches to the method of estimating dispersion parameters. Five new approachs are considered in some detail and a sixth is referenced briefly. There may be other methods that we are not aware of because of rapid developments in the field. Each of these new systems seems to offer something basically different from what we have considered previously.

Smith's (1973) System (Published in Pasquill, 1974)

Smith addressed the problem of predicting concentration patterns from a ground level source using the gradient transfer theory, incorporating numerical solutions of the diffusion equation, and height dependent diffusivity (K) values computed from the relation

$$K(z) = \varepsilon^{1/3} \lambda_m^{4/3}/15 \qquad (20)$$

(for a full discussion of this form of K and complete definitions of the terms see Pasquill, 1975). (In Eqn. 20, ε is the rate of turbulence energy dissipation and λ_m is a measure of the predominant eddy size.) Smith and S.A. Mathews obtained the numerical solution of the two dimensional diffusion equation

$$\frac{\bar{u}\partial C}{\partial x} = \frac{\partial}{\partial z} \left(\frac{K\partial C}{\partial z}\right) . \qquad (21)$$

The height dependent values of ε were obtained from a limited amount of data derived from captive balloon ascents near Cardington, England. The λ_m profiles were summarized on the basis of Busch's and Panofsky's (1968) studies of spectral scales. Several different atmospheric stability conditions were represented by the ε and λ_m observations.

Briefly, Smith's method involves specifying a geostrophic wind speed, a roughness value, and (basically) a surface heat flux. These determine the friction velocity u_* in the surface stress layer. Then, using generally accepted wind profile laws appropriate to the surface layer, an interpolation is made to match the profile in the surface layer to the geostrophic wind speed. It should be noted that Smith's method does not involve any change of wind direction with height. (The amount of crosswind dispersion which occurs at longer ranges from the source is influenced by the turning of the wind as has been noted earlier).

Having solved the two dimensional diffusion equation, Smith used the concentration profiles to obtain values of dispersion parameters directly from the relation

$$\sigma_z = \int Cz^2 dz \Big/ \int C dz \quad .$$

The practical use of Smith's method is illustrated by Pasquill (1974). A stability parameter P is specified in terms of wind speed at 10 m, and vertical heat flux or incoming solar radiation. If desired, a rough approximation to P can also be obtained from insolation (slight, moderate, and strong) and cloud amount. If the latter alternative is chosen, Pasquill categories A - F can be related to ranges of the parameter P. Once P is obtained the only remaining parameter to be specified is the roughness length. Convenient nomograms are provided to obtain σ_z versus x from z_o and P.

Smiths σ_z values, having been computed from the gradient transfer theory, are expected to be valid for vertical dispersion from a ground level source at all distances downwind (over homogeneous flat terrain), and to be a good approximation for elevated sources at long distances from the source. When the vertical spread is large compared with the height of the source, the concentration approaches the value one would obtain from a ground level source.

Lagrangian Similarity Theory

Pasquill (1975) has proposed an alternative to the usual formulation of similarity theory, for which the limitation of restriction to the surface-stress layer is less important. This proposal is based on replacing the surface stress and surface heat flux by the standard deviation of vertical wind speed σ_w and the scale of turbulence ℓ. Both of the latter are to be considered as local, as opposed to surface parameters, and both are regarded as functions of height in Pasquill's formulation.

To make practical use of the equations derived in this approach, it is necessary to assume that ℓ is proportional to the maximum of the vertical velocity spectrum λ_m (a kind of measure of the size of the predominant eddies). Observations of λ_m are available for use in application of the theory.

Using F.B. Smith's numerical solution of the two dimensional diffusion equation in terms of λ_m and ε, these similarity hypotheses have been tentatively verified for a range of values of z_o and heat flux H_F. The theory lacks direct observational testing, however. A useful feature of the foregoing is that for K profiles differing from those used by Smith, the vertical spread can be derived from demonstrated similarity relations, thus avoiding repetition of the numerical solutions of the diffusion equation.

Moore's Formulation for Power Plant Plumes

Moore (1972, 1974a,b) has given a semi-emperical formulation for predicting the maximum ground level concentration C_m and the downwind distance of this maximum. (Actually a virtual point source is introduced, which is moved upwind to take account of induced spread, and downwind to take account of plume trapping in inversions). One of the essential features of Moore's formulation is the recognition of the different functional growths of σ_y and σ_z with distance downwind, as follows:

$$\sigma_z = L^{1/2}x^{1/2} \tag{24}$$

and

$$\sigma_y = Bx \tag{25}$$

where $L = 2K/\bar{u}$ and B is a dimensionless constant relating σ_y to x.

An additional significant feature of Moore's formulation is that he tried to account for the induced spread of the plume resulting from heated stack gases. Complete details of this rather complex scheme including the values of L and B for various conditions are contained in Moore (1974b).

Deardorff's Free Convection Modeling

Dispersion in the daytime under clear skies and light winds is frequently dominated by convection. The condition known as "free" convection is reached when turbulence is independent of surface drag force. The atmosphere above such a convective mixing layer is capped by a stable layer (of height z_i). The turbulence and transfer properties under such conditions have been studied in the laboratory by Deardorff and

Willis (1974a,b). Preliminary reports of the laboratory modeling experiments indicate that the transport properties can be uniquely represented by a universal relation between σ_z/z_i and t_* where

$$t_* = w_*/z_i \quad \text{and} \qquad (26)$$

$$w_* = \left(\frac{gH_F z_i}{\rho CpT}\right)^{1/3}, \qquad (27)$$

w_* being a characteristic vertical velocity.

One of the important qualifications of this approach concerns the threshold wind speed in the atmosphere, below which one could expect the free convection model to apply. An example from Pasquill (1975) estimates that the wind speed below which it would appear reasonable to adopt the theory may be as little as 3 m/sec. In relation to the conventional categories such a wind speed condition would include category A completely, but categories B and C only for the lower end of the range of wind speeds associated with those classes. However, the whole question of applicability of the Deardorff "convective" model to real atmospheric flow has yet to be convincingly settled.

Second-Order Closure Modeling - Lewellen (1975)

Recently the problem of atmospheric dispersion, using the full fluctuation equations coupled with a second-order closure assumption, has been under investigation and is being actively studied by several groups. These studies seem to offer considerable promise in improving the rational basis of specifying σ_z in the Gaussian plume model, or of predicting the concentration distribution.

Lewellen (1975) has produced several curves of σ_z versus x based on the second-order closure approach. The curves are stratified on the basis of Richardson number Ri and Rossby number Ro. Agreement between Lewellen's values of σ_z and F. B. Smith's values is quite good in neutral conditions. As mentioned above, in Lewellen's solution the dispersion parameters are dependent on Ri and Ro. These parameters are computed from observations of wind speed, temperature, and roughness length. There is a correspondence between Ri and Smith's P parameter which Lewellen presents in graphical form.

The second-order closure approach offers, what seems to be at present, the only hope of theoretically determining σ_z for intermediate range for elevated sources, (i.e. $\sigma_z \simeq H/z$), at which range the statistical and gradient transfer theory approaches are both most questionable.

Briggs' Investigations of Very Stable Flows

Recently G. A. Briggs has been working on the problem of dispersion in very stable conditions. He has adopted the limiting form of K_m from the Monin-Obukhov similarity theory. Results of his work have not been published as yet.

SECTION 6

EFFECT OF RELEASE ALTITUDE ON DISPERSION PARAMETERS

HORIZONTAL SPREAD

Pasquill (1975) has summarized our limited understanding of the properties of the crosswind component of turbulence. In neutral flow the important eddy size range is independent of height. For crosswind spread in neutral conditions, the statistical theory ought to be appropriate, except for large distances downwind where, because of the large depth of the plume, wind direction change with height induces an enhanced crosswind spread. Pasquill estimates this distance to be greater than 5 km for an elevated source. For a gound level source the critical distance is larger, approaching 12 km.

For non-neutral conditions we do not know enough at present about the properties of turbulence to be able to predict the effect of release altitude.

VERTICAL SPREAD

As noted in Table 2 the statistical theory has proven useful in describing the vertical spread from an elevated source at short and intermediate distances, essentially upwind from the point where significant portions of the plume touch the ground. Otherwise, we are at present unable to specify the effect of elevation of the source in any definitive way.

Appendix 1: Symbols

C	time averaged concentration of passive material
C_m	maximum ground level time averaged concentration of passive material
C_{max}	maximum concentration during a transect of the plume
c_p	specific heat at constant pressure
g	acceleration of gravity
ΔH	plume rise due to bouyancy and inertia
H	height of the plume centerline above the ground
h_s	physical stack height
i	intensity of turbulence; e.g. $i = \overline{(u'^2}^{1/2}/\overline{u})$ etc.
H_F	vertical heat flux
ℓ	scale of turbulence
n	frequency
n_m	frequency at which $nS(n)$ is a maximum
λ_m	equals $\overline{u}/n_m$
Q	source strength
T	total sampling period
T_L	Lagrangian time-scale
T	absolute temperature
P	Smith's stability parameter
w_*	Deardorff's scaling velocity = $\left(\frac{gH_F z_i}{\rho c_p T}\right)^{1/3}$
t_*	equals $w_* t/z_i$
t	time
z_i	height of the inversion above the surface
z_o	roughness length
β	ratio of Lagrangian and Eulerian time-scales

L	equals $2K/\bar{u}$, a scaling length in Moore's formulation for power plant plumes; also Monin-Obukhov length scale
x,y,z	distance downwind, crosswind, and vertically upward, respectively
$\bar{u}$	average wind speed
t	time
x_m	distance downwind to the point of maximum concentration
x'	equals $\sigma_z \sqrt{2}/H$
y'	equals $y/a_o H$
ρ	density
σ_y^2	lateral variance of the concentration of the diffused material
σ_z^2	vertical variance of the concentration of the diffused material
σ_θ^2	variance of wind direction
σ_ϕ^2	variance of elevation angle of the wind
K	eddy diffusivity
ε	rate of dissipation of turbulence energy
Ri	Richardson number
Ro	Rossby number
θ	potential temperature or wind direction or angular crosswind of a plume
h	vertical dimension of a plume of windborne material, conventionally defined by a concentration of material 1/10 of the ground level or centerline value
u_*	friction velocity
a_o	a constant independent of x
S	a stability parameter; $S = \frac{\partial\theta/\partial z}{\bar{u}^2}$

S(n) spectral density as a function of frequency, $\int S(n)dn = \sigma^2$

u',v', w' components of velocity downwind, crosswind, and vertical, respectively, representing fluctuations from the mean, i.e., $u = \bar{u} + u'$

Appendix 2: Relationships Among Turbulence Categorizing Schemes

For convenience in reading this report we will detail briefly some of the relationships among turbulence categorizing schemes. Gifford's (1976) study contains a table (Table 4) showing relations among the various parameters and methods. Table 2 in this report is essentially the same as Gifford's, except for some deletions and additions; e.g. since Turner's categories are not used in the Workbook but rather Pasquill categories, those are deleted.

The first column on the left contains the Pasquill categories. These are based on solar insolation, surface wind speed, and cloud cover. A refers to the most unstable category and F to the most stable, D being neutral.

Category G is sometimes used in the U. S. in conjunction with dispersion parameter curves under very stable conditions. (See the discussion in Gifford, 1976 as to the origins of this category.)

The column labeled BNL represents the Singer-Smith or Brookhaven method of classification. This method is based on wind-vane direction traces. The vane is used to measure variations of wind direction in the horizontal plane. The standard deviation of this angle, σ_θ, can be related to Pasquill categories. (See Slade, 1968 for details).

The Richardson number is defined as

$$Ri = \frac{\frac{g}{T}\frac{\partial\theta}{\partial z}}{\left(\frac{\partial\bar{u}}{\partial z}\right)^2} \tag{49}$$

This is a nondimensional parameter expressing the ratio of two turbulence producing mechanisms in the atmosphere, i.e. buoyancy and mechanical production. It is often necessary and desirable to approximate the

Richardson number by measuring temperature and windspeed differences over a separation of a few meters in height. In that case a simple finite difference approximation is

$$Ri \simeq \frac{g}{T} \frac{\Delta\theta \Delta z}{(\Delta u)^2}$$

($\Delta\theta$ and Δu being the differences in windspeed and temperature between the height difference Δz. Richardson number, at heights other than near the ground, can be computed using a similarity law established by using experimental data (Businger, et.al., 1971)

The column label L is the Monin-Obukhov length scale and is defined as

$$L = \frac{-u_*^3 \rho c_p}{\frac{kgH_F}{T}} .$$

This parameter is a scaling length which is used to describe atmospheric turbulence. Note that the value of L corresponds to the distance from the ground where the mechanical production of turbulence term equals the buoyancy production term (Pasquill, 1974).

By comparison with the U. S. Nuclear Regulatory Guide 1.23, one can see that the temperature change with height column has been omitted. The use of temperature change with height is incorrect since it contains provision for only one of the turbulence production mechanisms. However, as a practical tool it continues to be favored by some groups, because of a lack of demonstrated inferiority to other systems in dispersion calculations, and difficulties in measuring many of the other parameters. For example, Pasquill's system requires either an observer or instrumentation recording wind speed, solar insolation, and cloud cover. The BNL and σ_θ methods require a windvane and (possibly) electronic averaging circuitry. Often vane response under low wind speed conditions is very unreliable.

The Monin-Obukhov length L requires sophisticated measurements of turbulence parameters making its direct measurment impractical.

RELATIONS AMONG TURBULENCE-TYPING METHODS
(From Gifford, 1976 Tables 1 and 4)

Pasquill[(a)]	BNL[(b)]	σ_θ[(c)]	Ri(at 2m)[(d)]	L[(e)]
A	B_2	25°	-1.0 to -0.7	-2 to -3
B }	B_1	20°	-0.5 to -0.4	-4 to -5
C }		15°	-0.17 to -0.13	-12 to -15
D	C	10°	0	∞
E		5°	0.03 to 0.05	35 to 75
F	D	2.5°	0.05 to 0.11	8 to 35

(a) Pasquill (1961 or 1974)

(b) Philadelphia Electric Co. (1970) (see below)

(c) Slade (1968)

(d) Pasquill and Smith (1971)

(e) Pasquill and Smith (1971)

B_2: range of fluctuations of wind azimuth between 40° and 90°

B_1: range of fluctuations of wind azimuth between 15° and 40°

C: fluctuations of wind azimuth exceed 15° but trace is "solid" and unbroken

D: fluctuations of wind azimuth very small (approximating a line) short-term fluctuations not exceeding 15°

(Fluctuations are recorded over a one hour period)

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TECHNICAL REPORT DATA *(Please read Instructions on the reverse before completing)*		
1. REPORT NO. EPA-600 /4-76-030a	2	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE ATMOSPHERIC DISPERSION PARAMETERS IN GAUSSIAN PLUME MODELING. Part I. Review of Current Systems and Possible Future Developments		5. REPORT DATE July 1976 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) A. H. Weber		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Geosciences North Carolina State University Raleigh, North Carolina 27607		10. PROGRAM ELEMENT NO. 1AA009 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711		13. TYPE OF REPORT AND PERIOD COVERED In-house Sept. 75 - Mar. 76 14. SPONSORING AGENCY CODE EPA-ORD
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

A recapitulation of the Gaussian plume model is presented and Pasquill's technique of assessing the sensitivity of this model is given. A number of methods for determining dispersion parameters in the Gaussian plume model are reviewed. Comparisons are made with the Pasquill-Gifford curves presently used in the Turner Workbook. Improved methods resulting from recent investigations are discussed, in an introductory way for Part II of this report.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution *Atmospheric diffusion *Wind (meteorology) *Plumes *Mathematical models	Gaussian plume	13B 04A 04B 21B 12A
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 69
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)