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DEVELOPMENT OF AN ATMOSPHERIC TRANSPORT MODEL

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ABSTRACT

The dilution of material released to the atmosphere depends on the time of travel and the lateral and vertical growth of the cloud. It is shown that diffusion data stratifies well in terms of stability when plotted in terms of the travel time, a significant improvement on the usual distance relationships. The lateral growth, σ_y , varies as the first power of time, t' , initially and varies as $t'^{1/2}$ in the limit. σ_y can be uniquely determined from the standard deviation of the wind direction and the mean wind speed, statistics which are routinely recorded. These results permit the assessment of the consequences of rather long releases in which exposure isopleths may take complex forms.

Introduction

The distribution of concentration or exposure that is a consequence of a release of material into the atmosphere is often represented as bivariate normal. That is, the values for exposure along slices taken across and vertically through the plume are distributed in a bell-shape curve with the peak value near the height of release and in the direction of the mean wind. The bivariate normal model has been verified reasonably well with experimental data for releases of short duration (say 1/2 hour), departures being tolerated because of the tractability of the equation. This diffusion equation in its simplest form is

$$E = \frac{Q}{\pi \bar{U} \sigma_y \sigma_z} \exp \left[-\frac{h^2}{\sigma_z^2} \right] \exp \left[-\frac{y^2}{\sigma_y^2} \right] \quad (1)$$

E (curie - sec/m³) is the air exposure; h (m) is the height of the source, usually easily determined; Q (curies) is the total amount released, assumed to be known, but often of some doubt; $\bar{U}$ (m/sec) is the mean wind speed in the layer in which the material moves. For the meteorologist, the parameters of particular interest are σ_y and σ_z , the standard deviations of the exposures crosswind and vertically through the plume. For a number of years, two objectives of experimental research have been to determine how these two growth parameters change with distance and to correlate plume growth with observed meteorological variations. The results of these studies have had a practical impact on industry providing guidance in the evaluation of a wide spectrum of problems. Most often the criterion for assessing the consequences of a release is an exposure-distance (or dose-distance) curve characterizing the least dilution from a set of experimental data. The dilution curve is an outer limit, a conservative estimate in the view of the hazards analyst. The second approach to the solution of problems is the direct calculation of the diffusion parameters from observed or expected meteorological variables. How much dilution can be expected given a value for the stability of the air, the wind speed, gustiness, etc.? This, of course, requires a knowledge of what factors are significant and how they are related to dilution. At the present time, meteorologists have not determined all of the significant correlations although progress has been made by many contributors in the last few years.

Research undertaken at Hanford is broad in scope, including both the theoretical and applied aspects of atmospheric sciences. Some results of an extensive analysis of data from atmospheric field tests have recently been published that are relevant to the general diffusion model and useful for engineering analysis. These results found are:

1. Experimental diffusion data when plotted as a function of the travel-time exhibits more order than when the data are plotted as function of distance. This infers (from the diffusion model) that σ_y and σ_z are time-dependent parameters. Not only has it been found that data obtained at a specific site can be best represented in the time-sense, but also that many of the variations that have been observed in data gathered at several sites can be significantly reduced by accounting for the wind speed differences by $t = x/\bar{U}$.
2. σ_y^2 , the horizontal variance, was shown to depend on the travel time, t ; the standard deviation of the wind direction over the period of emission, σ_θ ; and the mean wind speed, $\bar{U}$. The horizontal spread of the plume can be determined for any specific release from data currently being obtained on strip chart recording systems.
3. The horizontal distribution of the peak exposures, E_p , for any travel-time (or distance) can be predicted from these results in two ways:
 - a) Equation (1) can be solved directly if all the parameters are known. However, if the material in the cloud is depositing on the surface, Q then becomes a function of time and an

additional term is required. Because the present accumulated data on deposition are yet too meager to confidently specify the form of this function, an alternate empirical approach is often taken.

- b) For any given substance where experimental exposure maximums and lateral growth, σ_y , can be determined from known meteorological conditions, the distribution is readily constructed assuming normality. The effects of deposition are included in the experimental data plots. It is, however, required that the effluent being analyzed in the practical problem has characteristics similar to those of the atmospheric tracer of the diffusion experiments. Comparisons of data from the zinc sulfide tracer used at Hanford and a number of radionuclides (including I-131) have been favorable. For noble gases, where deposition is negligible, the direct solution of Equation (1) from existing σ_y and σ_z models is suggested. The objective of this paper is to present the concepts derived from analysis of zinc sulfide experimental test data and to demonstrate by example their application in problem solution. These concepts have recently been discussed from the basic viewpoint in the literature; the emphasis here is on application and presentation of supporting data that have not been published.

Diffusion, a time-dependent process

In a practical sense, the analyst is concerned with calculating

the exposure (or concentration) at some fixed distance from the source. Presentation of the results of experimental studies are usually in a form to be easily interpreted by the engineer, that is, as plots of concentration versus distance. From a given set of data, curves characterizing diffusion in stable, neutral and unstable conditions can be delineated. However, the graphical portrayal of the Hanford data in this manner is not at all satisfying. First of all, the scatter about the average lines are quite large. Secondly, the exposure data collected during unstable conditions do not differ from those of the stable cases as much as expected. In some instances, exposures observed in unstable runs actually exceeded those of stable experiments at a given distance, a result requiring explanation. From the applied viewpoint, the objective is to represent the data in such a way as to (1) stratify according to some specified meteorological conditions and (2) reduce the scatter about each group of data. In this way, relatively narrow zones are delineated for the specified stability criterion. Following the results of early theoretical derivations, the Hanford data have been examined in terms of the time required to travel to a fixed distance, this time being calculated as the ratio of the distance and the average wind speed at the release height. The improvement in stratification and, hence, the applicability of the technique as a predicting tool are significant. Figures 1, 2 and 3 show various ways in which air exposures have been presented in the literature. In each figure, E_p is the peak exposure, Q the total quantity of material released, and $\bar{U}$ is

the mean wind speed during the period of release. Figure 1, a plot of $E_p \bar{U}/Q$ versus x (distance), has little correlation, and is of doubtful value. Figure 2, a plot of E_p/Q versus x , shows only small improvement. In the past, most data have been presented in this form. Figure 3 has $E_p \bar{U}/Q$ plotted as a function of the travel time, T . Not only is the variance in the sets of stable and unstable data reduced, but a significant separation of the sets have been achieved. These comparisons have also been made for data collected at other sites. Although organization of the data in terms of travel-time does not show as much improvement as was found for the Hanford set, better stratification was observed in all data groups that were examined.

Lateral Growth, σ_y

The horizontal growth of a plume being emitted continuously will depend on the fluctuations in the wind that occur during the release. A practical problem of interest is that of determining plume growth for releases of several hours. Variations of the wind direction for this interval often will lead to greater plume growth than our present formulas indicate. Present growth models are based on data collected during field diffusion experiments in which release periods were generally less than one hour and, in most cases, are biased towards conditions in which the wind was steady. For releases of $1/2$ hour or less, it has been shown that the variance, σ_y^2 , can be represented in the form of a power law in x , or

$$\sigma_y^2 = \alpha x^p \quad (2)$$

α and p are parameters which supposedly vary with the length of the emission, but, because the experiments were necessarily limited in duration, their values for periods of release longer than one hour have not been determined. Recently, another expression for σ_y^2 has been derived from Hanford experimental data analogous to a theoretical development by G. I. Taylor. Taylor showed, with certain assumptions, that lateral growth depended on the average eddy fluctuations in the wind, a parameter that can be roughly approximated from wind data on existing wind records. In the Taylor model, the variance takes the form

$$\sigma_y^2 = At - A\alpha \int [1 - e^{-t/\alpha}] \quad (3)$$

The parameters A and α have been empirically determined from Hanford experimental data and depend only on the standard deviation of the wind direction over the release period and the mean wind speed:

$$A = 13 + 232.5 \sigma_\theta \bar{U} \approx 232 \sigma_\theta \bar{U} \quad (4)$$

$$\alpha = A/2 (\sigma_\theta \bar{U})^2$$

The solution of Equation (3) with the values of A and α given by Equation (4) is shown in Figure 4.

The constant, 232, is related to the average size of the atmospheric eddies characterizing the turbulence at the site. This value yields good results for growth in the mountain-valley regimes at Hanford and Arco, Idaho, but appears to be a factor of two higher than the appropriate value for those tests conducted over the very flat terrain at

Cape Kennedy, Florida and at O'Neill, Nebraska. Because the constants that are in the lateral growth equation were calculated from data obtained from a release of material near the ground surface, a question arises as to whether it can be appropriately applied to instances in which the release comes from some height above the ground. During 1956 and 1957, some lateral growth and associated wind data were obtained from a series of releases at the 200-foot level of the Hanford Meteorology Tower, which served as an independent data set to test Equation (3) with the derived dependence in Equation (4). The results of this independent test shown in Figure 4 are as encouraging as similar verifications made with ground release data, giving no cause to reject extrapolation in the lower few hundred feet of the atmosphere.

σ_y has been expressed through empirical fitting of experimental data, firstly, as a function of distance and, secondly, as a function of travel-time and wind variability. If these relationships are derived with these same data, what contribution has been made? The time-wind variability concept offers two advantages of direct importance in solving applied problems that the power function does not. First of all, the accounting for the wind variability permits more precise prediction than is possible with the simple power law form. This is well illustrated by using the data from which Healy developed a power function relation and comparing the predictions given by the two relations. Figure 5 shows the summary of this test, and there is no doubt that the inclusion of wind variability as a factor leads to a significantly

improved prediction. This is quite evident in spite of the fact that these are the same data (dependent sample) from which Healy's power law was derived, but was an independent set for verification of $\sigma_y - t$ equation. A second advantage inherent in the time-wind variability form is that the variations in growth brought about by the nature of the wind fluctuations over longer and longer release periods are predicted. Healy, for the power function form $\sigma_y^2 = \alpha x^p$, gives two sets of values of α , p characteristic of releases of a few minutes and for releases of 1/2 to one-hour duration. Following this procedure, it is required that more field experiments of varying release times be performed to determine the time dependence of α and p . The effects of the wind fluctuations brought about by changing the length of the release are determined by the $\sigma_0 \bar{U}$ factor in the new model. Present-day limitations in field technology limit the length of the release, making it difficult to obtain independent data to test the model for long releases. However, some data for release periods up to 3-1/2 hours have been checked, and these results, some which will be presented in a later section, are encouraging.

Exposure

Equation (1) relates the normalized exposure, $E\bar{U}/Q$, to the lateral growth, σ_y , and vertical growth, σ_z , of the plume. As stated earlier, the deposition phenomena introduce complexities that have not yet been solved. It is required that the deposition factor be defined in order that the σ_z parameter can be evaluated. For depositing materials, like

zinc sulfide, a direct and simple approach was taken to evaluate $E_p \bar{U}/Q$. Recognizing that (1) σ_y depends on wind variability, $\sigma_\theta \bar{U}$, (2) σ_z depends on the stability (some index like the Richardson number of stability ratio) and (3) that the time-dependence of diffusion appears justified, the parameters essential for constructing a meaningful, useful nomogram are identified. Figure 6 shows the summary of data from 46 high quality experiments where $E_p \bar{U}/Q$ has been plotted against T and the data have been stratified according to joint intervals of Ri and $\sigma_\theta \bar{U}$. The solid lines are the averages within each group; the dashed lines are the extreme values that were observed for each group. The relatively narrow limits and the separation of the groups are a desired feature of the graph, giving assurance that the selected parameters are the most significant ones. Data which are routinely collected at many stations can now be used as input to determine σ_y and $E_p \bar{U}/Q$.

The Prediction Routine

The results which have been presented permit the calculation of the exposure distribution at ground-level at any distance or travel-time for a release of any duration. The only assumption required is that the cross-wind exposure values are distributed normally. This may appear in some cases a severe restriction, particular for long release periods, but a simple innovation is used which successfully eliminates those difficulties experienced with these more complex situations. If, during the period of the release, trends and meandering of the wind are observed, it is probable that the distribution of the

exposures which result are not normal. In such instances, it is necessary to view the release as not one, but several which occurred end-to-end. For each of the subperiods, the wind is relatively steady, lending credence to the normality assumption. In all actual cases that have been analyzed, this procedure has not proven difficult and the subjectivity of the selection of time intervals has not been shown to significantly detract from the analysis. The remaining calculations are straightforward. The distribution is determined for each interval from the peak exposure given by the nomogram and the standard deviation, σ_y . The peak is centered on the mean direction, θ , observed in that interval. The final distribution is calculated by adding the exposures for the individual distributions. Stepwise, the calculations are as follows:

1. Divide the emission period into as many subintervals as necessary to assure steady wind direction within the period.
2. For each period compute
 - a) $\bar{\theta}$, the mean wind direction
 - b) σ_{θ} , standard deviation of 20-second average wind directions
 - c) $\bar{U}$, the mean wind speed
 - d) Ri , the Richardson number
3. For each period for the time (or distance) of interest obtain
 - a) σ_y (from Equation 3)
 - b) $E_p \bar{U}/Q$ (from Figure 6)
4. Plot the cross-wind distribution for each interval, assuming normality, and centering the distribution on the relevant $\bar{\theta}$.

5. Add the distributions.

Verification

Figure 7 shows the comparison of predicted and observed exposures for a release of 3 hours and 15 minutes. In this period, the wind shifted many times, so that it was necessary to divide that period into 11 intervals. The dotted prediction for the cross-wind exposure 2 miles downwind was obtained following the outline above. The 3 major peaks were predicted. Figure 8 summarizes independent verification of predicted and observed maximums at 3200 meters downwind for 11 releases. The solid dots represent zinc-sulfide releases and the encircled dot is associated with a trace release of elemental I-131.

General Application

The uncertainties associated with the deposition processes indicate that caution must be exercised in extending these results to materials other than zinc-sulfide particulates of diameters to 10 microns. However, it is encouraging that excellent prediction was made for the I-131 release. Furthermore, a comparison of the results obtained with a variety of gases and particulates in tests conducted in many regions of the U.S. shows remarkable agreement with the exposure values for the Hanford zinc-sulfide tracer. Figure 9 shows the comparison of exposure values at Hanford (zinc sulfide) and O'Neill, Nebraska (sulfur dioxide) for stable and unstable conditions. Figure 10 compares data obtained at Arco, Idaho (fluorescein) and Dugway, Utah (fission products) compared with the Hanford data. This analysis indicates that

differences between a variety of materials are not as great as initially expected. These results, however, do not apply to nondepositing agents; it is recommended that Equation (1) be solved directly using Equation (3) and an appropriate form for σ_z .

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FIGURE 1

FIGURE 2

FIGURE 3

$$\sigma_Y^2 = \alpha X^P$$

$$\sigma_Y^2 = A\tau - A\alpha [1 - \text{EXP}(-\tau/\alpha)]$$

$$A = 13 + 232.5 \sigma_\theta \bar{U} \approx 240 \sigma_\theta \bar{U}$$

$$\alpha = A/2 (\sigma_\theta \bar{U})^2$$

FIGURE 4

σ_y (PREDICTED VS OBSERVED) AT X = 2000 FT. FOR
RELEASE AT 200 FEET ON HANFORD TOWER

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10