INTRODUCTION TO
ATMOSPHERIC DISPERSION MODELING

NOTE - This chapter is intended for persons with a sound background in science or engineering but little or no background in meteorology. Persons familiar with air pollution meteorology will want to skip to the Screening Procedures section on page 1-8, which describes the U.S. Environmental Protection Agency's (EPA) guidelines for short-term screening calculations for a stationary source.

As an air pollutant is transported from a source to a potential receptor the pollutant disperses into the surrounding air so that it arrives at a much lower concentration than it was on leaving the source. Atmospheric dispersion models are used to estimate just how much reduction has occurred during transport.

The concentration of an air pollutant at a given place is a function of a number of variables, including the amount of the pollutant released at the source (the emission rate), the distance of the receptor from the source, and the atmospheric conditions. The most important atmospheric conditions are wind speed, wind direction, and the vertical temperature characteristics of the local atmosphere. Most commonly the air temperature decreases with height, which results in an "unstable" atmosphere that tends to mix pollutants into the higher layers of the atmosphere, keeping pollution concentrations moderate or weak at ground level. If the vertical temperature pattern is inverted, such that the upper air is warmer than the lower air, then the atmosphere will be "stable," with calm winds and potentially high pollution concentrations.

The concentration of pollutants often is expressed in terms of the total mass of the pollutant in a standard volume of air. The most frequently used measure in metric units is micrograms of pollutant in one cubic meter of air ($\mu g/m^3$). This measure can be used either for particles or for gases. Concentrations of gases can also be expressed as parts per million (ppm), where 1 ppm represents 1 cubic meter of the pollutant dispersed into 1 million cubic meters of air. A factor can be calculated for each gaseous pollutant to convert from ppm to $\mu g/m^3$, or vice versa. For example, for sulfur dioxide at reference conditions, 1 ppm = 2,620 $\mu g/m^3$.

Types of Dispersion Models

There are three general types of dispersion models: box, plume, and puff. A variation on the box model is the cell model. The

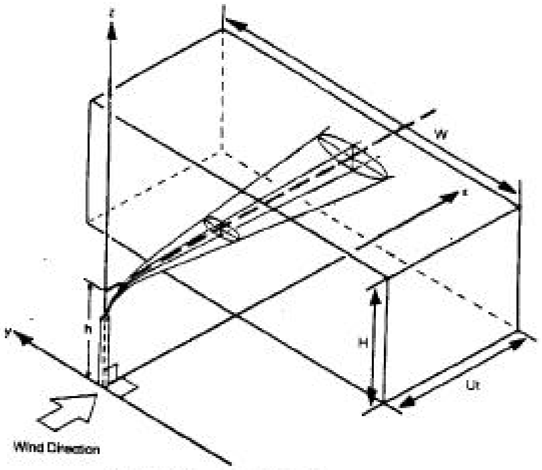

Figure 1-1. Box Model

box model is conceptually the simplest although some relatively complex models have been built on box model foundations. The plume and puff models are more involved and complex models have been constructed using these concepts. In addition to these three types, some very complex models have been developed that attempt to solve the basic physical equations of motion of the air parcels without using the approximations of the box, plume, or puff models.

The box model assumes that the plume from a source has expanded to include the entire area of the downwind face of a box of width W and height H, as shown in Figure 1-1. Thus the box model estimates the average concentration of the plume (or sum of all plumes) at all points on the downwind face. If as much pollutant is to leave the box as enters it in unit time then the thickness of the box is determined by the wind speed and the equation for the concentration is

$$C = c + \frac{Q}{WHU} \qquad (1\text{-}1)$$

where c is the background concentration of pollutants entering the box from the surroundings, Q is the emission rate of the pollutants from the source, and U is the wind speed, which defines the direction x. Often the width of the box may be fixed by some topographic feature, such as the width of a valley. The height may be fixed by the mixing height, a meteorological limit to upward dispersion. Pollutants will tend to be reflected off the atmospheric layer at the mixing height just as they are reflected off the earth's surface, leading to relatively uniform distribution, exactly as the box model assumes. Box models can be very useful as a approximation to define the magnitude of the

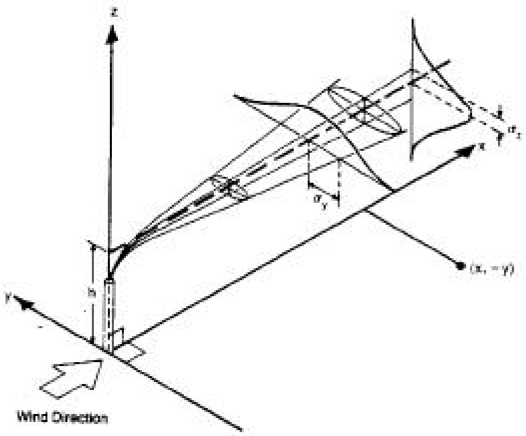

Figure 1-2. Gaussian Plume Model

potential concentration although the limitations should be apparent.

Plume models use a more realistic description of dispersion. Students of fluid mechanics will be familiar with the differential equation that describes the mixture through diffusion of one chemical into a surrounding fluid of another chemical. The solution of this equation is the exponential function that also describes the normal, or Gaussian, statistical distribution. In the Gaussian plume dispersion model the concentration of pollution downwind from a source is treated as spreading outward from the centerline of the plume following a normal statistical distribution. The constants of the distribution are determined by the stability of the atmosphere and the "roughness" of the earth's surface in the vicinity. The plume spreads in both the horizontal and vertical directions, as illustrated in Figure 1-2. The model based on the Gaussian equation is the most widely used plume model and is the basis for most of the computer models distributed by the EPA as a part of UNAMAP (User's Network for Applied Models of Air Pollution, a name that betrays its origins as a time-sharing computer network).

The Gaussian equation for the concentration at a receptor at the surface can be written

$$C = c + \frac{Q}{2BF_yF_zU} \exp\left\{-\frac{1}{2}\left\{\frac{y^2}{F^2_y} + \frac{h^2}{F^2_z}\right\}\right\} \qquad (1\text{-}2)$$

where, in addition to the terms defined for equation 1-1, y is the horizontal distance perpendicular to the wind direction, z is the vertical direction, h is the effective height of the plume (considering the additional height to which the hot gases rise above the physical height of the source), and F_y and F_z are the parameters of the normal distribution, here called the dispersion coefficients.

The Gaussian plume model assumes a flat plane surface between the source and the receptor. This will be a reasonable assumption for most sources relatively near the surface, for flat or gently rolling topography, and especially for neutral stability. With complex topography, such as a receptor at a site where the ground rises quickly from the base, a model which is designed to consider this, such as the Valley UNAMAP model, should be used.

Gaussian plume models have been developed for point sources (e.g., stacks), line sources (e.g., roads), and area sources (e.g., spoil piles). The basic Gaussian plume model assumes a point source. Line sources can be approximated as a series of point sources or a model that is specifically designed for line sources, such as the UNAMAP model HIWAY2, can be used. Area sources can be approximated by assuming the source is further away from the receptor than it actually is, such that the plume is already as wide as the area source at the correct distance. This is called a virtual point source. A different approach is to integrate over the area using the "narrow plume approximation." This is done in the UNAMAP models RAM and ISC. If the receptor is reasonably near the source and the angle between the wind direction and a line between the source and receptor is not greater than 45° the values obtained from a virtual point source estimate and a narrow plume approximation calculation will be roughly the same.

Concentrations from short time emissions, such as the spill of a volatile chemical, are better estimated with a puff model. A puff model assumes a sequence of individual puffs of pollutant are released from the source. These puffs are then allowed to grow in the horizontal and vertical using the same dispersion coefficients that are used with the Gaussian plume models. However, the individual puffs can be modeled with wind speeds and directions that change with position and time. This will also allow more accurate portrayal of conditions in an area of complex topography. The significantly greater computer resources that are required to keep track of each of the puffs and move them along restricts the use of puff models to those circumstances where they are specifically required.

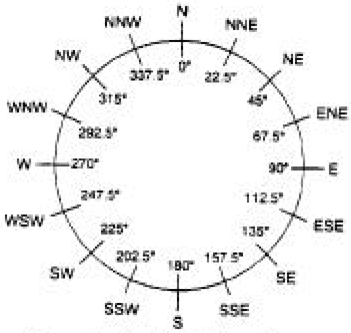

Figure 1-3. Wind Directions

Meteorological and Dispersion Variables

Most dispersion models measure the wind direction in terms of the direction that the wind is coming from, with winds out of true North as O° and winds out of true South as 180°. Winds can and do blow, at some time, from all of the 360° possible. When average wind directions are reported wind directions are grouped into 22.5° wide sectors, lying 11.25° on each side of a compass direction and labeled with the compass direction name, as shown in Figure1-3. Annual average frequency distributions of the wind directions and windspeeds are termed a "wind rose" and are available from the National Climatic Center(Asheville, N. Carolina) for National Weather Service (NWS) stations and from most local air pollution agencies.

The dispersion coefficients, F, define the spread of the plume. As with the normal distribution, 67% of the pollutant is assumed to be within ±F of the centerline of the plume. Thus a plume may be described as being approximately four to six F wide. The value of F is determined by the magnitude of the turbulence in the atmosphere, that is the size of the atmospheric eddys that move the pollutants about. These eddys may be easily observed as rolling and tumbling motions at the edges of plumes and in cumulus clouds. The larger eddys, and larger values of F, will be observed during periods when the atmosphere is unstable. The smaller eddys, and smaller values of F, will be observed when the atmosphere is stable.

Measurements of F have been made under a variety of atmospheric conditions. The measurements of F used in virtually all the UNAMAP models are those published by Turner' (called the "Pasquill-Gifford coefficients") from data taken in open, rural surroundings. Because of their origin they are appropriate for dispersion estimates in rural settings but less so for urban areas. The greater surface roughness and greater release of heat at the surface means that atmospheric conditions in urban areas are seldom as stable as in rural areas. The EPA Valley model compensates for this by using the dispersion parameters for neutral conditions when stable conditions are reported. An alternative approach is to use the measurements of dispersion made by McElroy and Pooler' in an urban area. These data are used by EPA in its RAM urban model.

The measurements of the Pasquill-Gifford coefficients were made over periods of 10 to 20 minutes and are strictly applicable only to such short time periods. They are applied to averaging periods of one hour as a conservative (over-) estimate of the one-hour average concentrations. Over a longer time the wind direction and stability cannot be expected to remain the same. In order to calculate long-term (e.g., annual) average concentrations it is necessary to take into account the wind speeds, direction, and atmospheric stability over the entire period. A report of the annual frequency distribution of wind speed, direction, and stability (called a "STAR" - STability ARray - or 'stability wind rose") observed at a nearby NWS station can be obtained from the National Climatic Center.

Table 1-1. Rule for Estimating Pasquill Stability Classes[3]

Insolation		Surface Wind Speeds (m/s)				
		<2.0>	2-<3.0	3-<5.0	5-<6.0	≥6
	Strong sun	A	A-B	B	C	C
Day	Moderate sun	A-B	B	B-C	C-D	D
	Weak sun	B	c	C	D	D
Day/ Night	Overcast	D	D	D	D	D
	Thin overcast or _					
Night	≥0.5 cloud cover	-	E	D	D	D
	≥0.4 cloud cover	-	F	E	D	D

The stability of the atmosphere is generally described as being in six classes, labeled A through F. Classes A through C are unstable conditions, class D is neutral, and classes E and F are stable. The most frequently observed classes are C, D, and E. The class can be estimated for any hour from readily available meteorological data. Analysis of the conditions that lead to more or less stable atmospheric conditions has resulted in a simplified rule, which is given in Table 1-1. In this table "Strong sun" refers to clear or partly cloudy hours with a sun angle (from the horizontal) of greater than 60°, "Moderate sun" refers to a sun angle less than 60° but greater than 35°. The sun angle will depend on the time of day, the day of the year, and the latitude of the observing site. Tables of sun angle and computer programs that calculate the sun angle are available. Estimates of the amount of cloud cover are routinely made at airports and NWS stations.

Although Gaussian dispersion model computer programs will generally allow a calculation of concentration estimates for any distance our understanding of dispersion and the dispersion coefficients decreases with distance. Additionally, it becomes much less probable that the stability class will not change as the travel time from the source increases. Thus as the distance from the source increases from a few kilometers to 10 kilometers confidence in the results decreases. Beyond 10 kilometers the confidence is significantly less. Special models that are specifically designed for long-range transport estimates must be used for distances beyond 100 kilometers.

Another important meteorological variable is the mixing height, which is the height to which pollutants can be expected to readily mix in the atmosphere. Under stable atmospheric conditions the mixing height can drop to less than a hundred meters. This can trap pollutants in a very thin layer near the ground and result in high concentrations. Pollutants trapped above the mixing height also can cause high concentrations when the mixed layer at the ground lifts and suddenly brings the pollutants to the ground. This process, called fumigation, is transient and rarely lasts for more than 1 to 2 hours, although it can cause some of the highest ground-level concentrations. It is not modeled by a Gaussian plume model. Average night and morning mixing heights in the United States range from 400 to 700 meters. Average afternoon mixing heights range from 800 to 1600 meters. Data which allow the computation of the mixing height are collected at the few upper-air NWS stations.

However, the NWS does not routinely reduce these data to estimate mixing heights. As an alternative, mixing heights may be approximated by ceiling height data from an airport or any NWS station. Maps of average seasonal mixing heights (and wind speeds) for the conterminous United States have been published by Holtzworth[4].

Most Gaussian dispersion models take into account the reflection of the pollutants off the ground and the atmospheric layer at the mixing height. The Bierly-Hewson plume trapping formula generally used with the plume models assumes that the pollutant is uniformly mixed between the ground and the mixing height after about five reflections. Beyond that point the Gaussian plume model behaves like a box model.

Most dispersion models also take into account the additional height above the source that the-hot gases rise to above the physical height of the source. The Briggs[5] plume rise formulas which are used in most of the UNAMAP models use empirical formulas (which were developed from a theoretical base) to calculate the plume rise from the stability class, the wind speed, and the temperature and flow rate of the stack gases. In some of the more recent UNAMAP models, such as PTPLU, the Briggs plume rise calculations also permit consideration of momentum plume rise and stack tip downwash.

Another complication that should be considered when using a dispersion model is the increase in wind speed with height above the surface. The increase is logarithmic with height up to about 100 meters. Thus the wind speed at the top of a stack may be quite different from the wind speed at the measurement station. The Gaussian model assumes that the concentration at ground level is determined by the concentration at the plume centerline, which is partly determined by the wind speed at the plume elevation. Thus the correct wind speed to use in making estimates is the wind speed at the plume height or, at least, the wind speed at the source height. The wind speed at any height (up to about <u>100</u> meters) can be estimated from the equation

$$U = U_O(Z/Z_o)^P \qquad (1\text{-}3)$$

where U is the wind speed at height z, U_O is the wind speed at height z_O, and p is the wind profile exponent. The three sets of wind profile exponents used in the UNAMAP models are given in Table 1-2. Using the wind speed at plume height rather than the wind speed measured at the anemometer height can result in a significant reduction in the estimated concentrations.

Table 1-2. Wind profile exponents.

Stability	PTPLU/ISC	RAM Urban	RAM Rural
A	0.10	0.15	0.07
B	0.15	0.15	0.07
c	0.20	0.20	0.10
D	0.25	0.25	0.15
E	0.30	0.40	0.35
F	0.30	0.60	0.55

Most of the UNAMAP models assume that the pollutant is inert, that is, it is not removed from the plume by reaction or by deposition on the ground. The Valley model allows a "half-life" to be specified for the pollutant. This would be the time for half of the pollutant to be removed from the plume. Sulfur dioxide does react to form sulfate particles and ozone is formed in the air from a reaction involving nitrogen oxides and hydrocarbons but neither of these reactions would ordinarily be considered in modeling these pollutants over the short distances that the Gaussian plume model is most applicable. Gases also will be removed from the plume by being absorbed at the surface but this is not significant over moderate distances. Particles do fall out of a plume, at a rate depending on the particle size. Particles larger than 20 micrometers will fall out rapidly (in less than a kilometer for stacks of moderate height) while particles smaller than 0.5 micrometers will remain airborne almost indefinitely.

Screening Procedure

The EPA recommendS3 the following procedure for an initial screening of short term air pollutant concentrations from point sources. First, if there is no significant building or topographic feature that may cause stack downwash, use PTMAX to obtain the highest concentration with A, C, E, and F stabilities. In addition, take the concentration for C stability at 2.5 m/second and double it. The maximum expected concentration from the Gaussian model is the largest of these five values. If downwash may be significant it is necessary to use PTPLU, which will also make a windspeed at stack height correction and take bouyancy induced initial dispersion into account. (Stack downwash generally will not occur if the stack gas velocity is greater than 1.5 times the wind speed.) If averaging periods longer than one hour are needed the following factors may be multiplied by the one-hour average to obtain a rough estimate of the concentration for the longer period:

Averaging time	Multiplying Factor
3 hours	0.9 ±0.1
8	0.7 ±0.2
24	0.4 ±0.2

Second, it is necessary to estimate a concentration for fumigation conditions. This cannot be done with the Gaussian model. The approximate downwind distance to the maximum fumigation concentration (in km) can be calculated from the formula

$$X = -9.94 + 0.111\ H + 0.176\ )h \qquad (1\text{-}4)$$

where H is the physical stack height (in m) and)h is the plume rise (that is, h-H; also in m) for F stability and 2.5 m/sec windspeed. Using PTDIS, the F_y and F_z are computed for this distance (but use 2 km if X is less than 2 km) and F -stability. The fumigation concentration is then calculated from

$$C = \frac{Q}{(2B)^{1/2}\ U(F_y + h/8)(h + 2F_z)} \qquad (1\text{-}5)$$

where all the terms are as defined in equation 1-1. This would be a one-hour average concentration and should not be used for longer averaging times.

If it is desired to make a screening estimate for concentrations at a specific location (e.g., a nearby residence or property line) first use PTMAX (except that when stack downwash may be significant, use PTPLU) to estimate the stability and wind speed combinations that will produce the maximum values at the downwind distance of the specific location. If you use PTMAX the windspeed given is the windspeed at the top of the stack, but if you use PTPLU be certain to read off the stack top wind speed from the second set of columns. Now use PTDIS and the maximum wind speed and stability combinations to estimate a concentration at the specific location. Use the plume height (h) for the mixing height for stabilities A-D and 5000 m for E and F. If none of the stability and wind speed combinations produce a maximum value near the specific location make an estimate for each of the following cases:

Stability	Windspeed
A	1,3 m/sec
B	1,3,5
C	1,3,5,10
D	1,3,5,10,20

If more than one stack is to be modeled, first calculate for each stack

$$k = \frac{hVT_s}{Q} \qquad (1\text{-}6)$$

where V is the stack gas flow rate and T_s is the stack (absolute) temperature. The stack with the smallest value of k is used in

PTMAX to select the maximum wind speed and stability conditions. Then use PTMTP for modeling the concentrations either at a specific point or over a network of points.

If the ground is not relatively flat in the vicinity of the source it will be necessary to use a model that takes topography into account. The Valley model can be used in a screening mode for a 24-hour average concentration by selecting the short-term option and using 6 hours of F stability with a wind speed of 2.5 m/s.

Conversion Factors

Most of the input data for the UNAMAP models are required to be i.n metric units. Conversion factors from the more common English units to metric units are given in Table 1-3.

References

1. D. Bruce Turner, Workbook of Atmospheric Dispersion Estimates, Rev. Ed. (Gov. Printing Office, 1970T

Table 1-3. Conversion factors.

To convert from	to	multiply by
Inches	Meters	0.02540
Feet	Meters	0.30480
Miles	Meters	1609.34
Square feet	Square meters	0.09290
Acre	Square meters	4046.86
Feet/second	Meters/second	0.30480
Feet/minute	Meters/second	0.00508
Miles/hour	Meters/second	0.44704
Knots	Meters/second	0.51443
Cubic feet/second	Cubic meters/second	0.02832
Cubic fe-et/minute	Cubic meters/second	0.00047
Grains	Grams	0.06480
Pounds	Grams	453.592
Pounds/minute	Grams/second	7.55987
Pounds/hour	Grams/second	0.12600
Pounds/day	Grams/second	0.00525
Tons(short)/hour	Grams/second	251.996
Tons(short)/day	Grams/second	10.4998
Tons(short)/year*	Grams/second	0.02877
jig/cu meter	g/cu meter	.000001
ppm CO	g/cu meter CO	.001145**

ppm N02	g/cu meter NO_2	.001880**
PPm S02	g/cu meter SO_2	.002620**
ppm H2S	g/cu meter H_2S	.001390**
µg/cu meter CO	ppm CO	8.7336 x 10-4**
µg/cu meter NO_2	ppm NO_2	5.3191 x 10-4**
µg/cu meter SO_2	ppm SO_2	3.8168 x 10-4**
pg/cu meter H_2S	ppm H_2S	7.1942 x 10-4**
°F	°C	0.55556(°F-32)
°C	°K	°C + 273.16

* Assumes constant operation 365 days/year, 24 hours/day
** Valid only at 298 °K and 760 mm Hg

2. J. McElroy and F. Pooler, The St. Louis Dispersion Study, Vol. II (Nat. Air Poll. Control Admin., 1968)

3. L. J. Budney, Guidelines for Air Quality Maintenance Planning and Analysis Vol. 10 (Revised): Procedures for evaluation of Air Quality Impact of New Stationary Sources(U.S. Envir. Prot. Agency, 1977)

4. G. C. Holtzworth, Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States' (U.S. Envir. Prot. Agency, 1972)
5. G. A. Briggs, Plume Rise,(U.S. Atomic Energy Com., 1969)