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Chapter 15B

Odor Modeling

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Abstract: Atmospheric dispersion modeling is an invaluable tool in the control and management of air pollution. It has been used for many years in the regulatory arena for the assessment of the air quality impacts from a wide variety of sources of air pollution, such as powerplant stacks, industrial chimneys, and mobile sources. Dispersion models apply mathematical equations, often modified with empirical factors, to convert a mass emission rate from a source of air pollution to an ambient air concentration at some distance downwind of the source. It has been found that atmospheric dispersion modeling can also be an extremely useful tool in the assessment of offsite impact to evaluate control and better manage odors. However, there can be significant differences between the traditional pollutant-specific modeling and modeling that is performed for odor assessment. Modeling used for air quality compliance purposes, for example, is usually concerned with fixed time-averaged concentrations for direct comparison to ambient air quality standards and criteria (generally 1 hour to 1 year). Odors, on the other hand, can be recognized on the order of seconds or minutes. In addition, unlike air quality standards which have been quantified based upon exposure and health related responses, the response to odors can be very subjective and are historically based on nuisance. This chapter discusses the techniques used to model odors, and details the differences that must be addressed from both theoretical and practical points of view when applying dispersion models to odor assessment.

Key Words: Odors, odor modeling, odor dispersion modeling, air quality modeling, odor impacts.

1 Modeling for Odors in the Atmosphere

The quality of the air we breathe has traditionally been based on levels of ambient air concentrations of pollutants known to have adverse health effects. However, as "quality of life" emerges as a strong public concern, odor is increasingly linked to air quality. A difficult problem with that association is that unlike specific air pollutants like sulfur dioxide or carbon monoxide, which have quantifiable levels protective of public health (i.e., ambient air quality standards), the perception of odor is subjective and not easy to quantify. For example, in the late 1970s, the United States Environmental Protection Agency (USEPA), given the responsibility of developing regulations for hazardous air pollutants, initially proposed odor regulations. However, these odor standards were never promulgated because the link between odor and health was not established, and odor was considered to be a local issue better left to the states.

Atmospheric dispersion modeling has been an invaluable tool in the control and management of air pollution. It has been used for many years in the regulatory arena for the assessment of the air quality impacts from a wide variety of sources of air pollution, such as power plant stacks, industrial chimneys, and mobile sources. Atmospheric dispersion models apply mathematical equations, often modified with empirical factors, to convert a mass emission rate from a source of air pollution (mass per unit time) to a mass-based ambient air concentration (mass per unit volume) at some specified distance downwind of the source.

Over the years, atmospheric dispersion modeling has also been used for offsite impact assessment in the control and management of odors. This type of odor impact analysis is important for determining effective control strategies, identifying key odor sources, and demonstrating reduced odor impacts within the community. Much of the basic understanding of odor transport can come from an understanding of atmospheric dispersion processes. However, there can be significant differences between the traditional pollutant-specific modeling and modeling that is performed for odor impact analysis. For instance, modeling used for air permit purposes is concerned with time-averaged concentrations for direct comparison to ambient air quality standards (generally 1 hour to 1 year), whereas recognition of an odor can occur on the order of seconds. In addition, air quality standards, developed to protect the public, are based upon quantifiable health effects, whereas nuisance odor thresholds are highly dependent upon the receiving population, so that one person's nuisance odor can be another person's sweet perfume or fondest memory. These differences must be understood before selecting a dispersion model and modeling methodology for predicting odor impacts.

2 Odor Measurement

One distinction between standard dispersion modeling and odor modeling is in the characterization of the odors themselves. Modeling performed for air permits or environmental assessments generally evaluate the transport of known pollutants and use pollutant-specific mass emission rates. Emission rates or emission fluxes, in units of mass emitted per unit time and mass per unit time per unit area, are determined from source sampling, emission factors, or theoretical emission formulas. Likewise, concentrations at the receptor are generally in terms of mass concentration in units of mass per unit volume. Odorous emissions, on the other hand, may often be complex combinations of compounds, where the components can sometimes be identified, but are not necessarily quantitative indicators of the odor itself. In addition, odor-emitting facilities, such as wastewater treatment plants or animal feedlots, may generate a number of different odors from a number of different processes, and the fate of these odors as they are transported with the wind is difficult to determine. In the face of such complex emissions, a single indicator compound with a low odor threshold and high emission rate has sometimes been used as representative of the sources under consideration; however, this approach can lead to significant underestimation of odor impacts offsite (Duffee and O'Brien, 1992).

Odor is currently evaluated by five parameters:

Character Odor *character* or odor quality is reported in terms of standard descriptors, such as "fruity," "earthy," "musty," etc. Odor observers are trained to use such standardized descriptive terminology in order to identify an odor.

Hedonic Tone *Hedonic tone* measures the pleasantness or unpleasantness of the odor, independent of the character. Different scales may be used. The most common is a 20-point scale, where 0 would be neutral, +1 to +10 would be pleasant, and -1- to -10 would be unpleasant. This is a subjective parameter since the pleasantness or unpleasantness of an odor is often based on the experience and memory of the person smelling the odor.

Intensity Odor *intensity* is the relative strength of the odor above the threshold. This is often referenced against a standard odorous gas, such as n-butanol. Using the standard n-butanol method, a device called a butanol wheel delivers varying concentrations of butanol in odor-free air to eight sniffing ports. The concentration of n-butanol in the mixture at the ports has an increasing concentration ratio of 2 on a binary scale. The odor *intensity* is then expressed in terms of parts per million of n-butanol by volume of air.

Concentration The *detection threshold* can be defined as the lowest concentration of a substance that can be detected above a blank (odor-free) sample by an odor panel. The *recognition threshold* (RT), on the other hand, is the lowest concentration of a substance that can be recognized based upon the character of the odor. Published *odor threshold* values for specific compounds have generally been derived in the laboratory, and represent the concentration at which the "average" person can detect a compound. These *odor threshold* values can vary widely for a given population and a given odor. Hydrogen sulfide (H_2S), for example, has reported *odor thresholds* that vary from 1 ppb to 130 ppb (IAH, 1989). Another method of presenting odor concentration is the concept of a dilution to threshold ratio. The *dilution ratio* (*D/T,* dilutions to threshold value) is the estimated number of dilutions with equal volumes of clean air needed to make the odor non-detectable. When dealing with odors that are complex mixtures of compounds, concentration is denoted in terms of dilutions or odor units per unit volume.

The highly subjective nature of our response to odors makes odors very difficult to assess and quantify. Odors can trigger both physiological and psychological responses. While research continues in an effort to develop instrumentation that can objectively measure odors, the industry standard for measuring odors today is with the use of a trained *odor panel* using a *dynamic olfactometer*. The olfactometer has a sniffing port supplied alternately with three samples; one sample contains a diluted sample of the odorous gas, the remaining two are odor-free air. Trained individuals making up the odor panel are asked individually to select which of three samples presents an odor different from the other two (Figure 1). The concentration of odorous gas is then increased until the odor is detected or recognized.

Figure 1. Dynamic dilution olfactometer test (courtesy of St. Croix Sensory).

Another odor sampling device, called a field olfactometer (or *scentometer)*, measures odors directly in the field by varying the proportions of ambient air and air filtered through activated carbon (to remove the odors) that is introduced to the individual using the instrument. The ratio of the ambient air to the carbon-filtered air at the point where the odor is detected is the *dilution to threshold* value of the odor. Figure 2 shows one of the newest versions of the field olfactometer.

Persistence The rate of change of intensity with odor concentration is called the *persistence*. While it seems logical to assume that the intensity of an odor is related to its concentration, the rate of change of intensity with odor concentration is not the same for all odors. Intensity and odor concentration (in D/T) are plotted on a log-log scale and the flatter the slope, the more persistent the odor.

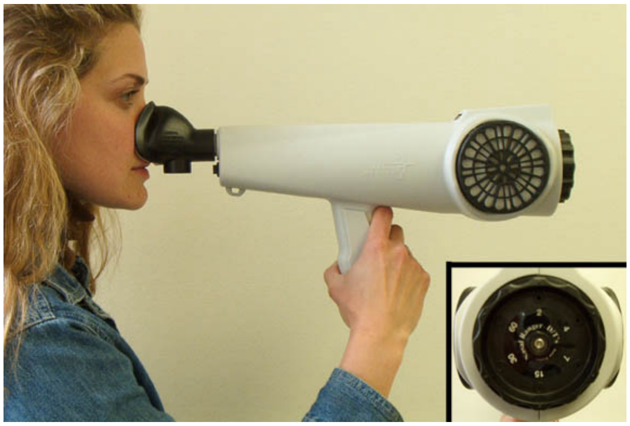

Figure 2. Field olfactometer (courtesy of St. Croix Sensory).

Field olfactometers commonly have D/T ratios set at 2, 4, and 7, which are in the range of existing standard ambient odor guidelines. Additional D/Ts such as 15, 30, 60 and higher dilution ratios are also available.

3 Odor Modeling-Related Issues

Differences between traditional dispersion modeling and odor modeling appear in at least three areas: at the source of the odors (wastewater treatment plant, rendering plant, etc.), en route from the source of the odors to the receptor, and at the receptor (i.e., the human nose). Often, the methodology used for an odor assessment will be based upon consideration of only one of these factors (e.g., the short detection or recognition time characteristic of odors at the receptor) without regard for the effect of the other factors. This can lead to results that appear to overlook the physical phenomena associated with the project. Therefore, it is important to look at the "big picture" before deciding on the appropriate approach when planning an odor assessment.

3.1 Source Characteristics

In general, most sources can be categorized as a point, area, or volume source. Sources responsible for odor complaints are generally continuous sources (e.g., stacks, scrubbers, or basins); although routine but instantaneous or very short-term releases (e.g., from digester pressure release valves at wastewater treatment plants) can also pose problems at nearby receptors. Depending upon the rate of release relative to odor perception's short time frame, intermittent sources can be classified as either continuous sources (release rate on the order of minutes or longer), or instantaneous sources (release rate on the order of seconds).

If the odors can be characterized by distinct chemicals, or if different odorous sources at a facility can each be characterized by distinct chemicals, then the model emissions can be put in terms of the individual mass emission rates.

Assuming that there are no significant chemical reactions that occur during the transport process, the odor model is not much different from the traditional air quality model. When dealing with complex odorous emissions, the odor emission rates are generally modeled as D/T or odor units (ou) per unit time (for point or volume sources), or per unit time per unit area (for area sources). This "odor emission rate" is based upon determining a source concentration in D/T or odor units and multiplying this concentration by a volume flowrate or flux at the source. An important distinction between modeling a single odorous compound, such as H_2S, as opposed to a complex odor comprised of multiple compounds is the interactive nature of odors. Models can easily and appropriately assess single compound-specific odors in terms of mass concentrations. However, it may not be appropriate to use models to assess the cumulative offsite odor impacts from different sources or different processes at a single facility (e.g., odors from the headworks and odors from the digestion process at a wastewater treatment plant), in units of D/T, unless the odors from these sources and processes are similar.

Whatever the method used to determine the odor emission rate at the source, it is important that the emission rate is truly representative of that particular source, whether the emissions are stated in terms of mass per unit time, or as D/T or odor units per unit time. This generally will require that site-specific source sampling be conducted in order to determine the odor emission rate.

3.2 Effect of Averaging Time

There are a number of locations where time and time-averaging come into play in odor modeling and odor assessment.

At the source A source emits odors at some rate, duration, and frequency. The odors can be emitted on a continuous basis (for example, odors from an odor control stack), or on a sporadic basis (odors from a pressure relief valve). Continuous odors may be emitted at a single rate, or at a rate that varies over time. Sporadic odors may be emitted for a short or long duration, frequently or infrequently, and regularly or irregularly. Depending upon the rate of release relative to odor perception's short time frame, intermittent sources can be classified as either continuous sources (release rate on the order of minutes or longer), or instantaneous sources (release rate on the order of seconds).

At the receptor At the receptor (e.g., the nose of someone in the community), there is a time associated with detecting an odor, recognizing the odor, and ultimately, a time frame after which the odor is so annoying that the person feels that they must lodge a complaint. Parameters associated with an odor include the concentration, intensity, character, and degree of pleasantness or unpleasantness of the odor, but time-related issues such as frequency and the duration of the odor are also important considerations. A person may detect an odor in a matter of seconds, but the difficult question is what combination of parameters leads to an odor being annoying or offensive enough to complain?

During transport The time it takes for the odors to reach the receptor can play a major role in the perceived nature of that odor. Surface obstructions like buildings and trees, terrain effects like valleys or mountains, and meteorological conditions like wind speed and turbulence during the transport process can have significant influence on the odor levels at the receptor. The effects of travel path and time should be a consideration when designing a modeling analysis.

During sampling In addition to the time scales described above, there are time scales associated with the sampling of odor. The time that is used to fill Tedlar® sampling bags or Summa® canisters, for example, can be varied from minutes to hours depending upon the sampling flowrate. This controls the range of fluctuations that can be measured using such techniques since high fluctuations that occur at smaller time steps will be blended with lower concentrations as the sample is collected. Hence, the sampling time can influence the characterization of source emission rates along with interpretation of the community monitoring results, and should be another consideration in the design of an odor study.

The fact that odor can be perceived in a very short time is often noted; however, what that short time period is and what it represents in odor modeling analyses varies. Important, but not so easily answered questions include:

1. What constitutes an odor impact? Is it exceeding odor detection, exceeding odor recognition, or exceeding some enhanced factor based upon one of these that considers a complaint level?
2. What time frame is most representative of odor impact? While most researchers agree in principle that the perception of odor occurs in a short time, what constitutes "short" in an odor analysis varies significantly.

The question of the appropriate time considerations has been one of the primary distinctions cited for modifying standard dispersion modeling methods for use in odor assessment, or for applying specialized models with features that attempt to account for the concept of time. Since most of the currently used dispersion models incorporate empirical factors which are time-averaged values, such as the turbulent diffusion coefficients, the model output is also related to these averages. If we photograph a plume of smoke from a stack, an instantaneous snapshot of a smoke plume will primarily show the plume meandering around its centerline under the influence of larger scale atmospheric turbulence. As the exposure time increases, the photograph will capture both the meander and the internal spread of the plume; detail within the plume is smeared (from the small scale atmospheric turbulence), and the boundary of the plume will spread with increasing distance and time to account for the plume meander. Far downwind, even the boundary of the time-averaged plume can meander around the centerline under the influence of very large-scale atmospheric turbulence. Figure 3 is a schematic showing the meander and crosswind spread of a smoke plume visualized at increasing averaging times from an instantaneous view to a 2 hour time-averaged view.

Crosswind concentration profiles of the plume would show that the centerline concentration for the instantaneous plume is significantly higher than that for the time-averaged plume, that is, the shorter the sampling time (exposure time following the camera analogy), the larger the fluctuations from the longer (exposure) time mean concentration. In short, the use of a fixed averaging time filters out the very high (peak) and very low concentration fluctuations. Since odors can be perceived within seconds, the issue of averaging time can play a much greater role than in traditional dispersion modeling where longer term averaging is the objective.

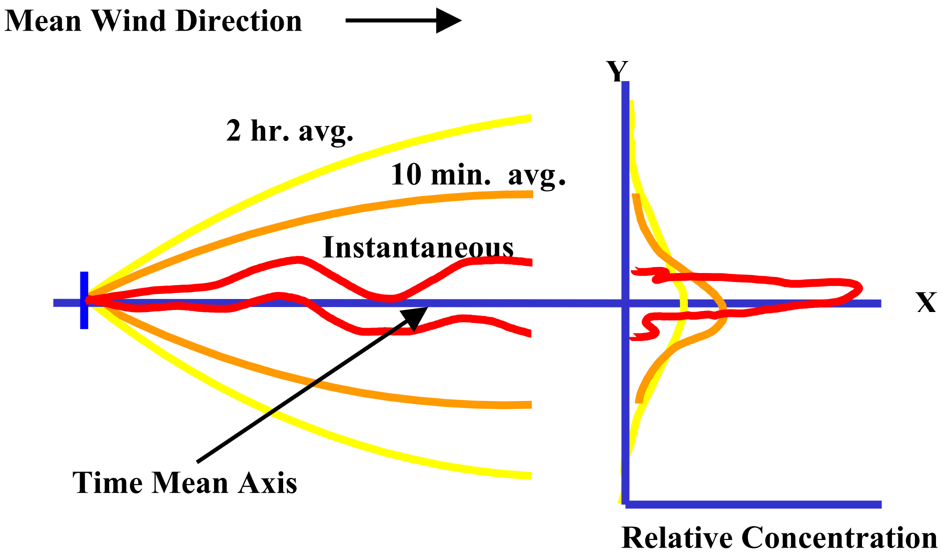

Figure 3. Plume vs. Averaging Time (adapted from Slade, 1968).

Traditional atmospheric dispersion modeling generally assumes that the emissions from a stack are continuous, and that the mass emission rate (mass per unit time) does not vary over the travel time from the source to the receptor. As Figure 3 indicates, measurements of time-averaged concentration profiles downwind of such sources have been shown to approach a bell-shaped, or Gaussian distribution. An instantaneous, or short-term release, such as a puff of gas from a pressure relief valve, however, may have a different release pattern, especially in the near-field region, where the puffs are transported bodily by large-scale turbulent eddies in the atmosphere. Measurement of concentration profiles downwind of these instantaneous or intermittent releases may produce periods of high concentration alternating with periods of zero or very low concentration. Alternative methods may need to be developed to determine these peak concentrations.

The literature presents an assortment of time scales used in odor modeling (Mahin, 1997). Frequent mention is made of the fact that odor can be perceived in a very short time; what that short time period is and what it represents in odor modeling analyses varies. Table 1 presents a listing of some of the time periods that have been used in recently published odor analyses (Diosey, 2001).

Table 1. Examples of Time Scales Used in Odor Modeling.

Time Scale	Criterion	Source
2 second	Odor recognition	Compost facility
30 seconds	4 D/T	Compost facility
< 1 minute	Odor complaint	Compost facility
2 minutes	4 D/T	Wastewater treatment plant
3 minutes	"Nuisance-causing odor complaint"	Wastewater treatment plant
5 minutes	3 D/T	Portland cement plant
5 minutes	5 D/T	Wastewater treatment plant
10 minutes	Odor threshold	Hazardous waste landfill
1 hour	50 dilutions	Compost facility
1 hour	2 D/T	Composting facility
1 hour	1 ppb H_2S	Local environmental quality review odor threshold (NYCDEP, 2001)

Table 1 indicates there is currently a significant variation in both the "effective" time scale used to characterize an odor impact as well as variation in the odor criteria. It is clear that while most researchers agree in principle that the perception of odor occurs in a short time, what constitutes "short" in an odor analysis varies significantly.

Many of the empirical factors used in the dispersion equations are based upon field sampling data collected over finite sampling duration. Most of the models currently approved for regulatory purposes are the so-called Gaussian models. Gaussian models are empirically based and rely on sampling data that are time-averaged, such as the turbulent diffusion parameters, σ_y and σ_z. In addition, Gaussian models assume a steady-state condition. This makes Gaussian-based dispersion models, such as the Industrial Source Complex – Short Term (ISCST3) model and AERMOD model, appropriate for averaging times of 3 minutes to 1 hour. If the odor criterion for a particular odor assessment is on the order of seconds, then the time-averaged formulas could conceivably underestimate a shorter-term peak odor impact.

4 Odor Criteria

In the United States, there are currently no federal odor standards. A number of states and some localities have odor regulations; the majority of these are nuisance laws. However, growing concern over odors from sources such as concentrated animal feeding operations (CAFOs), composting facilities, rendering plants, landfills, wastewater treatment plants, and geothermal energy facilities, especially in an age of development where the traditional buffer zones between such facilities and the community are shrinking or non-existent, has led to surge of interest in measuring and managing odors. Recent surveys of odor standards and criteria used within the United States and in other countries around the world (Mahin and Pope, 1999; Mahin, 1997; and Malcolm Pirnie, 2002) indicate that there are a number of different odor levels currently being used to regulate odors, including the *detection threshold*, the *recognition threshold,* and *odor threshold* (See Table 2).

Table 2 - Odor Standards and Criteria.

Location	Compound	Standard/Criteria
California	Hydrogen sulfide	30 ppbv (1 hr average)
Connecticut	Hydrogen sulfide	6.3 µg/m^3
"	Methyl mercaptan	2.2 µg/m^3
"	N/A	7 D/T
Illinois	N/A	8 D/T (residential), 24 D/T (industrial), 16 D/T elsewhere
Kentucky	N/A	7 D/T (state standard)
Michigan	Hydrogen sulfide	1 µg/m^3 (24 hr average)
"	Methyl mercaptan	10 µg/m^3 (1 hr average)
Minnesota	Hydrogen sulfide	30 ppbv, 50 ppbv (30 min average)
Nebraska	Total reduced sulfur	100 ppbv (30 min average)
New Jersey	N/A	5 D/T (wastewater/solids handling)
New York	Hydrogen sulfide	14 µg/m^3 (1 hr average, state standard)

Location	Compound	Standard/Criteria
North Dakota	Hydrogen sulfide	# 50 ppb
"	N/A	7 D/T non-H_2S
Pennsylvania	Hydrogen sulfide	100 ppbv (1 hr average)
"	"	5 ppbv (24 hr average)
Texas	Hydrogen sulfide	80 ppbv (30 min average, residential/commercial area)
"	"	120 ppbv (industrial or vacant lands)
Quebec	Hydrogen sulfide	10 ppbv (1 hr average)
Alberta	Hydrogen sulfide	10 ppbv (1 hr average)
"	Ammonia	2,000 ppbv (1 hr average)
Ontario	N/A	1 ou/m^3 (10 min average)
WHO (Europe)	Hydrogen sulfide	1.3 ppbv (30 min average, guideline)
Denmark	N/A	0.6 - 1.2 ou/m^3 (1 min average)
Hong Kong	NA	5 ou (5 sec average)
Japan	Hydrogen sulfide	20-200 ppbv (depending on location)
"	Dimethyl disulfide	9-100 ppbv
"	Methyl mercaptan	2-10 ppbv
"	Butyric acid	1-6 ppbv
"	Ammonia	1,000-5,000 ppbv
Taiwan	N/A	50 ou/m^3 (petrochemical park)
Victoria, Australia	Hydrogen sulfide	0.1 ppbv
"	Methyl mercaptan	0.42 ppbv
"	Ammonia	830 ppbv
"	Chlorine	33 ppbv

Due to the subjective nature of odor perception, odor criteria are often site-specific, and developed from actual field sampling data and community-based odor panel assessment. Regulatory odor criteria are sometimes receptor-specific as well. Some criteria are to be met at the fenceline, others at a residence, still others at sensitive receptor locations including homes, schools, nursing homes, churches, etc. Other odor criteria are activated only upon receipt of one or more official complaints. Consideration of what the target level should be and where this target level needs to be met must be included in the odor modeling methodology, since the odor criterion will set the threshold and often the timescale of concern, while the receptor will determine the locations that must be modeled and range of the analysis.

Most odor assessments are performed to either prevent or mitigate odor complaints. Willhite and Dydek (1991) questioned whether the odor threshold is the same as the nuisance level, which is a level that would generate complaints. They noted that the nuisance level appears to be related to the "odor acceptability", which is based upon an individual's attitude and experience with the odor. The results of a field study (Ontario Ministry of Environment, 1988) that they reported implied that people will complain, in general, when the odor reaches approximately four times the odor threshold. They also noted that the levels at which people complain differ for unpleasant and pleasant odors. In this case, those chemicals with unpleasant odors have a complaint level approximately three times the odor threshold, while pleasant odors will not be recognized as a nuisance until the ambient odor levels exceed five times the odor threshold.

5 Odor Models and Modeling Techniques

As with other air pollutants, the dispersion of odors in the atmosphere is primarily a result of turbulence, or eddies in the atmosphere. Atmospheric eddies range from small-eddies on the order of a centimeter, to very large scale eddies, tens of meters across. When there is a continuous plume from a source of odors or pollutants, the smaller eddies in the atmosphere (i.e., smaller than the size of the plume) work to expand the plume around its center, diluting the plume internally as it travels downwind. Field observation of dispersion in the atmosphere also indicates the presence of large-scale, short-term fluctuations in concentration, which is a characteristic feature of atmospheric dispersion. Larger-scale atmospheric eddies work to transport the plume bodily, primarily in the crosswind and vertical directions (meander), while providing little in the way of dilution. In between the smaller and larger scale eddies, those equivalent to the size of the plume both dilute and transport the plume.

If the effects of plume spread and meandering are viewed at a fixed location, (e.g., sampling location along the X-axis in Figure 3), the monitor would "see" periods of turbulent concentration fluctuations as the plume travels past the monitor, and periods of zero concentration, or intermittency, when the plume meanders away from the monitor (see Figure 4). Based upon these observations, the dispersion of the plume can be viewed as the result of two distinct processes: the instantaneous spreading out of the plume in the vertical and crosswind directions (from the small-eddy turbulence), and the meandering, or fluctuation of the entire plume about its mean position as it travels downwind (from the large-scale eddy turbulence). A "true" model of atmospheric dispersion should be able to correctly simulate both of these processes. The mean, or average concentration, can be significantly less than the peak concentrations measured by the monitor.

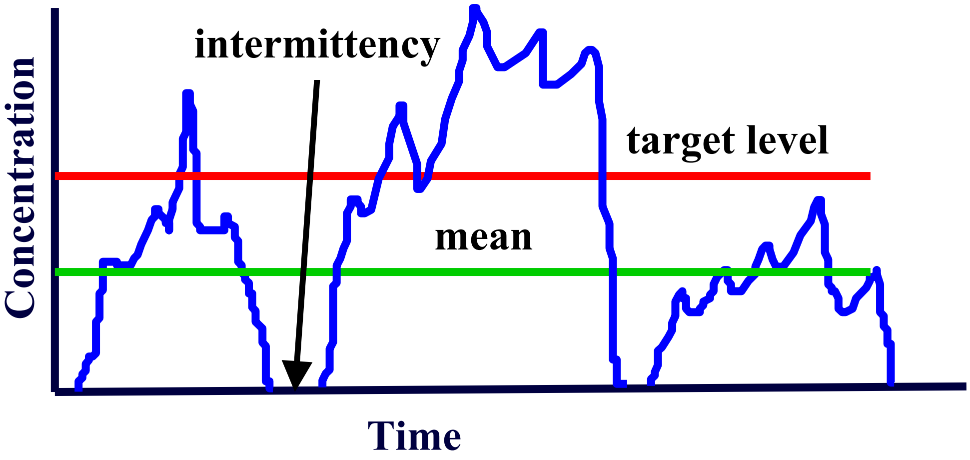

Figure 4. Concentration Timeline (at a fixed monitor).

The ultimate goal of a dispersion model is to accurately predict the odor or concentration of a contaminant as it travels downwind of a source (or sources) under any and all atmospheric conditions. While our understanding of atmospheric processes is increasing rapidly, the complexities are so great that all currently-used models have limitations on their applicability. Models have been developed to evaluate different source types (point, area, volume), different terrain (simple or complex), different locales (urban, rural, coastal), different release rates (plume, puff), different meteorological conditions (stable, convective), and different ranges (short-range and long-range transport). As with other forms of modeling, the model(s) that most closely approximates the parameters of the odor source and the characteristics of the dispersion process under analysis should be selected, and the limitations should clearly be recognized.

5.1 Odor Models

Similar to the decision process used to select the appropriate model for regulatory air quality modeling, the selection of the appropriate dispersion model for odor assessment starts with the source type and release scenario. In general, most sources can be categorized using the traditional designations of point, area, or volume sources. The sources responsible for most odor complaints tend to be from continuous sources (e.g., stacks, scrubbers, or basins); although routine but instantaneous or very short-term releases (e.g., from digester release valves) can also pose problems at nearby receptors. Depending upon the rate of release relative to odor perception's short time frame, intermittent sources can be classified as either continuous sources (release rate on the order of minutes or longer), or instantaneous sources (release rate on the order of seconds). Other practical considerations may also come into play, such as matching the model to the objective of the analysis. The use of very conservative models and modeling techniques provide a level of safety for regulatory compliance analyses, but may result in costly over-design if the model is being used as part of the design process. Similarly, the model output must be able to match the criteria of concern.

5.1.1 Puff Models

Quasi-instantaneous and short-term releases are frequently viewed as "puff" releases. A puff release scenario assumes that the release time and sampling times are very short compared to the travel time from the source to the receptor. Högström (1972) considered the total spread (sigma, σ, to be a combination of the meandering of the puffs (σ_r) about a relative axis and the spread relative to the puff centroid (σ_c). He performed a series of field experiments and was able to give estimates of σ_r and σ_c in the downwind, crosswind and vertical dimensions for a sampling time of 30 seconds. In light of the limited data available to estimate the diffusion coefficients for puff diffusion, a number of models use the Pasquill-Gifford values. Since these coefficients were developed specifically for plumes, their use in puff models is questionable. In addition, most puff models assume a normal, or Gaussian concentration distribution within the plume. This assumption overlooks fluctuations within the puff. CALPUFF and AUSPUFF are examples of two currently used non-steady-state puff models.

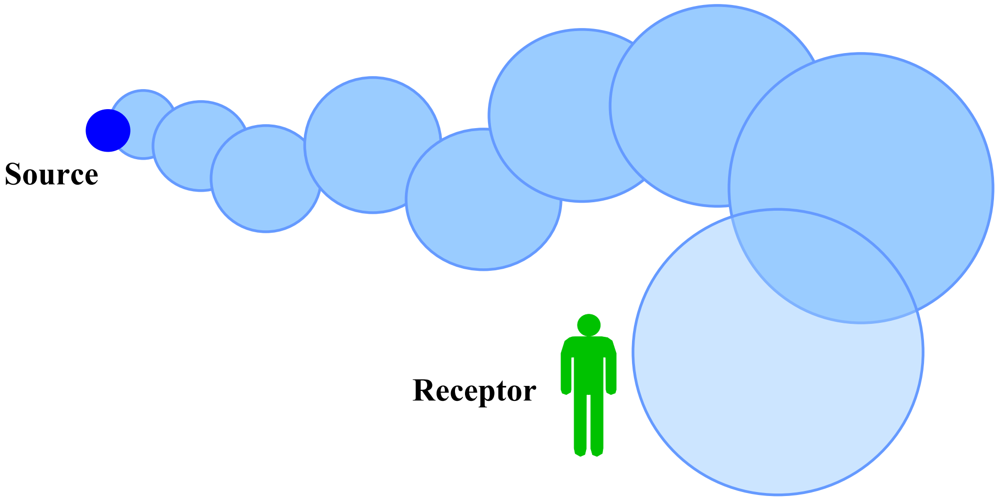

Figure 5. Schematic of Puff Dispersion.

5.1.2 Plume Models

Continuous releases are generally modeled as a plume. The assumption here is that the release time is much greater than the time of travel from the source to the receptor. There are a number of approaches to modeling plumes, each with its own focus, assumptions, and limitations. These approaches can be categorized as (Hanna et al., 1982):

- Meandering (fluctuating) plume models
- Gaussian plume models
- Probability distribution function (pdf) models
- K models
- Statistical models
- Similarity models
- Second order closure and eddy simulation models

Within these categories are a number of different models. However, not all of the models using these approaches are at a developmental stage where they can be practically applied. Some, like the statistical and second-order closure approaches, are too computer-intensive for routine use. Many of the other model types have little in the way of the field validation needed in order to be confidently applied to real-world situations. The most frequently used types for dispersion model used for odor modeling among the list are the fluctuating plume-puff model and the Gaussian model.

5.1.2.1 Fluctuating Plume-Puff Model

The fluctuating plume-puff model, first developed by Gifford (1960), is a hybrid model that simulates the emissions from a source as a series of continuously emitting puffs. The model assumes that the dispersion is separated into two separate parts: one due to the instantaneous spreading out of the Gaussian plume in the crosswind and vertical directions, and another due to the meandering, or fluctuation of the entire plume around its mean position. Gifford visualized the fluctuating plume as an infinite series of overlapping disks. The model tries to follow the path of the puffs (or disks) of contaminant under the influence of varying wind fields and stability conditions, and attempts to predict the peak concentration as a discrete puff passes a given receptor.

One problem with this type of model is that limited data are available to help in determining the diffusion coefficients, σ_y and σ_z, needed to estimate the spread of the disks. Högström (1972) developed a form of the fluctuating plume-puff model from his field experiments (noted above) to determine the values of the diffusion coefficients. As with most of these types of models, it was assumed that the concentration distribution within the instantaneous plume relative to the centerline to be constant and Gaussian (i.e., fluctuations within the instantaneous plume are not considered).

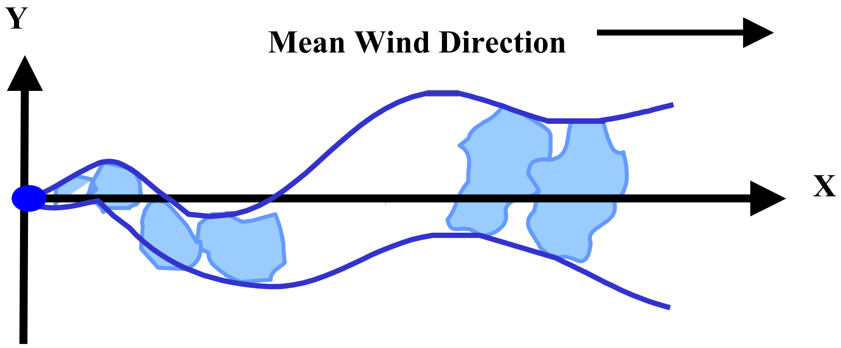

Figure 6. Fluctuating Plume-Puff Model.

5.1.2.2 Gaussian Plume Model

The Gaussian model of diffusion is the most widely used model for atmospheric dispersion modeling. Gaussian models currently used include the Industrial Source Complex - Short Term (ISCST3) model and AUSPLUME. Stable conditions in the AERMOD model are also described in Gaussian terms. One of the most attractive features of Gaussian models is that they were designed to fit what we see and experience in the real world for a range of conditions. In addition, the mathematics of the model is fairly straightforward. On the other hand, Gaussian models need significant empirical input in order to be used for practical dispersion estimates, making the model results highly dependent upon the conditions of the sampling used to derive the empirical values.

The basic assumptions of the Gaussian models are:

- conservation of mass
- continuous emissions
- steady-state conditions
- lateral and vertical concentration profiles follow normal distribution

A problem with the Gaussian model arises because the model assumes a time-averaged distribution in the plume and assumes that the meteorological conditions (including wind direction) are constant during the time required for the plume to travel from the source to the receptor. Under these conditions, results are applicable for time periods from approximately 3 minutes to 1 hour. This time averaging may not fully account for the turbulent concentration fluctuations within the plume, or the meander of the plume from the mean direction. Therefore, using this approach could lead to underprediction of the short-term concentration.

However, Gaussian models have significant advantages. They have been widely applied and modified to consider numerous source types with an assortment of site-specific characteristics, such as terrain and building wake. The ISCST3 model, for example, underwent extensive field-testing and validation so that it has widespread regulatory approval. In addition, many of the Gaussian models are in the public domain, and the source codes can be obtained from regulatory agencies or through governmental electronic bulletin board systems. This significantly reduces the cost of an odor assessment, and allows the modeler the opportunity to match the model to the specific project.

5.2 Peak to Mean Ratio

In general, most of the concentration and turbulence field data used to determine empirical factors found in many dispersion models are collected over relatively long sampling times (on the order of minutes) because of the difficulty of measuring high-speed fluctuations in the atmosphere. For any fixed sampling time, the mean concentration (mean), which is assumed to remain nearly constant, can be determined. However, as Figure 4 shows, within that long-term sampling time, there may be significant short-term fluctuations. These short-term fluctuations may exceed the mean by as much as two orders of magnitude. If the averaging time of the modeled odor concentration (represented by the "mean" line in Figure 4), is greater than the averaging time of the odor criterion, then the odor level predicted by the model may be an underprediction.

Considerable effort has been spent trying to account for the difference between peak and mean concentration (Gifford, 1960; Singer et al., 1966; Hino, 1968; Islitzer and Slade, 1968; and Pasquill, 1975). Analysis of numerous field data have led to estimates of a "*peak to mean ratio*" for different source/receptor configurations. Once a *peak to mean ratio* appropriate for the project is determined, the averaged model output from the model can be used to estimate a peak concentration. One advantage of this approach is that the analysis retains the benefits of using the more standard dispersion models, which are commonly understood and have regulatory approval, while considering the short-term peak concentration that may be required by the odor assessment.

In those analyses where the model predictions are representative of averaging times greater than the selected odor criterion, many researchers have used a power law relationship to estimate a peak, short-term odor impact. The power law relationship is expressed as:

$$C_p = C_m * (t_p / t_m)^p \qquad (1)$$

where,

C_p = peak concentration
C_m = mean concentration
t_p = time period for C_p
t_m = time period for C_m
p = empirical constant

The values of *p* are generally determined empirically. Inoue (1950) postulated that the width of a smoke cloud increased in proportion to the –1/2 power of the sampling time, or $C \propto t^{1/2}$. Stewart et al. (1954) and Cramer (1957) reported a –1/5-power law relationship between sampling time and concentration at heights near the height of release for short sampling times. Hino (1968) confirmed the –1/2 power law for sampling times between 10 minutes to 5 hours, but noted that the –1/5 power law reported by Nonhebel (1960) was valid for sampling times less than 10 minutes.

The concept of peak versus mean concentration has been studied in both the field and the laboratory, and it has been shown that there are a number of factors that must be considered in both (either determining or using such a factor in an odor modeling assessment). Factors such as distance, terrain, stack height, and turbulence-inducing obstructions have all been shown to affect *peak to mean* values.

5.2.1 Effect of Distance

Gifford (1960) studied a series of field studies for an elevated source (stack heights from 24 meters to 108 meters) and found that the ground level *peak to mean* ratio decreased with increasing distance downwind. Plots of the data indicated that the ratio reached its theoretical limit of 1 at some 20 to 50 stack heights downwind. Since distance is associated with increased travel time, it makes sense that atmospheric turbulence has more opportunity to disperse the plume with increasing distance, thus smoothing out the peak concentrations until ultimately, the peak concentration approximates the mean.

5.2.2 Effect of Stack Height

Peak to mean values were found to increase when the stack height increases (Gifford, 1960). Values of the *peak to mean* ratio from 50 to 100 were found to occur at the ground near a moderately tall (50 - 100 meter) stack. However, for sources and receptors at approximately the same height, the *peak to mean* ratio ranged from 1 to 5, at least one order of magnitude lower.

5.2.3 Effect of Elevated Terrain

In their review of field experiments performed at Brookhaven National Laboratory, and three other studies (Meade, 1960; Stewart et al., 1954; and Wipperman, 1961), Singer et al. (1963) concluded that the surface roughness, such as an urban geometry, "practically obliterates all short term fluctuations of concentration depending on the location of the receptor with respect to the source." This is intuitively clear if we recall that concentration fluctuations are, for the most part, the result of turbulence in the atmosphere. Any physical obstruction that alters or modifies the structure of this turbulence, such as surface roughness, is likely to affect the structure of the concentration profiles.

5.2.4 Effect of Building-Induced Turbulence

Meroney (1982) considered the effects of building wakes on the *peak to mean* ratio. Flow around a simple structure can be divided into three zones: the free flow zone far upwind and downwind of the structure unaffected by the building; the wake zone where the flow recognizes the obstruction and bends around it; and the high turbulent and recirculating cavity wake region, attached to the top, back, and sides of the building. Because the flow must bend to flow around the building, the velocity along the streamlines changes, resulting in a corresponding change in pressure. In general, there is a positive pressure area upwind of the building, and a negative region along the top, sides, and leeward face of the building. This negative pressure entrains pollutants into these recirculation regions, leading to highly concentrated, highly fluctuating flow. It is clear that the location of the source and receptor with respect to these zones will affect the dispersion and resulting concentration.

If a stack emits odorous compounds high above the wake or cavity (i.e., within the free flow region), then there is little or no effect of the building on the dispersion (unless and until the plume intersects the building wake region farther downwind). A slightly lower stack may be affected by the contoured flow around the structure. In this case, the plume will be brought more quickly to the ground than if the structure were not there (i.e., the plume rise will be decreased due to the flow around the building), however, the plume keeps its distinct structure with the highest concentrations along the plume centerline. On the other hand, emissions from a very short stack, or vent, may be partially or entirely captured within the cavity. Due to the complicated flow within the cavity, even ground level sources within the cavity can cause high concentrations on the roof.

Meroney determined that the peak concentration in the wake of a building did not exceed the mean concentration by more than a factor of 2 more than 10% of the time at any reasonable distance downwind of a building. For highly noxious gases, a safety factor of 10 was recommended in order to prevent a specified concentration from occurring more than 1% of the time.

5.2.5 *Peak to Mean* Factors

If using this peak to mean approach, it is important to understand the timeframe that the mean impact represents. The 1-hour impact predicted by ISCST3 and other similar Gaussian models, for example, actually represented an averaging time of between 3 to 15 minutes (Pasquill, 1975). This is because the empirical data used in this model were based upon sampling times of 3 to 15 minutes (Pasquill, 1975). This added conservatism to the use of such models for regulatory purposes, since the 1-hour average is likely to be lower than the shorter time average, but it can cause confusion when used for odor modeling if the 1-hour impact is converted directly to shorter time averages with the use of a *peak to mean* factor.

Some odor analyses have made the conversion to shorter time averages by first setting the 1-hour output equal to a 15-minute average, and then converting from 15 minutes to a shorter averaging time (e.g., Engel et al., 1997). Others have taken the 1-hour model output as representative of a 1-hour average, and converted that impact directly to the shorter term impact. The Hong Kong Environmental Protection Department Guideline (Hong Kong Environmental Protection Department, 2000) recommends converting the 1-hour modeled concentration to a 3-minute concentration based upon a stability-dependent power-law relationship, then using a conversion factor to go from a 3-minute to 5-second averaging time. Other researchers have reported using a *peak to mean* conversion factor based upon other parameters, such as distance from the source and height of the source relative to the receptor. The CALPUFF model has incorporated the 1/5 power law for use in odor assessment (Scire et al., 2000). Table 3 lists *peak to mean* conversions from recently published odor modeling analyses (Diosey, 2001).

Table 3. Conversion Factors Used for Determining Short-term Impacts.

Time Scale	Conversion Factor	Conversion Method *
5 second	45 to 9	Power law (stability dependent) + conversion factor
30 second	1.97	Modified power law, p = -0.2
< 1 minute	6	Power law, p = -0.30
2 minutes	2	Power law
2 minutes	---	Power law, p= -1/5
3 minutes	4.47 to 1.65	Power law, p is stability dependent
5 minutes	1.7	Conversion factor
5 minutes	---	Power law, p = 1/5
5 minutes	2.29	Conversion factor
10 minutes	1.82	Conversion factor
10 minutes	1.35	Conversion factor
1 hour	1	None

6 Summary

Modeling the impact of odors downwind of a source can be performed using many of the same tools used for atmospheric dispersion analysis. However, there are some distinct differences that must be accounted for before proceeding with this approach. One difference is that odors are detected and recognized at timescales that are generally far shorter than the averaging times used in routine air quality analysis. Most standard dispersion models have not been validated for such short averaging times. However, a number of techniques developed to adapt the standard dispersion models for potentially shorter averaging times were discussed. Secondly, odors can be complex mixtures at a given source, can vary from source to source at a given facility, or can become more complex as they are transported downwind. Unlike the specific compounds that are studied in routine air quality analyses, such distinct odors are not necessarily additive at locations downwind of the source(s).

The key to selecting the appropriate odor modeling technique is to understand the objective of the odor analysis, and to understand the characteristics of the site itself. What are the criteria that must be met, what model and modeling techniques offer the best simulation of the odor transport process, and who will be reviewing the analysis. These are all questions that must be determined as part of a practical odor modeling analysis.

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