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Contractor's Report to the Board

Comprehensive Compost Odor Response Project

Produced under contract by:



March 2007



Introduction

Odor is generally recognized as *the* critical issue for composting. Odor has been called composting's "Achilles heel" (Wilmink and Diener, 2001), a "thorn" in the side this otherwise environmentally-friendly pursuit (Haug, 1993) and "the issue" in public acceptance of composting facilities (McGinley and McGinley, 2005) and the "number one reason" for the closure of facilities (Cotton, 2005). More than any other factor, odor stands in the way of widespread adoption of composting and the many benefits that accompany composting and compost use.

It was once commonly believed that the presence of odors signaled a "problem" at the composting facility. The premise for this belief was that composting, a natural aerobic biological process, does not generate odors *when properly practiced*. The logic was – "if there is an odor, then something has gone wrong with the process." This paragon still persists in some circles. However, several decades of commercial-scale composting practice have convinced most discerning observers that odor generation is an inevitable result of the inevitable decomposition of organic matter – which composting advances.

Odoriferous compounds inherently form as raw organic materials decompose (Haug; 2004). This fact applies to both aerobic (i.e. with oxygen) and anaerobic (i.e. without oxygen) decomposition, although the latter tends to be much more objectionable. This fact also applies to both naturally occurring organic substances (e.g. leaves) and those resulting from human activities (e.g. biosolids, food residues). Thus, even a low level of odor generation can build into detectable odors when large volumes of decomposing organic materials are amassed in one location. If these odors *always* dissipate before leaving the composting site, all would be well, but that is not *always* the case.

Recognizing the reality—that the formation of odoriferous compounds is an unavoidable fact—the composting industry has shifted its odor control emphasis from perfecting the process to managing the facility. The goal is to reduce the impacts of odors on the community to acceptable levels. The ideal is to eliminate the impacts. The hope is to limit the impacts to some level of tolerance.

Managing odors to minimize impacts still requires knowledge of, and attention to, the composting process because the process largely determines the level and type of odors generated. However odor management also requires knowledge of, and attention to, other factors including feedstock characteristics, odor sources, odor release and meteorological and geographic conditions. These factors affect odor dispersal and travel, odor containment, treatment methods, materials handling, air handling, facility siting, predictive modeling, odor chemistry, odor measurement, community relations and politics. The conditions that lead to an off-site odor impact can be complex.

This report summarizes the current state of knowledge and practice concerning the odor impacts from composting facilities. The information has been drawn from a variety of publications and references, primarily related to composting specifically. However, literature associated with other odor-relevant fields was consulted including wastewater treatment (WWT), municipal solid waste management (MSW), agriculture and industrial processes (e.g. rendering). In order to address the complexities of odor incidents, the report examines the following questions:

- What are "odors" and what are their effects?
- How are odors detected and measured?

- What chemical compounds are responsible for odors at composting?
- What conditions lead to the formation of odorous compounds?
- What conditions and factors lead to off-site impacts (e.g. odor complaints)?
- What determines the severity of off-site impacts?

Together the answers to these questions address the broader question: what causes, conditions and factors lead to odor problems from composting facilities? The next broad question to ask is: how can these odor problems be resolved, anticipated and prevented?

What Are “Odors” and What Are Their Effects?

Before questioning what causes odors, it is helpful to understand just what constitutes an “odor.” An odor, or smell, is the sensation that our brains generate in response to certain chemicals in the air and breathed in through the nose (Dalton, 2003b). The stimuli for odors are airborne environmental chemicals – “odorants” or odorous compounds—those react with receptors in the nose and, in turn, produce the odor sensation in the brain. Examples of chemicals that commonly translate to odors at composting facilities include ammonia, hydrogen sulfide, dimethyl sulfide, butyric acid, putrescine and terpenes. These chemicals arise in nature, as a result of the decomposition of organic substances. The resulting odors are our perceptions of them. Humans can perceive most odors even at relatively low concentrations of the chemicals, in parts per billion in many cases (Dalton, 2003b).

Perhaps because they are perceptions, odors are subjective. Humans differ in their sensitivity to the odorous compounds in the air. Where some people detect an odor to be strong, others sense it as weak or even non-existent (Schiffman, 1998). In addition, people differ in their reaction, preference and aversion to the odors that they perceived. An objectionable odor to one person can be tolerable to another. The perception of odor depends on both the characteristics and concentration of the odorant and the characteristics of the person smelling the odorant (see later section).

A person can find an odor to be pleasant or objectionable, depending on the nature of the odorants and their concentration. In composting situations, odors imply an objectionable sensation. When an unpleasant odor persists or occurs frequently, especially in an unexpected location, it is likely to create a nuisance and lead to complaints. Odor complaints are often accompanied by claims of impaired health from exposure to the odors (Schiffman et al., 2000). However, there is little evidence linking odors directly to physiological effects at the odorant concentration levels typically found outside of composting facilities (or livestock farms or waste treatment facilities) (Cain, 2006; Dalton, 2003a; Schiffman et al., 2003).

How Humans Perceive Odors—The Human Olfactory System

Human odor sensation starts when air is breathed in through the nose. Some of the air breathed in passes through the olfactory system of the nose—a serpentine pathway with protrusions, hair-like cilia, mucous membranes and chemical receptor-cells that together filter and react with numerous chemical compounds (i.e. odorants). The part of the nose containing the odor receptors is the olfactory epithelium, which is situated in the upper

and back section of the nose. During normal breathing, approximately 10 percent of the air breathed in passes to the olfactory epithelium (Dalton, 2003b). Deliberate or involuntary sniffing can increase that to 20 percent (Chiumenti et al., 2005). Through a series of chemical reactions, signals travel from the odor receptors to nerves in the olfactory bulb, which translates the signals to the brain (Dalton, 2003b). How the brain processes these signals and relates the odor sensation to experiences and memory is apparently complex and not completely understood (Shiffman, 1998).

Two separate nerve systems are at work, each creating a different type of sensation in response to airborne chemicals (although the brain combines them into a single perception of the odor). The first, known as the first cranial nerve, or olfactory nerve, generates perceptions associated with the qualities of odor – flowery, fruity, putrid, etc. (Dalton, 2003b). The second system, the fifth cranial or trigeminal nerve, produces sensations of irritation or pungency. The odor sensations from the olfactory nerve apparently do not produce a physiological response (Dalton, 2003b). However, sensations from the trigeminal system can produce responses such as a running nose, red eyes or sneezing when an irritant, like ammonia, is detected in sufficient quantity (Das, 2000; Dalton, 2003b). The chemical concentrations required to trigger irritation from the trigeminal system are typically many times (>7x) greater than the concentrations at which odors are detected (Haug, 1993; Dalton, 2003b, Wilmink and Diener, 2001).

Odors as a Nuisance

Malodors are primarily considered to be a nuisance. The term nuisance has taken on a legal meaning because of conflicts between neighboring land uses (and not necessarily on adjacent land). In general, a nuisance occurs when one person interferes with the right of other people to enjoy their own property or life (Brant and Elliott, 2004). Each state has its own statutory or judicial definition, which generally follow this general definition. McGinley et al. (2000) list the following examples:

- "Anything which is injurious to health, or indecent or offensive to the senses, or an obstruction to the free use of property, so as to interfere with the comfortable enjoyment of life or property, is a nuisance." (Minnesota)
- "...air contaminants (including odor) in quantities and duration to injure human health and welfare." (Alabama)
- "...unreasonably interfere with enjoyment of life and property." (Alaska)
- "...unreasonable interferes with the comfortable enjoyment of life or property of a substantial part of the community." (Arizona)
- "...Odor constitutes a nuisance if it unreasonably interferes with the enjoyment of life or use of property." (Connecticut)
- "...odors beyond his property...to create a public nuisance... defined includes affecting a considerable number of persons and injurious to health or interfere with the comfortable enjoyment of life and property." (Montana)

In determining whether an odor, or any other intrusion, constitutes a nuisance, courts usually apply the concept of "reasonableness" to the situation (Brant and Elliott, 2004). For instance, it may be necessary to determine if a composting operation is reasonably well-managed and took reasonable steps to prevent odor impacts. Also, it may be questioned whether the complaining neighbors are being reasonable in their demands to

eliminate or reduce the odor levels. Farms, and on-farm composting, are often afforded more protection against nuisance complaints because the nature of farming (i.e. inherently odorous) and because of their historic connection to the land. Nevertheless, even farms must operate in a reasonable manner to retain that protection.

In California, the regulation of nuisance odors is more procedural and official than in most other states. All commercial composting facilities in California are required to “prepare, implement, and maintain” a site-specific Odor Impact Minimization Plan or *OIMP* (Title 14 California Code of Regulations, Chapter 3.1 §17863.4; California Integrated Waste Management Board. 2005).

The OIMP process was developed as a response to legislation that gave primary authority over odor complaints at composting facilities to the CIWMB (Health and Safety Code 41705), but required the CIWMB to develop odor regulations and procedures. The OIMP process relies on a philosophy of constant improvement, rather than prescriptive standards. California does not have numeric criteria for when an odor becomes a nuisance. Rather, a facility handling compostable organic materials is required to prepare, implement, and maintain an OIMP. The OIMP must describe design and operational procedures for minimizing odors.

The OIMP also describes meteorological conditions and a complaint response protocol. The OIMP and the facility are typically inspected monthly (although some types of facilities are inspected quarterly). The LEA determines whether or not the facility has an OIMP and is implementing the practices described in the OIMP. If the LEA finds that the facility is not implementing the procedures outlined in its OIMP, the LEA may issue a Notice and Order. If the LEA finds that the OIMP is being fully implemented, but odor impacts are still occurring, the LEA may require the operator “to take additional reasonable and feasible measures to minimize odors.” A complete copy of the regulations relating to Odor Impact Minimization Plans is contained at the end of this chapter.

At best, an unpleasant odor is annoying and makes one uncomfortable. However, because people react strongly to unpleasant odors, the word “nuisance” may seem too mild of a term. Odors bring information to a person about the surrounding environment (Dalton, 2003b). Odors say whether the things before us are good or bad, safe or dangerous.

Odors provide clues about food (e.g. good to eat or spoiled), substances to avoid that might harbor disease (e.g. fecal matter) and even the presence of danger (e.g. smoke). While some of these associations are subconscious, rooted in evolution, others are more deliberate. For example, Dalton (2003) explains that before microorganisms (i.e. germs) were discovered, disease and sickness were attributed to the “miasma” of the ambient air. Because odors defined the character of the air, odors were considered a cause. The association between odors and disease still persists, even though it is well known that germs cause disease, not the chemicals that generate odors.

Considering the vital information that the sense of smell provides, particularly as a primordial function, it is understandable why malodors bring such a strong reaction. People continue to equate bad odors with bad things. To many people odors imply risks, hazards and danger. Ironically, people have apparently become more sensitive to and intolerant of odors, even while the risks in the environment have declined and air quality has improved. Dalton (2003) attributes this phenomenon to the fact that there is less a background odor, or odor “noise” to distract us. With little background odor, people better detect and concentrate on individual odors, and their risks. The relatively clean

background environment makes even low levels of odor stand out as unusual and intolerable.

Odors and Health

With the possible exception of enclosed spaces and vessels, the chemical compounds responsible for odors at a composting facility are not present in large enough concentrations to cause direct physiological harm (Dalton, 2003b; Pelossi, 2003). That is, the concentrations are below the threshold levels that cause irritation via the trigeminal system. Yet, people still claim to experience symptoms of ill health due to odors. The symptoms most often reported include nausea, eye, nose and throat irritation, headache, shortness of breath and drowsiness (Chiumenti et al., 2005; Schiffman, 1998). Without a cause-and-effect relationship, the question that follows is: Are the symptoms real (i.e. physiological) or perceived (i.e. psychological)?

The answers offered by researchers are not definitive but appear to suggest that symptoms arise from people's reaction to odors rather than a direct physiological effect. In 1998, a conference of experts, held at Duke University, examined the potential health effects of odors from livestock farms, wastewater treatment and biosolids recycling (Schiffman et al., 1998). The participants identified the following three ways in which odors might cause health symptoms:

1. A person is exposed to an odorous chemical compound at concentrations high enough to produce sensory irritations. The person associates the symptoms with the odor, although they are actually caused by the chemical odorant. As mentioned above, odorous compounds are rarely present in high enough concentrations to cause direct irritation. Therefore, this situation is not prevalent.
2. A second agent may accompany the odor, such as pathogenic bacteria. The person becomes ill from exposure to this second agent but associates the symptoms with the odor. Although this scenario cannot be easily ruled out, there is little or no evidence that suggests it occurs.
3. Odors at concentrations high enough to be detected but below the irritant threshold affect people in other ways. They change their behavior or thoughts in ways that lead them to experience the symptoms. (For example, when exposed to an odor, a person may alter their breathing by holding their breath, taking shallow breaths or breathing only through their mouths. Hence, they may become light-headed or develop a sore throat (Dalton, 2003b)). Persistent or frequent odors may increase stress, depress a person's mood or cause them to negatively change their behavior in ways that bring on physical symptoms. The conference participants concluded that more research is needed to assess and better understand the associations between these "biological and behavioral/psychosocial factors" (Schiffman, 2000).

Assuming that the third scenario is a reasonable explanation of the situation, one might say that people are making themselves sick in response to the odors. The odors themselves are not the direct cause of the reported health effects. Some odor scientists agree that there is an absence of cause and effect when it comes to health and nuisance-level odors. In an article by Pelosi (2003), William Cain of the Chemosensory Perception Laboratory at University of California, San Diego is quoted, "You can have symptoms from odors you don't like but this is not illness. Most of these are non-specific symptoms that can have any number of origins." Dr. Cain repeated this sentiment at the recent U.S.

Composting Council Conference and reiterated his view that there is “almost no” evidence to link the sensation of odors with illness (Cain, 2006).

California Odor Minimization Plan

17863.4. Odor Impact Minimization Plan [OIMP]

- (a) All compostable material handling operations and facilities shall prepare, implement and maintain a site-specific odor impact minimization plan. A complete plan shall be submitted to the EA with the EA Notification or permit application.
- (b) Odor impact minimization plans shall provide guidance to on-site operation personnel by describing, at a minimum, the following items. If the operator will not be implementing any of these procedures, the plan shall explain why it is not necessary.
 - (1) an odor monitoring protocol which describes the proximity of possible odor receptors and a method for assessing odor impacts at the locations of the possible odor receptors; and,
 - (2) a description of meteorological conditions effecting migration of odors and/or transport of odor-causing material off-site. Seasonal variations that effect wind velocity and direction shall also be described; and,
 - (3) a complaint response protocol; and,
 - (4) a description of design considerations and/or projected ranges of optimal operation to be employed in minimizing odor, including method and degree of aeration, moisture content of materials, feedstock characteristics, airborne emission production, process water distribution, pad and site drainage and permeability, equipment reliability, personnel training, weather event impacts, utility service interruptions, and site specific concerns; and,
 - (5) a description of operating procedures for minimizing odor, including aeration, moisture management, feedstock quality, drainage controls, pad maintenance, wastewater pond controls, storage practices (e.g., storage time and pile geometry), contingency plans (i.e., equipment, water, power, and personnel), biofiltration, and tarping.
- (c) The odor impact minimization plan shall be revised to reflect any changes, and a copy shall be provided to the EA, within 30 days of those changes.
- (d) The odor impact minimization plans shall be reviewed annually by the operator to determine if and revisions are necessary.
- (e) The odor impact minimization plan shall be used by the EA to determine whether or not the operation or facility is following the procedures established by the operator. If the EA determines that the odor impact minimization plan is not being followed, the EA may issue a Notice and Order (pursuant to section 18304) to require the operator to either comply with the odor impact minimization plan or to revise it.
- (f) If the odor impact minimization plan is being followed, but the odor impacts are still occurring, the EA may issue a Notice and Order (pursuant to section 18304) requiring the operator to take additional reasonable and feasible measures to minimize odors.

Authority cite: Sections 40502, 43020, 43021 and 43209.1 of the Public Resources Code.

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Reference: Sections 43020, 43201 and 43209.1 of the Public Resources Code.

The California Integrated Waste Management Board regulations are posted here:
<http://www.ciwmb.ca.gov/Regulations/Title14/ch31.htm#article3>

There's some additional background here:
<http://www.ciwmb.ca.gov/LEACentral/Organics/OdorIssues/>

How Are Odors Characterized, Detected and Measured?

Odors are sensations—perceptions of numerous chemical compounds. Therefore, detecting, measuring, monitoring and even describing odors are not straightforward procedures. The human element cannot be completely removed from the process because odors are subjective and because they are perceived at very low odorant concentrations. Odor science has developed special terms and techniques to describe and measure the nature and strength of specific odors. (Note: more detailed discussions of odor detection and measurement is provided by St. Croix Sensory, Inc., 2005 and Brant and Elliot, 2004).

Odor Characteristics and Parameters

There are numerous ways to characterize odors. Due to the nature of odors, both qualitative and quantitative descriptors are necessary. An odor may be described and measured according its threshold concentration, pervasiveness, descriptive quality, degree of pleasant or unpleasantness and the concentration of the odor-causing chemicals present.

Concentration of Odorants

Thanks to chemical technology, it is a relatively easy matter to measure the concentrations of chemicals in air. Therefore, it is feasible to measure and monitor for odors by sampling the air and analyzing the samples in a laboratory for the presence and concentrations of selected odorous compounds. The results are expressed in terms of the concentrations of individual compounds such as parts per million (ppm) of ammonia and or parts per billion (ppb) of methyl mercaptan. These concentrations can then be compared to data that indicate the concentrations at which humans detect, recognize and/or otherwise react to the odor caused by the chemical in question (see Table 1).

Measuring the concentrations of selected individual chemicals can be indicative of the odor situation. Tracking one of more specific compounds can help identify the sources and root causes of odors and to monitor the effects of odor mitigation practices. This practice is most useful when a particular chemical or class of chemicals dominates the odor. However, relying on chemical concentrations to indicate odors has several major limitations.

First, odors are rarely the result of a single odorant but a combination of chemicals each lending their character to the resulting overall odor. The combined effect may be greater than the sum of the individual effects. Measuring the concentrations of a single compound cannot truly represent either the quality or strength of the odor. Second, odors are detectable to humans when the odorants are present a very low concentrations. Conventional analytical techniques may not be practical or accurate at these low

concentrations. Therefore, in most cases, the human nose remains the best tool for detecting and measuring odors.

“Odor” Concentration—Dilutions to Threshold

Given the limitations of measuring individual compounds, odor science has developed a method for defining the concentration of an odor *in its entirety*. This odor concentration is determined by a panel of human subjects that smell samples of the odor at various levels of dilution with fresh air (see description in following section). The concentration is expressed in terms of the number of dilutions required for the panel members to no longer detect the odor. This value is called either the dilutions-to-threshold (D/T), or effective dilutions (ED). The two terms are equivalent. Usually, the concentration is taken to be the point at which 50% the panel no longer detect the odor and it is written as D/T₅₀ or ED₅₀. A few other terms and symbols are for odor concentration but they are less popular and essentially the same as D/T (Haug, 1993).

The value of D/T reflects the strength of an odor as perceived by the odor panel. A large D/T value means that the odor is strong because it requires many dilutions with fresh air to disappear. For example, at D/T₅₀ of 10 means that the odor sample was diluted with a volume of fresh air 9 times the volume of the sample before half the panel members could not detect the odor. An odor with a D/T value of 5 is not as strong because it disappears with fewer dilutions.

Threshold Concentrations

Threshold concentrations refer to the concentrations that the odor or odorant results in a reaction from humans. For example, a *detection* threshold is the minimum concentration at which humans detect the odor. The *recognition* threshold is the minimum concentration at which humans can recognize or identify the odor. The recognition threshold is typically 2 to 10 times higher than the detection threshold (Brant and Elliot, 2004). Threshold concentrations can also be established for points of annoyance, tolerance and irritation, which are higher than the recognition threshold. Again, because humans vary in their sensitivities to odors, threshold concentrations are set at the point where some percentage of the populations considers the odor just detectable or recognizable. Usually the percentage is 50% and it is determined by studies with human odor panels.

Threshold concentrations can be established for overall odors and expressed as in D/T50. Also, threshold concentrations can apply to individual odorants using conventional units of concentration like ppm. Table 1 lists detection and recognition threshold concentrations for selected odor-causing compounds (see following section on “Odor Index”).

Odor “Potential”—Odor Index

The potential of a particular chemical to cause an odor problem depends on several of its odor “characteristics.” Threshold concentrations reflect the amount of the odorant that is required for people to perceive the chemical’s odor at various reaction levels, such as detection, recognition, annoyance, irritation. Whether or not the reaction is positive, neutral or negative is determined by odor characteristics that include the chemical’s odor intensity, hedonic tone, quality and pervasiveness (see previous section).

However, before an odorant can be perceived as an odor, it must first volatilize. Therefore, an important characteristic is the chemical’s vapor pressure, which indicates

the chemical's tendency to volatilize. Vapor pressure can be considered the pressure required to prevent the chemical from changing phase from a liquid to a gas. When the ambient pressure equals the vapor pressure of a chemical, the chemical starts to boil. Thus, chemicals with a low vapor pressure vaporize easily. Another way to express the tendency to vaporize is by the chemical's boiling point (i.e. temperature). Chemicals with a low boiling temperature readily vaporize.

Haug (1993) and Das (2000) each discuss the concept of "odor index" (OI). Odor index is a measure that considers both the tendency of the odorant to vaporize and its ability to be perceived. It is a dimensionless parameter defined as the ratio of the vapor pressure to the recognition threshold concentration as follows:

$$\text{Odor index} = \text{OI} = \frac{\text{Vapor Pressure (ppm)}}{\text{Odor recognition threshold (100\%)(ppm)}}$$

When a compound vaporizes easily and is recognizable at low concentrations, it has a high OI value. Thus, compounds with higher OI values are more likely to create odors, assuming that they also have objectionable odor qualities or unpleasant hedonic tone levels. Table 1 lists the OI and other odor characteristics for selected odor compounds.

Odor Units (ou)

The strength of an odor is sometimes quantified in terms of "odor units" (ou). An odor unit is conceptually similar to D/T, although it is not well explained in the literature and can be confusing. The odor unit value essentially refers to the number of dilutions (of fresh air) required to reduce the odor to its detection threshold (Chiumenti et al., 2005). Thus, air with a large odor unit value of has a strong odor. An odor unit is a dimensionless quantity but is written as "ou," D/T or ED (Haug, 2003).

Table 1: Threshold odor concentrations, odor index and boiling point for selected odorants

Odorant Category Chemical Compound	Detection Threshold (ppmv) ¹	Recognition Threshold (ppmv) ¹	Boiling Point Temperature (°C) ²	Odor Index
Acetic acid	0.008	0.2	63 @ 100d mm Hg	15,000
Ammonia	0.370	47	-33	167,300
Butyl mercaptan	0.0005		65	43,340,000
Butyric acid			61 @ 10 mm Hg	50,000

Diethyl sulfide	0.0008	0.005	88	14,400,000
Dimethyl amine	0.047	0.047		
Dimethyl sulfide	0.001	0.0056		
Ethylamine	0.026	0.83	17	1,445,000
Ethyl Mercapton	0.0005		65	43,340,000
Hydrogen sulfide	0.00047	0.0047	62	17,000,000
Methyl mercaptan	0.0011	0.0021	8	53,300,000
Propionic acid			66 @ 40 mm Hg	112,300
Skatole	0.0012	0.47	95 @ 1 mm Hg	30,000
α -Pinene	0.011		37 @ 10 mm Hg	469,000
Butanone			80	3,800

1. ppmv = parts per million by volume
2. Unless otherwise noted (in parenthesis), the boiling point temperature is for a vapor pressure of 760 mm Hg (equivalent of standard atmospheric pressure)

Source: adapted from Haug, 1993)

Odor Intensity and Pervasiveness

Odor intensity is the perceived strength or pungency of an odor (Brant and Elliott, 2004). It is an important factor in determining the tolerance that humans have for an odor (Haug, 2003). Intensity is primarily a qualitative characteristic but it can be expressed in quantitative terms.

Odor intensity is evaluated by comparing the intensity of a sample odor with the intensity of a standard odorant at various concentrations. The most common reference odorant used in the U.S. is 1-butanol, following ASTM standard E544 (Das, 2000; Haug, 1993). The intensity is reported in terms of the corresponding butanol concentration (e.g. ppm),

or with a scale number that coincides with the butanol concentration range. Brandt and Elliott (2004) describe a second method for gauging odor intensity in which human subjects simply rate the intensity of an odor sample on a scale of 0 to 6. An overpowering odor would be rated 6 and no odor would be 0.

Odor intensity and concentration both indicate the strength of an odor. They are related but different qualities. Quantitatively, intensity (I) and concentration (C) are related by Steven's Psychophysical Law as follows (Das, 2000; Haug, 1993):

$$I = k C^n$$

The equation holds for either an overall odor or an individual odorant. For an overall odor, the threshold concentration would be used, expressed in D/Ts. For an odorant, the actual concentration applies. The constants k and n vary with the particular odor or odorant.

The constant n indicates how easily the odor intensity decreases when the air is diluted—that is, the concentration decreases. The value of n ranges from 0.2 to 0.8 for most compounds (Das, 2000). A low n value means that the intensity changes little as the air is diluted. The odor is said to be “pervasive.” When n is large, diluting air readily reduces the intensity and the odor is non-pervasive. For example, ammonia and aldehydes have high values of n—they are easily diluted. Hydrogen sulfide and amines are examples of odor-causing compounds with low n values—their odors disappear slowly as they are diluted (Haug, 1993).

Odor Quality or Character

Odors have a quality that can only be identified descriptively by relating the to other odors that are generally familiar or widely recognized. The odor *quality* is what a person would say “an odor smells like” (Brant and Elliot, 2001). Lists of standard descriptors exist that can be used by one person to convey the quality of an odor to another person (Table 2). More than one descriptor can be used and the presence of one or more type of “smell” can be weighted.

Hedonic Tone

The *hedonic* tone is a rating of the pleasantness or unpleasantness of an odor. It is a subjective measure but it can be averaged for a group of individuals evaluating an odor. Hedonic tone can be rated on a scale from -10 for very unpleasant to +10 for pleasant (Chiumenti et al. 2005). Ratings scales can be “standardized” by relating the scale to reference odorants, such as isovaleric acid, as a model for a very unpleasant odor, and vanillin for a very pleasant odor (Haug, 1993). Hedonic tone is not an independent quality of a compound or odor. It depends on the odor intensity, concentration, duration and frequency of exposure, as well as the perceptions and associations of the individual.

Table 2: Examples of standard descriptors for odor quality

Odor Character Category							
Chemical	Medicinal	Floral	Fruity	Vegetable	Earthy	Offensive	Fishy
Coal	Alcohol	Almond	Apple	Celery	Ashes	Blood	Amine
Creosote	Ammonia	Cinnamon	Cherry	Corn	Burnt Wood	Burnt	Dead Fish
Diesel	Anesthetic	Coconut	Citrus	Cucumber	Chalk-like	Burnt Rubber	Perm Solution
Gasoline	Camphore	Eucalptus	Cloves	Dill	Coffee	Decay	
Grease	Chlorinous	Fragrant	Grapes	Garlic	Grain Silage	Fecal	
Paint	Disinfectant	Herbal	Lemons	Green Pepper	Grassy	Garbage	
Plastic	Menthol	Lavender	Maple	Nutty	Mold	Landfill Leachate	
Resins	Soapy	Licorce	Melon	Potato	Mushroom	Manure	
Rubber	Vinegar	Marigolds	Minty	Tomato	Musky	Mercaptane	
Solvent		Perfumy	Orange	Onion	Musty	Putrid	
Sulfur		Rose-like	Strawberry		Peat-lie	Rancid	
Varnish		Spicy	Sweet		Pine	Raw Meat	
Car Exhaust					Mouse-like	Urine	
Burnt Plastic						Vomit	
Foundry							
Turpentine							

Source: adapted from St. Croix Sensory, 2005.

Measuring Odors

Odors are measured for a variety of reasons—for research on process management or human exposure, to troubleshoot the process and improve methods, to gather data for odor models, for regulatory compliance and for legal evidence. In these instances, the measurements must be reasonably reliable, quantifiable and/or qualified in a generally accepted manner. Standard procedures and methods of sampling and measurement are involved.

Practices tend to be less rigorous when odors are measured in the field for monitoring purposes. Odor monitoring is conducted to anticipate and prevent odor problems, improve process management, verify a complaint and/or spot check for regulatory compliance. Monitoring is, or should be, a regular activity so cost is a factor. Expensive procedures for sampling and analyzing odors or odor components are not often used for field measurements. Instead, human noses usually make on-site evaluations, increasingly with the aid of devices that gather and handle odor samples in the field.

In any case, there are two approaches to measuring odors – (1) observe and record the odor sensation or reactions that humans have to odors or odorous compounds; and (2) capture and measure the chemical compounds stimulating the odors. The human-based approach, known as olfactometry, is more common (Brant and Elliott, 2004). However, both approaches are used in science and practice to determine the presence, quantities and qualities of odors. Both methods require accurate sampling of the odorous air.

Sampling

Sampling is a critical element of analytical and olfactometry measurements (see following sections). Odors are usually sampled by collecting a proportional volume of air at or near the odor source. The rate at which the sample volume is collected can indicate the rate of emissions. Where odors quality is of chief importance, samples of odors also can be gathered by placing an odor-adsorbing medium, like a fabric swatch, at the source for a period of time (Brant and Elliott, 2004).

In the field, air samples are collected using a collection orifice or tube placed within the air emissions of the odor source. Air is drawn into the collection tube by either a hand operated pump (e.g. flexible bulb or piston) or a small battery-powered vacuum pump (Wilmink and Diener, 2001). The volume of air sampled must be known and is determined by the number of hand pumps or time that the vacuum pump runs. The sample air is gathered in a flexible bag that will not react with the target chemicals, commonly made of tedlar. The sample is then promptly taken to the laboratory for chemical analysis. In laboratory situations, or in applications that include real time monitoring, air samples are typically drawn from sample ports either manually or automatically, and transported to the lab for analysis.

Odors emitted from buildings and stacks are sampled from the exhaust vents, usually by taking multiple samples at predetermined points to get an accurate representation of the average airflow. Field sampling of area sources, like compost piles and biofilters, requires a hood that covers the sample area. Multiple sample areas may be necessary when the airflow is not uniform.

Olfactometry—Odor Measurement by Humans

The human nose is better at detecting and distinguishing odors than any analytical instrument currently available. Therefore, using the odor sensitivities of people is the

most reliable and most accepted way to measure odors. This approach is called olfactometry.

At the laboratory level, olfactometry employs a panel of people, usually with some training, to sniff odor samples and then rate, describe and/or react to them. Because individuals sense and perceive odors differently, odor panels contain several members, preferably 5 to 10 (Haug, 1993). Their collective response is expressed statistically. For example, odor thresholds are usually defined by the point at which 50% of the panel no longer detects the odor (e.g. D/T₅₀).

Standard techniques are used to prepare the odor samples and present them to the panel and to register the responses of the panel members. A number of standard methodologies exist for olfactometry, including at least two ASTM standards (Haug, 1993).

The general procedure involves taking a sample of the odor source, as described above, and transporting the sample to the odor panel lab. The odor sample is then presented to the panel members, often at various levels of dilution. For example, an odor sample is progressively diluted at various levels and presented to panel members in order to determine a detection of recognition threshold (i.e. D/T). In nearly all cases, the nature of the sample is unknown to the panel member.

Odor panelists may also be exposed to undiluted samples for rating odor quality, intensity of hedonic tone. Some applications also may include control samples that have no odors or odorants. In some cases, panel members are presented standard comparison samples with known odorants at known concentrations. Olfactometry makes use of air handling devices that easily control the sample dilution level and/or airflow rate to the panel. Some devices make it possible to conduct olfactometry measurements in the field. However, the background odor “noise” and adaptation of the human subjects to the ambient odors can compromise the results. These devices are more often used for odor monitoring purposes (see following section).

Several portable devices have been developed for olfactory measurements of odors in the field, such as at the boundaries of the composting site. Generally, these *field olfactometers* collect a sample of air and then guide it to the user’s nose, which is isolated from the surrounding ambient air by a mask or cup covering the nose. Two commercial field olfactometers have received particular attention in the composting literature—the “scentometer,” manufactured by BernebeySutcliffe; and the Nasal Ranger, available from St. Croix Sensory, Inc. (McGinley and McGinley, 2005; Myers, 2004; Das, 2000)

These devices have filters to provide fresh air to dilute the odorous air reaching the human user. They also have valves to adjust the mixture of fresh and odorous air. In addition to providing for more user-friendly operation, field olfactometers have developed to more accurately control the dilution rate. Thus, field measures can estimate threshold concentrations in D/Ts.

Analytical Measurements

Analytical measurements quantify the amount of concentration of a specific chemical using various chemical, electrical or physical techniques. For odor measurement, the analytical approach is practical when one or a few specific and identifiable compounds dominate the odor. Analytical measurements also can be useful when measuring changes in odor-relevant situations. For example, one can use analytical methods to track hydrogen sulfide concentrations in response to some odor mitigating practice, like adding

a porous amendment to improve aeration. Even if hydrogen sulfide is not the offending odor, its presence and concentration may be indicative of odors.

Numerous analytical techniques and instruments are commonly used. The target odor chemical and the range of concentrations that need to be measured typically determine what techniques are feasible. The combined use of gas chromatographs and mass spectrometers is especially versatile, accurate and popular.

Detection Tubes

Detection tubes serve as both sampling and analytical devices. They are convenient for evaluations of odors in the field. One of the more common types of detection tube is called a Dragger tube, which is often used to measure ammonia concentrations on the spot. The detection tube contains a chemical that reacts with the target odorant compound and changes color, expands or changes in some fashion in proportion to the amount of odorant present. The scale on the tube is calibrated to display the concentration of the odorant.

A fixed volume of air (e.g. set number of hand pumps) must be drawn into the tube for the calibration to be accurate. Detection tubes are only moderately accurate in analyzing concentrations (Wilmink and Diener, 2001). However, they are convenient and inexpensive devices for field use in monitoring changes and determining if a particular compound is present. A different type of detection tube is required for different target compounds. Although detection tubes are available for a large number of compounds, many are not sensitive or accurate enough at the low concentrations at which odors typically arise.

Laboratory Analytical Methods

Samples taken to laboratories are analyzed via a variety of analytical techniques that yield a measure of the chemical concentrations. The technique used depends on its suitability to the target chemicals, accuracy required, capabilities of the laboratory and cost. Commonly used techniques for analyzing odorous compounds include the following (Brant and Elliot, 2004; Wilmink and Diener, 2001):

- Wet chemistry: Appropriate for analyzing target compounds that are soluble in water. Ion specific electrodes (ISE) are commonly used.
- Electrochemical sensors: An electrode that reacts with a specific gas, causing an electrical signal that can be translated to a concentration. The electrodes are fast, and sensitive to low concentrations but can suffer from interference from non-target gases.
- Semiconductor sensors: Metal oxide semi-conductors increase in electrical conductivity in the presence of reducing gases. These sensors can be used to detect certain categories of gases (e.g. solvents) at low concentrations but not specific chemicals. They do not appear to be broadly applicable to the chemicals that typically cause composting odors.
- Photoionization detector: Uses UV light to ionize and then measure the concentration of volatile organic compounds.
- Gas chromatography (GC) and mass spectrometry (MS): These common laboratory techniques separate and analyze individual volatile or gaseous chemical compounds

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from a mixed air stream. Used together, a GC/MS system can analyze a wide variety of organic compounds with accuracy.

Electronic Nose

Brant and Elliott (2004) put the “electronic nose” in the category of “emerging odor management strategies.” An electronic nose, or artificial nose, is an instrument that includes a system for sampling air (or gases generally), multiple gas-detecting sensors and a computer with an artificial intelligence program (e.g. neural networks). Each sensor detects and quantifies a different specific chemical gas and sends a corresponding electronic signal to the computer.

The computer program recognizes the pattern of signals generated by the array of sensors. An electronic nose is intended to mimic the human olfactory system. Like a human nose, the sensors detect a combination of gaseous chemical compounds, at varying concentrations, and electronically inform the “brain,” in this case a computer, which recognizes and describes the odor (Stetter and Penrose, 2001).

According to the *Whatis.com web site (2003)*, electronic noses have been used for years, primarily for quality control in the food and beverage industry. Until recently, the large size and expense of the instruments have hampered widespread use. Electronic noses have been shrinking in size and expense due to research and development efforts. Brant and Elliott suggest that electronic noses must be “trained” to perceive odors like humans based on the perceptions of human odor panels -- a time consuming process. Also, they note that the capabilities of the gas sensors also limit the applications to concentrated odor sources (e.g. point sources).

Electronic noses appear to be improving and might soon become practical for automated odor detection. A good technical article describing electronic noses (Stetter and Penrose, 2001) can be found on the Electrochemical Encyclopedia web site at <http://electrochem.cwru.edu/ed/encycl/art-n01-nose.htm>.

What Chemical Compounds Are Responsible for Odors At Composting Facilities?

The odor associated with composting is not the result of a single “smell.” Organic materials inherently generate a large number and variety of volatile chemical compounds that humans can sense as odors—good and bad. These compounds can coexist and interact with one another to produce a diverse menu of aromas. A compound’s volatility—that is, its conversion to a gaseous phase and subsequent migration into the air—is what causes it to be sensed by human noses (and “noses” of other animals). Volatility is necessary for chemicals to be odorous.

As an organic material decomposes, the mix of volatile compounds changes, and so does the characteristic odor. A smell may “appear” where one was not apparent before, or the reverse may be true—a smell may disappear. In any case, the quality of the odor changes as organic materials pass through different stages of decomposition. The quality also changes with the variation in conditions responsible for the formation and movement of specific volatile compounds. During composting, many volatile chemicals are formed, destroyed and/or emitted due to the innumerable combinations of raw feedstocks and the diverse and ever changing process conditions. They can coexist and interact with one another to produce a diverse menu of aromas.

Before considering the specific compounds associated with composting odors, it is important to recognize the following “truisms:”

- Usually, the characteristic smell of a given material is a result of a mix of several volatile compounds, each related to the chemical composition of that material. A particular volatile chemical can dominate the mix and produces the characteristic odor.
- Most odorous compounds are transient. After forming, or being liberated, they decompose, immobilize, change phase and/or disperse relatively quickly, depending on the environmental conditions (e.g. oxygen, temperature—see following section).
- The concentration of a particular compound determines whether or not its odor is detected, recognized and considered objectionable. Odorous substances that are generally considered pleasing can become offensive at high concentrations (e.g. perfume, pine oil). Whether people find an odor good or bad, pleasant or unpleasant, is a quality known as “hedonic tone.” The hedonic tone says nothing about the character of the odor (e.g. pungent, septic, fishy), just how good or bad it is perceived to be.
- The concentration at which a compound is detected by people, its detection “threshold,” varies greatly among volatile compounds. Some compounds can be detected at extremely low concentrations while others require high concentrations.
- The character and strength of odors are highly subjective—sensed and judged differently by different people.

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- An individual's sensitivity to an odor, and his/her reaction to it is greatly influenced by personal experience, gender, psychology and societal factors (Dalton, 2000a, 2000b).

Many compounds formed during composting are "odorous," that is considered offensive by at least some humans. Several individual compounds stand out as odorous, such as ammonia and hydrogen sulfide. However, because of the large number of chemical species involved, odorous compounds are frequently identified by categories of similar chemicals. The primary categories identified with organic materials are mercaptans, organic sulfides, ammonia, amines, indoles, volatile fatty acids (VFAs), terpenes, alcohols, ketones and aldehydes, (Haug, 1993; Miller, 1993; Epstein, 1997; Goldstein, 2002). The first two in this list, along with hydrogen sulfide are compounds that contain sulfur. Amines, indoles and ammonia are nitrogen-based compounds. Volatile fatty acids (VFAs) are most closely associated with carbohydrates and lipids (i.e. fats and oils). The remaining groups are common organic compounds with volatile members.

Table 3 lists compounds and groups that are commonly associated with odors at composting facilities. The characteristics of individual compounds and groups are described below.

Table 3: Common odorous compounds released during handling and decomposition of organic materials

Compound Name	Odor Descriptors	Chemical Formula	Molecular Mass
Volatile Sulfur Compounds			
Hydrogen sulfide	Rotten egg	H_2S	34
Methyl-mercaptan	Pungent, rotten cabbage, skunk, garlic	CH_3SH	48
Ethyl-mercaptan	Rotten cabbage, leek-like	C_2H_5SH	62
Carbon disulfide	Disagreeably sweet, rotten pumpkin	CS_2	76
Dimethyl sulfide	Sulfurous, rotten cabbage,	$(CH_3)_2S$	62
Dimethyl disulfide	Putrid, sulfurous	$(CH_3)_2S_2$	94
Volatile Nitrogen Compounds			
Ammonia	Pungent, sharp, irritating	NH_3	17
Putrescine	Putrid, nauseating	$NH_2(CH_2)_4NH_2$	88
Cadaverine	Putrid, decaying flesh	$NH_2(CH_2)_5NH_2$	102
Methylamine	Putrid, fishy, rotten fish	CH_3NH_2	31
Dimethylamine	Fishy, rotten fish	$(CH_3)_2NH$	45
Trimethylamine	Fishy, pungent	$(CH_3)_3N$	45
Ethylamine	Ammonia-like, irritating	$C_2H_5NH_2$	45
Indole	Fecal, nauseating	$C_6H_4(CH_2)_3NH$	117
Skatole	Fecal, nauseating	C_9H_9N	131
Compound Name	Odor Descriptors	Chemical Formula	Molecular Mass
Volatile Fatty Acids (VFAs)			
Formic acid	Biting, pungent	$HCOOH$	46
Acetic acid	Vinegar-like, pungent	CH_3COOH	60
Propionic acid	Rancid, pungent	C_2H_5COOH	74
Butyric acid	Rancid butter, body odor	C_3H_7COOH	88
Valeric acid	Unpleasant, sweat	C_4H_9COOH	102

Compound Name	Odor Descriptors	Chemical Formula	Molecular Mass
Iso-valeric acid	Rancid cheeses	$(\text{CH}_3)_2\text{CH}_2\text{COOH}$	102
Caproic acid	Pungent	$\text{C}_5\text{H}_{11}\text{COOH}$	116
Capric acid	Unpleasant, offensive	$\text{C}_9\text{H}_{19}\text{COOH}$	172
Terpenes			
α -Pinene	Sharp, terpine	--	--
Limonene	Sharp, lemony	--	--
Ketones and Aldehydes			
Phenol	Medicinal	$\text{C}_6\text{H}_5\text{OH}$	1094
Acetone	Pungent, solvent	CH_3COCH_3	58
Methyl ethyl ketone (Butanone)	Sweet, solvent	$\text{CH}_3\text{COCH}_2\text{CH}_3$	72
Formaldehyde	Acrid, medicinal	H_2CO	30
Acetaldehyde	Green, sweet, fruity	CH_3CHO	44

Compiled from: Brant and Elliott, 2004; Chiumenti et al., 2005; Williams and Miller, 1993; Wilmlink and Diener, 2001; and Epstein, 1997

Sulfur Compounds

The element sulfur (S) is a common to several of the more objectionable, potent and recognizable odorous compounds associated with organic matter decomposition. Sulfur is a relatively abundant element in many composting feedstocks including food residuals, produce, paper, gypsum, manure and biosolids (Miller, 1993). It is a component of the amino acids cystine and methionine, which serve as precursors for volatile sulfur compounds, as organic matter decomposes (Miller, 1993). Many volatile sulfur compounds form under both aerobic and anaerobic conditions, although the latter produces and/or accumulates more (Walker and Gossett, 1999, Haug, 1993). Sulfur compounds principally identified as odorous include hydrogen sulfide, mercaptans and organic sulfides (e.g. dimethyl disulfide).

Hydrogen sulfide

Hydrogen sulfide (H_2S) is a reduced and inorganic form of sulfur that produces the familiar rotten egg smell. While it can form at low oxygen concentrations (anoxic), it primarily is an anaerobic product. The presence of hydrogen sulfide is an indicator of anaerobic decomposition of organic matter (Nobel et al., 2001). Although hydrogen sulfide produces an offensive odor, and it can be detected at very low concentrations, it does not appear to be a major source of odors at composting facilities. Few field-based studies have implicated this compound as a primary offending odor. This result may stem from the tendency of hydrogen sulfide to dissipate and/or oxidize quickly in the

environment (Walker and Gossett, 1999). Also, hydrogen sulfide is not volatile at pH levels above 8 (Das, 2000). However, hydrogen sulfide has been reported is a prominent odor in certain circumstances such as where large quantities of gypsum (e.g. dry wall) are used for mushroom substrate composting (Miller, 1993). Hydrogen sulfide is heavier than air and can accumulate in confined environments, raising the possibility of asphyxiation.

Mercaptan (thiols)

Mercaptans, also termed *thiols* by chemists, are another group of volatile organic sulfur compounds that are characterized by a strong odor and detectable at low concentrations (Haug, 1993). Naturally occurring mercaptans are responsible for the odors that skunks emit and the aromas of garlic and onions. Two specific compounds associated with composting are ethyl mercaptan, also known as ethanethiol, and methyl mercaptan, or methanethiol. Of the two, methyl mercaptan is more often identified as a composting odor. Its characteristic odors is described as rotten cabbage or sulfide-like, (Wilmlink and Diener, 2001; Miller, 1993). It is used in low concentrations to impart an odor to natural gas. In decomposing organic matter, mercaptans result from the early steps of protein degradation (Miller, 1993). They can form aerobically but form or accumulate to a greater extent under anaerobic conditions (Epstein, 1997, E & A Consultants, 1993). Mercaptans have been identified as contributors to composting odors from several feedstocks, including food, paper processing residuals, biosolids and swine manure (Fraser and Lau, 2000, Walker and Gossett, 1999, Kuroda et al., 1996, E & A Consultants, 1993, Haug, 1993).

Organic Sulfides

Volatile organic sulfur compounds associated with odors include dimethyl disulfide (DMDS), dimethyl sulfide (DMS) and carbon disulfide (CS). These sulfur compounds have a strong offensive odor and likewise are detectable at low concentrations. They are often cited as the dominant sources of odors where manure, and especially biosolids, are handled. Organic sulfides are generated from the successive degradation of sulfur-containing proteins and “intermediate” by-products (e.g. methyl mercaptans). CS and DMDS are reported to form non-biologically (i.e. strictly chemical reactions) as well as biologically (Miller, 1993; Derix et al., 1991). While these sulfur compounds can form whether oxygen is present or not, they persist under anaerobic conditions. They further decompose to innocuous compounds under aerobic conditions. Thus, when degradation is predominantly anaerobic, the concentrations present (and emitted) are much higher, by a factor of 10 or greater (Walker and Gossett, 1999). Of these organic sulfides, DMDS appears to be the major odor source at biosolids composting facilities (Goldstein, 2002, Epstein, 1997, Hentz et al., 1996, Derix et al., 1991). However, DMDS and, to a lesser degree, the other organic sulfides appear to be primary contributors to odors with any feedstock that contains moderate to high sulfur contents, including food, manure and paper sludge (Miller, 1993; E & A Consultants, 1993; Noble et al., 2001; Defoer et al., 2002; Derix et al., 1991; Kuroda et al., 1996; Walker and Gossett, 1999).

Nitrogen Compounds

The decomposition of proteins and other organic substances generates a number of nitrogen-based compounds that are volatile and odorous. Ammonia is by the far the most prominent and important of these in terms of nitrogen (N) loss (Kuroda et al., 1996; Miller, 1993). Because of their offensive odors, two groups of organic nitrogen compounds are also notable -- amines and indoles. Whenever nitrogen is abundant, and especially where carbon to nitrogen ratios (C:N) are low (< 25:1), odorous nitrogen

compounds are likely to be emitted. Greater quantities are generated as the proportion of available nitrogen increases. These nitrogen compounds develop inherently as proteins decompose. Under aerobic conditions they continue to decompose and disappear relatively quickly, with the exception of ammonia.

Ammonia

The pungent smell of ammonia is familiar to most people. Ammonia and its pungent odor are present at many composting facilities, at least at those facilities that handle feedstock mixtures that have a high nitrogen content (e.g. with healthy proportions of manure, biosolids, fish, grass). In fact, ammonia is appreciably generated and emitted wherever high-nitrogen wastes are produced, stored or handled. Chemically, ammonia is the nitrogen analog to hydrogen sulfide. Ammonia (NH₃) is an inorganic volatile and reduced form of nitrogen that results from the degradation of protein, urea and nearly any degradable compound with nitrogen. It forms under both aerobic and anaerobic conditions. Ammonia is generated in large concentrations and amounts whenever the C:N ratio of the combined material is relatively low (< approximately 20:1) and the pH is elevated. With increasing pH, the water-soluble ammonium ion (NH₄) shifts to the volatile and odorous gaseous form of ammonia (NH₃).

Because of its strong smell and presence, ammonia is an odor concern for composting facilities, but usually within the facility's bounds. It is rarely the cause of odor complaints that occur beyond the facility. There are several reasons for this situation. First, ammonia has a high odor threshold (i.e. it takes relatively high concentrations to be detected). The character of the odor is not particular offensive to most individuals. Many people are familiar with the smell of ammonia and do find it suspicious. Perhaps most importantly, like H₂S, ammonia tends to dissipate rapidly after it is emitted (Haug, 1993). In short, because of its ubiquitous nature, ammonia remains an important odor compound but, in most cases, primarily near the point where materials are stored and handled. However, ammonia can be a serious problem with feedstocks that carry very high nitrogen contents such as poultry manure and fish waste, especially where large amounts of these materials are concentrated.

Amines

Amines are foul smelling volatile organic nitrogen compounds, that result from the decomposition of proteins and amino acids (Haug, 1993). In chemical structure, some amines are similar to organic sulfur compounds. The odor character of amines is suggested by the common names of two particular compounds – putresine and cadaverine. Both of these putrid-smelling compounds occur in decaying animal tissue. Some other amines that may contribute to odors include methylamine, ethylamine and trimethylamine. These amines tend to impart an odor that is often described as fishy and/or ammonia-like. While amines are often cited as potential sources of odor, none of the field studies reviewed specifically identified amines as a major component of odors at composting sites. Nevertheless, one would intuitively expect them to be present and to affect the odor quality at facilities that handle highly degradable nitrogen-rich feedstocks like fish waste, animal mortalities, poultry manure, grass and biosolids.

Indoles

Indoles are a group of *heterocyclic* nitrogen compounds (which means that they have a molecular ring structure with a nitrogen atom in place of a carbon). Two compounds in this group, indole and skatole, are known for their feces-like odor. Skatole is often noted

for its descriptive name. These compounds are produced by bacterial decomposition of the amino acid tryptophan and other proteins (answers.com 2005; Sawyer and McCartney, 1978). Bacteria in animal intestines produce indole and skatole, which produce the offensive smell of fecal matter. However, plants also produce indoles (e.g. the pigment in indigo). Ironically, at low concentrations these compounds can have a pleasant odor. They are the source of scent in some perfumes and flowers (e.g. orange blossoms) (answers.com, 2005). Indoles and skatole have not been identified as major odor sources at composting facilities. However, they undoubtedly contribute a negative character to the general odor quality where manure and biosolids are handled and processed. They would be most apparent when handling these feedstocks and at the early stages of composting. These compounds do not persist under aerobic conditions (Wilmink and Diener, 2001)

Volatile Fatty Acids (VFA)

Volatile fatty acids (VFA) are also referred to by the more general term volatile organic acids. They result from the decomposition of long chained organic acids that are common components of carbohydrates, fats and oils. As these compounds (and long chained acids) decompose, they split off low molecular weight VFAs. If oxygen is present, VFAs further decompose into carbon dioxide and water. If oxygen is not present, they accumulate and readily volatilize, potentially leading to odors. Depending on the parent compounds, numerous VFAs can develop during decomposition, each with a characteristic odor. In large enough concentrations, the odors are offensive. The most recognizable VFA is acetic acid or vinegar. Formic, propionic, valeric and butyric acids are other examples with disagreeable odors that range in quality from rancid to putrid (see Table 1). A VFA with a higher molecular weights tends to have a more intense odor than a VFA with a lower molecular weight (Goldstein, 2002).

Odors from VFAs are possible with almost any organic material, especially when anaerobic conditions prevail. VFAs are more likely to be the primary contributor to odors when nitrogen and sulfur are not abundant, and thus sulfides and amines do not dominate the overall odor. Green wastes, food and mixed MSW composting facilities can be troubled by odors from VFAs. For example, the characteristic smell of “garbage” is attributed to butyric acid. However, VFAs can be a significant contributor to odors even in feedstocks with abundant nitrogen and S, like swine manure (Kephart and Mikesell, 2000).

Terpenes

Terpenes are aromatic compounds that are naturally produced by various plants (see Table 1). They contribute to the fragrance of many plants including lemons, geraniums, rose, mint, pine and eucalyptus (Haug, 1993). As plant materials are amassed, processed (e.g. chipped and shredded) and handled, these aromatic compounds are liberated from the plant cells. If they remain within the confines of the composting pile or vessel, they decompose. However, when exposed to the air, or drawn out by air currents, these readily volatile compounds are released.

By themselves, at low to moderate concentrations, the smell of terpenes is not offensive to most people. However, at high concentrations, terpenes may present an odor that is annoying, if not offensive. Also, when mixed with the soup of other odors of decomposing materials, they may add to the intensity of an overall disagreeable smell. At composting facilities, terpenes appear to be prominent where woody materials are

composted, such as brush and tree branches at green waste facilities, sawdust bedding in manure, and wood chip bulking agents used in composting biosolids (Epstein, 1997)

Other Volatile Organic Compounds

Odors can emanate from several other categories of common volatile organic compounds including ketones, aldehydes and alcohols, among others. These groups encompass very common organic substances that form and disappear as nearly all types of organic compounds react with one another. For example, aldehydes and ketones are produced from the oxidation of different types of alcohols and further oxidize to form organic acids. Alcohols result from the oxidation of hydrocarbons.

These types of compounds occur naturally as complex organic substances degrade. In aerobic environments they tend to be short lived. Many compounds within these groups have an odor associated with them. Whether or not the odors from alcohols are unpleasant depends on the concentrations, intensity, human sensitivity to these compounds and the presence of other odorous substances. In general, they are rarely a primary component of malodors at a composting site but can contribute negatively to overall odor character. In certain situations, or with specific materials, an alcohol, ketone or aldehyde may produce a detectable and dominant odor.

Alcohols

Alcohols occur readily as organic molecules decompose. They can form aerobically or anaerobically but accumulate under anaerobic conditions (e.g. fermentation of wine). In composting, they would be detected if anaerobic conditions persist or if other conditions interfere with their continued aerobic decomposition. Such conditions occasionally occur when carbohydrates are abundant and their subsequent decomposition leads to an accumulation in organic acids.

The organic acids can depress the pH low enough to retard further decomposition of the alcohols that form. With time (and oxygen), the pH increases and alcohols eventually decompose but in the meantime, the material can emit the sour smell of alcohols. This situation is a typical of feedstocks that are rich in easily degradable carbohydrates (e.g. potato culls, some food wastes). It can be prevented by adding a liming or buffering agent to counteract the pH drop (Woods End Research Laboratories, 1990). When odors result from alcohols, the situation is relatively short-lived. Humans sensitivity to alcohols is moderate to low (Goldstein, 2002; Haug, 1993).

Ketones

Ketones such as acetone and methyl ethyl ketone (butanone) are quite volatile and have a “sweet” solvent-like odor (Miller, 1993). However, human sensitivity to these compounds is low (i.e. it takes a high concentration to detect them). Thus, although ketones are common byproducts of decomposition, they are not major odorants in themselves at composting sites. With other odorous gases, they can contribute to the overall malodor of decomposing organic materials.

Aldehydes

Several types of aldehydes develop in nature and from the decomposition of organic substances. Although it is concentration dependent, aldehydes of low molecular weight tend to have sharp objectionable odors while higher molecular weight aldehydes have a pleasant flowery odors (answer.com, 2005). Low molecular weight aldehydes include

formaldehyde, acetaldehyde (ethanal) and propionaldehyde (propanal). The most familiar aldehyde is formaldehyde, which is recognized by its penetrating medicinal odor. Acetaldehyde is a diverse and widely dispersed substance. It has a variety of industrial uses and can occur in variety of materials including, fruit, coffee, alcohol, tobacco, wood smoke and engine exhaust. Its characteristic odor also carries a variety of descriptions including green, fruity, suffocating and garbage-like (Miller, 1993; answers.com, 2005; Goldstein, 2002). Its hedonic tone is apparently a matter of concentration and/or environment.

In addition to the preceding compounds, countless other volatile organic compounds, which humans can sense as an odor, can develop as organic material decomposes. These compounds may contribute to the overall quality of odors or become evident in unique and particular circumstances (e.g. a load of pesticide treated vegetation or solvents in MSW). Such compounds include aromatic chemicals (e.g. benzene, toluene) and phenols (e.g. methyl phenol, ethyl phenol). Epstein (1997) presents several lists of individual volatile organic compounds that have been identified in studies of emission from composting facilities. These compounds may be more relevant in their impact on healthy air quality (in enclosed spaces) than nuisance odors.

What Conditions Lead to the Formation of Odorous Compounds?

Odors experienced at composting facilities are a result of some combination of the compounds that have been discussed in the previous section. The compounds primarily responsible for malodors appear to be organic sulfides (particularly DMDS and DMS), mercaptans, amines and VFAs (Goldstein, 2002; Miller, 1993; Epstein, 1997). In addition, terpenes can contribute to the strength of the generally disagreeable soup of odors (Haug, 1993).

These offending compounds are either present in the greatest quantities, detectable at low concentrations, or have the strongest odor intensity and unpleasant hedonic tone. With certain feedstocks, ammonia and, to a lesser extent, hydrogen sulfide, are emitted in relatively high concentrations. They represent important nutrient losses and can cause problems related to air quality and on-site odors. However, they are not often contributors to off-site odors. The remaining compounds identified are either minor components of odor or cause problems in only a few specific situations. For instance, the odor of alcohol can be the problem when the pH drops excessively.

Knowing the chemicals that lead to odors, the subsequent question to ask is why and how do these offending compounds develop? The single broad answer is that they form from the natural, and primarily biological, decomposition of organic matter. Organic matter contains various combinations and species of carbohydrates, proteins and lipids, which decompose into simpler compounds. Odorous compounds can form via different biochemical processes, depending on the conditions (e.g. anaerobic vs. aerobic) and parent compounds available. Most of these chemicals are intermediate compounds in a progression of biochemical reactions; that is, they form and then change into other compounds. In a composting environment, compounds can transform in either direction: (a) they can degrade into simpler and more stable (i.e. more oxidized) molecules, such as carbon dioxide and water (and liberate energy); or (b) they can become the constituents of more complex organic compounds as microorganism use them for cellular material (thereby incorporating energy). The resulting compounds may or may not be volatile and

odorous Therefore, an additional question to ask is how and why odorous compounds persist and accumulate to levels that result in detectable odors.

Important factors in the formation and fate of odor-causing compounds include the feedstocks, nutrient balances, oxygen, aeration, time, moisture, bulk density and porosity, temperature and pH.

Feedstocks

The type and mix of feedstocks composted are important determinants of odor. Feedstocks are probably the most important factor in determining what particular intermediate and potentially odorous compounds develop. The feedstocks establish the molecules and elements available for biochemical reactions, and their relative proportions. Thus, for example, feedstocks that do not contain appreciable amounts of sulfur will not produce appreciable quantities of organic sulfides. In addition, the relative mixture or proportions of different feedstocks influences what compounds ultimately form and accumulate (see nutrient balances below).

Miller (1993) provides examples of several precursors of selected odorous compounds, and these precursors are contained within the feedstocks. He identifies the amino acids cystine and methionine as sources of sulfur, with lesser amounts in other organic compounds. According to Miller, poultry manure is particularly rich in these amino acids and sulfur generally (0.56%).

Also, biosolids can have sulfur contents ranging from 0.3 to 1.2%. Other feedstocks identified include mixed food wastes (0.4%), other types of manure (0.25-0.3%) and garden trimmings (0.3%). Precursors identified for volatile nitrogen compounds include amino acids, proteins, urea and other organic compounds with N. Feedstocks high in nitrogen in manure (especially poultry), biosolids, grass clippings, fish wastes, blood, meat and many types of food processing wastes (Rynk, 1992). In general, any feedstock rich in protein can be expected to be a potential source of volatile nitrogen (ammonia, amines, indoles), and possibly volatile sulfur as well (organic sulfides, mercaptans, hydrogen sulfide).

VFAs may form from any organic feedstock. However, they are more likely to accumulate in feedstocks with abundant and rapidly degrading carbohydrates, fats and oils, especially without sufficient oxygen (Miller, 1993). Phenol forms from the decomposition of lignin, which is abundant in wood (Miller, 1993). Particular terpenes emit from their associated plant materials, such as limonene from lemons, pinene from pine and cineol from eucalyptus.

In addition to its molecular composition, a feedstock's degradability also influences the creation of odorous compounds. Degradability refers to how quickly and completely a material decomposes. Feedstocks that degrade quickly tend to produce more odors, in part because oxygen is used up quickly and cannot be replaced fast enough. Hence, anoxic conditions prevail. In addition, with rapidly degrading feedstocks, the first stages of decomposition may simply outpace the subsequent stages, regardless of the availability of oxygen. Therefore, odorous intermediate compounds accumulate. As mentioned earlier, feedstocks that are rich in easily degradable carbohydrates can accumulate alcohols, which may be followed by aldehydes and ketones. In addition, quickly degrading feedstocks can lose porosity as they decompose, further challenging aeration. With most feedstocks, degradability is closely associated with lignin concentration (Richard, 2005).

It is important to recognize that when feedstocks are delivered to the composting site, they carry the associated odorous compounds, already formed or well on their way to being formed. Indeed, raw feedstocks are often the principle source of odors at composting sites (as opposed to odors that arise from the composting process). The amount, extent and impact of the raw feedstock odors depend on their volume and their previous history and handling. The following factors that influence the formation of odorous compounds during composting also influence the formation of odorous compounds within the raw feedstocks prior to composting.

Nutrient Balances

As feedstocks decompose, they provide nutrients to the decomposer organisms. The organisms use nutrients in proportion to their metabolic needs. Microorganisms do not readily process the excess nutrients, which then persist, possibly in a volatile form. Because carbon (C) is the element needed in greatest proportion, nutrient balances are often expressed in ratios with carbon.

Carbon to Nitrogen (C:N)

The prime example of the importance of nutrient balances is nitrogen (N). If nitrogen is abundant relative to carbon (e.g. C:N ratio < 20), volatile forms of nitrogen, mostly ammonia, are produced from the surplus N. However, if the same amount of N is available with a proportional amount of available C (or more), the available N is used by microorganisms and incorporated into their biomass (e.g. compost).

On the other hand, when the C:N ratio is very high, an excess amount of C exists. In this situation, decomposition slows because other nutrients limit the microbial metabolism. However, if easily decomposable C sources are present, volatile C compounds can accumulate and become noticeable as the dominant odor—VFAs, alcohols, phenols and terpenes, for example.

Carbon to Sulfur (C:S)

The same situation is likely to exist with other key elements like sulfur (S). Miller (1993) notes that stable organic matter has a C to S ratio of about 100:1. He implies that sulfur compounds would tend to volatilize from feedstocks with C:S ratio appreciably lower than 100:1. Because sulfur compounds are important odorants for organic materials, the C:S ratio may be a useful indicator of odor potential. It is conceivable that the addition of sulfur-rich feedstocks, like gypsum, may push the C:S ratio high enough to cause odor problems.

Carbon Availability and Lignin

The C:N ratio is customarily calculated from laboratory analyses, which provide the total concentrations of C and N. However, total C is often a poor indicator of how much C is available to the microorganisms (Das, 2000). Many carbon-compounds are inaccessible to even microbial enzymes and cannot be degraded in the normal time frame of a composting system. This situation occurs to some degree with all feedstocks but it is particularly relevant to wood and some types of paper (e.g. newsprint). The determining factor appears to be the amount of lignin present (Kayhanian and Tchonbanoglous, 1992). Lignin is a complex organic compound formed in plants, and is especially abundant in wood. It is difficult to biochemically decompose. Lignin also physically blocks microorganisms from attacking other more readily degradable organic compounds, like cellulose (Richard, 2005).

In feedstocks that have a high lignin content, the C:N ratio (and the C:S ratio) is artificially high. The *effective* C:N ratio is actually much lower because a large portion of the carbon is unavailable to the microorganisms. Tchobanoglous et al. (1993) suggests determining the biodegradability of a feedstock based on its lignin content according to the following empirical equation.

$$BF = 0.83 - (0.028) \times LC$$

Where BF is the biodegradable fraction of the volatile solids and LC is the lignin content of the volatile solids as a percent of dry weight. The numbers 0.83 and 0.028 are empirical constants.

Das (2000) presents a procedure for adjusting the C:N ratio using the above equation and work published by Kayhanian and Tchobanoglous (1992). However, it should be recognized that particle size also affects the availability of carbon and other nutrients (larger particles reducing availability). Richard (2000) offers a good review of the effect of lignin and other factors on biodegradability, carbon availability and C:N ratio.

Oxygen (aerobic vs. anoxic vs. anaerobic decomposition)

Oxygen is a critical factor in the genesis of composting odors. Oxygen determines the biochemical processes at work (i.e. anaerobic vs. aerobic) and the compounds that result. Many odorous compounds can form simply because organic materials degrade –in both aerobic and anaerobic environments. However, the situation is much more severe when anoxic or anaerobic conditions exist. The terms anoxic and anaerobic often used interchangeably to describe no-oxygen conditions; even though, they refer to different metabolic modes. Anoxic refers to the metabolism where microorganisms use an oxygen bond in other molecules such as NO₂-3 (nitrate) as the terminal electron acceptor; whereas, anaerobic means microorganisms use other molecules.

In the presence of oxygen, many of the odorous compounds do not form at all, or they are so transient that they can be said not to form. When sufficient oxygen is present, nearly all of the odorous compounds that do develop ultimately transform into non-odorous products (ammonia being an exception). Without enough oxygen, odorous compounds form and accumulate more readily and to a greater extent. This condition greatly increases the intensity, unpleasantness, and duration of the odors that occur. Maintaining adequate oxygen levels, i.e. aerobic conditions goes a long way toward avoiding odor problems during composting and correcting problems that arrive with anaerobic feedstocks.

The odorous compounds that are problems essentially *only* when anoxic and anaerobic conditions prevail include hydrogen sulfide, organic sulfides (e.g. DMDS, DMS) and VFAs. Compounds that might be evident in aerobic situations but reach problem levels under anoxic and anaerobic conditions include amines, indoles, mercaptans, alcohols, ketones and aldehydes. Although oxygen advances the degradation of terpenes, they are often detectable in any case when they are liberated from plant cells.

Aeration

Aeration is the mechanism that brings and distributes oxygen-carrying air to the mass of composting materials. Aeration also removes heat, moisture and other gaseous products of the decomposition occurring within the mass. Aeration delivers the fresh air and removes the exhaust air through the intricate network of air-filled pores within the mass. From those pores, oxygen diffuses into and through the films of moisture that cling to the

solid particles that are undergoing these chemical transformations. In composting, aeration occurs by natural or passive air movement (thermal convection, diffusion, wind) or by forced aeration (fans).

The primary effect of aeration on the formation of odorous compounds is related to its impact on oxygen concentration, as discussed above. Odorous compounds can form in problem quantities if the aeration fails to deliver enough fresh air and oxygen or if it fails to distribute the air evenly. In the latter case, odorous compounds can develop in the air-starved *sections* of the composting mass. If there isn't sufficient oxygen surrounding those sections to degrade the odorous compounds, then odors are released when those sections are exposed or if the aeration system carries those compounds to the ambient environment.

A secondary affect of the aeration system on the formation of odorous compounds concerns temperature and moisture. Removing excess moisture and heat (thus controlling the temperature) are additional functions of aeration. The effects of temperature and moisture on the formation of odorous compounds are discussed below.

Aeration is an important factor in the transport of odorous compounds from the composting mass to the outside environment. The aeration system may remove an odorous compound before it has the opportunity to further decompose in place (Elwell et al., 2004). Odor released due to aeration is discussed in a later section.

Turning

For passively aerated composting methods, like windrow composting, turning is the primary tool for operators to control the process, and thus the formation of odors. Turning introduces fresh air, improves the distribution of water and nutrients and may improve porosity in some cases. It advances the composting process and improves odors in the long run. Even with forced aeration, turning overcomes the stagnation exhibited by static composting and advances the process. However, at the same time, turning opens the interior of piles and windrows and releases trapped odorants.

The conditional effects of turning on odors are evident from a pair of excellent studies of green waste composting from the late 1990s. Buckner (2002a, 2002b) examined how green waste composition (e.g. grass, leaves, wood chips) and turning frequency influenced oxygen concentration and odor emissions. Michel et al, 1996 examined the effects of these factors plus pile size on odors, oxygen and other composting process parameters. Together, the two studies suggest that turning has the following effects.

- Turning stimulates decomposition and oxygen demand.
- Turning has little impact on internal windrow/pile temperatures. Overall, temperatures recover to pre-turning levels, achieving neither a lasting heating nor cooling effect.
- The frequency of turning has little effect on internal oxygen concentrations. Any positive effects on aeration rate may be negated by the higher oxygen demand as the process is stimulated. In fact, Buckner found generally higher oxygen concentrations in windrows turned once per week compared to six times per week. Feedstock composition and porosity have a greater effect on oxygen concentration than turning frequency.

- The effects of turning on odors depend on the feedstocks and their porosity. Turning is more effective at suppressing odors with feedstocks that decompose quickly and without the benefit of good porosity (e.g. grass and leaves). On the other hand, these types of feedstocks release more odors upon turning, regardless of the frequency.
- Odors are greatest with the first turning and subside quickly with subsequent turnings. Odor spikes can occur later with subsequent turnings if the turning schedule is relatively infrequent (e.g. weekly vs. daily).
- Daily or almost daily turnings are required to maintain elevated oxygen concentrations indicated of truly aerobic conditions during the early stages of composting (Michel, 2002). However, even with infrequent turning (e.g. monthly), decomposition tends to be primarily aerobic rather than anaerobic, supported by passive air movement and diffusion.
- Turning does not necessarily improve the porosity of the feedstocks by fluffing, as has been suggested (Rynk, 1992). In fact, Michel et al. found that the chopping effect of turners reduces particle size in mixtures of leaves and grass. Thus, these mixtures become denser shortly after turning. The influence of turning on porosity, its “fluffing effect,” may be dependent on the condition of the feedstocks. Turning may temporarily increase the porosity (i.e. decrease the bulk density) of feedstocks, like manure, that already have fine particles. With bulky feedstocks that easily shred, like leaves, turning produces “reverse fluffing”—they increase in density and decrease in porosity, Michel et al. discovered.

Time

Time is an odor factor because decomposition is not a steady process. It advances quickly at first and gradually slows in pace. In the early stages, the most readily degradable compounds decompose in a fast and accelerating pace. In this time, intermediate compounds form and transform, temperature climbs and oxygen demand is great. As the process continues, the moderately degradable compounds in the feedstocks begin to breakdown along with the resulting intermediate compounds. The biological activity and oxygen demand settle to a high but steady pace. Over time, the rate of decomposition and oxygen demand gradually fall to relatively low levels until the compost matures.

The connection to odor is that odorous compounds are formed and/or released in greatest quantities in the first stage of the process, during the same period that the need for oxygen is greatest. Therefore, the likelihood of odors is greatest during the first days, and up until the first week or two of composting. Indeed, the process may have started before feedstocks arrive at the site, depending on how and how long they were stored and handled. Several investigators have tracked emissions of odorous compounds over time and concluded that most odors are released in the first 3 to 14 days of composting (Epstein, 1997).

The high early emissions of odorous intermediate compounds rather than oxidized end products (e.g. CO₂ and H₂O) may be due to the high oxygen demand at this time. The aeration mechanisms may not be able to supply enough oxygen to meet the demand. Alternatively, regardless of the mode of aeration, the rate of oxygen diffusion from the interstitial pores to the microorganism may not be fast enough to match their O₂ consumption (see Moisture section below).

Yet another possibility is that the subsequent steps of decomposition are not keeping pace. For examples, given the large amount of substrates in the feedstocks, one set of microorganisms may be forming mercaptans faster than the next set can oxidize them. In any case, with time, fewer odorous intermediate compounds are emitted.

Moisture

Moisture is related to odors in several ways—in its effects on aeration and oxygen diffusion; in its influence on decomposition; and in regard to retaining volatile compounds in solution.

Moisture greatly effects the "oxygen status" of decomposition—that is, whether or not, oxygen is available to the decomposer microorganisms and how much oxygen is available. It impacts oxygen first in its effect on aeration -- the movement of air into the pore spaces of the composting mass.

If too much moisture is present then water occupies the pore spaces (reducing "free air space," or FAS) and makes it more difficult to oxygen-carrying air to enter the mass, and for carbon dioxide and other gases to leave. The second effect is for moisture to interfere with the diffusion of oxygen from the pore spaces through the liquid film (i.e. water solution) surrounding the solid particles that are decomposing.

The decomposer microorganisms inhabit that liquid film and rely on diffusion to deliver oxygen. Because diffusion of oxygen through water is relatively slow, a thicker film, due to higher moisture content, reduces the oxygen supply to the microorganisms. Via both effects, higher moisture contents lead to lower oxygen levels and more anoxic and anaerobic environments.

On a practical level, the moisture threshold for avoiding anaerobic conditions is approximately 60% (wet basis). However, this number represents a compromise and a practical target. The optimal moisture content depends on the feedstocks (e.g. particle size, degradability) and the stage of composting (Richard et al., 2002).

Furthermore, it does not ensure that anaerobic conditions are avoided. It simply reduces the occurrence to a practical and tolerable level. Overall, excessive moisture (> 60%) increases the occurrence of anaerobic conditions and the formation and persistence odorous compounds (Wilber and Murray, 1990).

Moisture is necessary for active decomposition. More moisture generally advances the rate of decomposition and thus increases the generation of the products of decomposition. If the feedstock is dry, decomposition proceeds slowly or not at all. Odorous compounds that result from decomposition are not emitted from dry materials. However, dry materials can emit odorous compounds that are inherent to the feedstock, such as terpenes from wood and green wastes.

In some cases, the release of some odorous compounds can conceivably increase as the material dries. As the moisture content decreases, the concentration of potentially volatile compounds in the remaining water solution increases. This increase can shift the equilibrium between soluble and volatile forms, encouraging volatilization. For example, as moisture decreases ammonium in solution becomes concentrated and, in turn, some ammonium converts to ammonia. Conceivably, the same situation can occur with terpenes in freshly cut pine branches. The impact of this drying effect on composting odors is probably small because it represents a situation where odor problems are not likely to be serious.

Bulk Density and Porosity

Bulk density affects odors because it influences aeration and oxygen concentration. Bulk density is determined by the size and shape of particles and the density of the individual particles. These factors also determine the material's *porosity* and *free air space* (FAS). Porosity is the proportion of a bulk material occupied by pore spaces. FAS is the pore space that is not filled with water. Bulk density and porosity are closely related (Day and Shaw, 2001). Moisture is an important factor in determining bulk density, and it can confound generalizations about how bulk density affects aeration, oxygen and odors. However, if one considers "dry" bulk density, or assumes a moderate level of moisture, some generalizations are reasonable.

Dense feedstocks tend to have small particles and narrow pore spaces between particles. The closely-spaced matrix of particles offers considerable resistance to air movement within the materials. This situation inhibits both passive and forced aeration and reduces the resupply of oxygen. In addition, at a given moisture content, as the bulk density increases there is generally a greater mass of organic matter to decompose—per unit volume.

Thus, oxygen demand and oxygen consumption are greater—per unit volume. In short, anaerobic conditions are more likely to occur in feedstocks and feedstock mixes as the bulk density increases. Buckner (2002a, 2002b) found that odors from composting grass clippings were better controlled using mixtures with higher proportions of wood chips. Similarly, Epstein (1997) reported the data in Table 4 showing an increase in mercaptans with increasing bulk density of a mixture of green waste and food residuals (produce wastes).

In comparing the last two columns, note that bulk density alone is not the only factor. The higher proportion of food waste in the 4:2 mix ratio elevated the mercaptan emissions even though the bulk density was slightly lower than the 4:1 ratio mix (although for practical purposes the bulk densities of the two mixes are equivalent).

For this reason, dense feedstocks are typically mixed with light or bulky feedstocks (i.e. bulking agents) to reduce the overall bulk density and improve porosity and aeration. Generally composting recommendations suggest that bulk density should be less than 1000 lbs/cu. yd. (Oshins, 2006).

Table 4: Effect of initial bulk density on the formation of odorous compounds (mercaptans)

Initial mix ratio of green waste to produce (food) waste	4:0	4:1	4:1	4:2
Preprocessing	None	None	Hammermill - all material	Hammermill - all material
Bulk density – lbs/yd ³ (kg/m ³)	255 (151)	425 (252)	1273 (755)	1187 (704)
Oxygen concentration (sample at 3 ft. high and 4 ft. deep)	20%	19%	0.3%	0
Total mercaptans (sample at pile surface)	0.2	0.5	25	100

Source: adapted from E&A Consultants, Inc., 1993, after Epstein, 1997.

Temperature

Temperature has numerous effects on the composting process and the compounds that arise. Temperature influences the composition of the microorganisms (Miller, 1993; Strom, 1985), the rate of biological activity, the rate of chemical reactions, moisture loss, aeration (e.g. thermal convection), oxygen diffusion and the transport of gaseous compounds.

Up to a limit of approximately 60°C (Miller, 1993), increasing temperature generally increases biological activity and, hence, the rate of decomposition. Therefore, all other things equal, a rise in temperature also brings a rise in oxygen demand. Fortunately, this situation (higher temperature – faster decomposition) is usually accompanied by greater aeration. With passive aeration, the higher temperature tends to increase air movement due to thermal convection (assuming that there is enough porosity to accommodate the additional air flow).

With forced aeration, when the rate of composting increases the aeration system is activated more often because aeration is usually controlled by temperature for cooling purposes. On one hand, as temperatures increase, potentially odorous compounds form faster due to faster rate of decomposition and greater oxygen demand (at least up to 60°C or so). On the other hand, the additional aeration and/or the faster decomposition of the odorous intermediate compounds tend to reduce the potential for odors. In regard to odor formation, some evidence suggests that the “other hand” prevails – that increasing temperatures reduce odors.

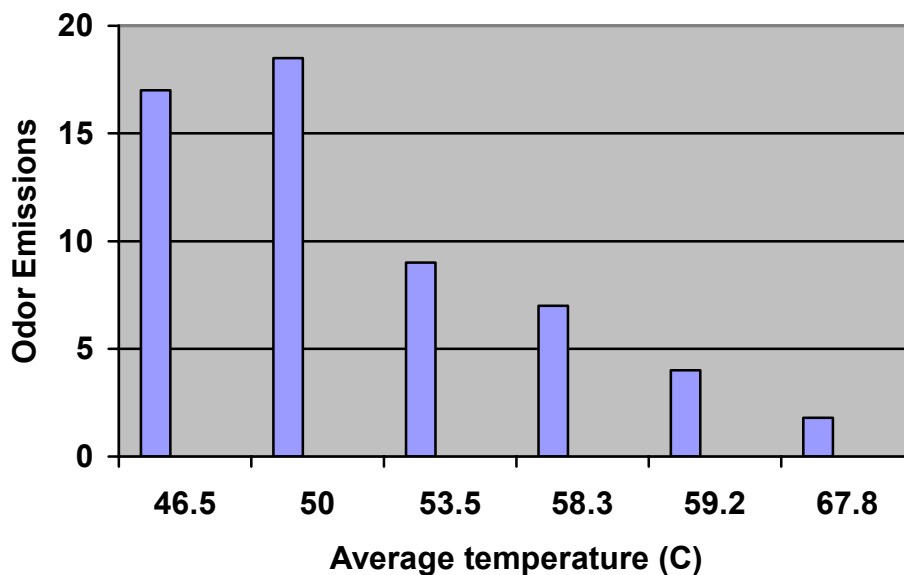
Epstein (1997) reports a study by Wilbur and Murray (1990) that shows decreasing odor emissions at a biosolids composting facility with increasing temperature, from 46 °C up to 68 °C (Figure 1). At the upper limit, these results seem to contradict citations by Miller (1993) that indicate a reduction of odors below 60°C. However, the upper temperature threshold for composting is still debated. Several researchers have suggested thresholds greater than 60°C (Epstein, 1997).

Chemical reactions also increase with temperature (by about a factor 2 for every 10°C rise). At very high temperatures, chemical reactions can generate odorous compounds, at a faster rate, without the counteracting benefit of microbial oxidization of those compounds. For example, Derikx et al (1991) reported the increasing rates of DMDS generation with increasing temperatures up to 90°C. At these high temperatures DMDS can form more rapidly but cannot be degraded biologically. Thus, it accumulates to a higher concentration.

Temperature has another profound effect on odors – it increases the vapor pressure of most compounds. Volatile compounds volatilize and become air borne more readily as temperature increases. In fact, there is a double penalty in this relationship because, as noted earlier, aeration also tends to increase with temperatures. Thus, with higher temperature, volatile compounds become more volatile and there is also more air flow through the material to carry those volatile compounds toward someone’s nose. This effect has more to do with the impact of odorous compounds than their formation (see following sections).

Generalizations about the relationship of temperature to odors are difficult, given the multiple influences that temperature has on decomposition and odor transport. The net effects likely depend on specifics such as the particular volatile compounds present, the stage of composting, the availability of oxygen, exposure to the ambient environment and the feedstocks and their degradability. In general, if conditions (e.g. oxygen, moisture, pH) are favorable for composting, odorous compounds generally decrease with increasing temperatures, at least up to some maximum between 60°C and 70°C.

Figure 1: Effect of temperature on odor emissions



Source: from Wilbur and Murray, 1990, after Epstein, 1997.

pH

pH indicates the acidity and alkalinity of the chemical environment or solution. It is a measure of the relative concentration of hydrogen (H) and hydroxide (OH) ions. pH affects, and is affected by, the chemistry and biology of composting. It helps determine the microorganisms that thrive and the direction and nature of chemical reactions. Specific enzymes tend to have relatively narrow pH ranges (Sawyer and McCarty, 1978).

Because of the inherent robustness of the composting process and the great diversity of microorganisms that participate, composting takes place over a broad range of pH levels (Oshins, 2006). Still, there are benefits to keeping the pH closer to neutral (6.5 to 8.0). In addition, extreme pH levels can substantially inhibit biological activity, which is normally a problem but can also be used to one's advantage.

pH shifts the chemical equilibrium of several important volatile compounds. At high pH (> 8), soluble ammonium (NH_4^+) is converted to volatile ammonia. The smell of ammonia is particularly evident with feedstocks that have a high pH, including poultry manure, and feedstocks that include wood ash or lime (e.g. lime-treated biosolids). In contrast, lower levels of pH (<7) favor the formation of hydrogen sulfide, relative to the soluble sulfide ions, S^{2-} (Sawyer and McCarty, 1978, p. 478). In the absence of oxygen and at acidic pH (<7), hydrogen sulfide is likely to form, and smell, if sulfur is available. At higher pH (> 8), hydrogen sulfide odors are unlikely in any case.

The combination of low pH and anoxic conditions constitutes a "reducing environment." In reducing environments, incomplete biological processes prevail including anaerobic decomposition and fermentation. In this situation, chemical elements tend to exist within "reduced" states, meaning that they are not completely degraded. Reduced compounds retain some energy. When oxygen is present, they are further degraded (i.e. oxidized) by organisms.

Thus, reduced compounds are often termed intermediate compounds. Many odorous compounds identified with composting are intermediate and reduced forms, including hydrogen sulfide, organic sulfides, amines, ammonia, VFAs and alcohols. Reducing potential is influenced by *both* the concentration of oxygen and the pH but extremes of one or the other can lead to reducing conditions. As previously mentioned, alcohol can accumulate during the early stages of composting when the pH drops to a very low level. The alcohols result from fermentation of the organic substrates and then accumulate because of the lack of either oxygen or biological activity (due to the low pH).

Composting feedstocks have a strong buffering capacity that tends to resist changes in pH. However, large additions of very acidic or very basic materials can produce extreme changes. Lime and wood ash have been intentionally added to raw composting feedstocks with the purpose of temporarily slowing the biological activity and prevent the formation of odorous compounds (Lystad, et al., 2002; Campbell et al., 1997).

For example, Lystad (2002) reported results of a project at a composting facility in Norway in which lime was added to food and green wastes ("biowaste") to raise the initial pH to 11.9 in order to control the odor emissions during handling and the early stages of composting. The investigators reported that the overall odor situation improved and that the pH recovered to levels below 8 after a few days of composting in an enclosed vessel (and before the partially composted feedstocks were placed in outdoor windrows). Campbell et al. (1997) used a similar approach, adding wood ash to biosolids to improve odor performance. While the high pH amendments had little impact on the compost

quality in the project in Norway, Campbell et al. reported that the finished compost had a lower maturity and higher final pH and salts due to the wood ash additions (Das, 2000).

Degradation versus Dispersal (exposure and transport)

Volatile intermediate compounds eventually degrade within the composting mass, given a population of suitable microorganisms and enough time for oxygen to find its way to the compounds. In the meantime, the compounds accumulate within the solution or within the pore spaces of the composting mass. Alternatively, volatile compounds can be carried away by the aeration system or volatilized upon exposure to the ambient environment via agitation or turning. Thus, the fate of odorous compounds, once formed, also depends on the aeration system and the extent and timing of turning and other means of agitation.

The dispersal of odorous compounds can have positive or negative effects on the facility depending on the specific situation. For instance, if the concentration of odorous compounds is high, their dispersal may cause odor problems. If compounds are continually or frequently dispersed at low concentrations, below detection thresholds, the dispersal may reduce their accumulation and lower the potential for problems when the composting mass is eventually disturbed. This line of thinking raises the question of whether frequent turning is preferred to infrequent turning.

What Conditions and Factors Lead to Off-Site Impacts (For Example, Odor Complaints)?

In order for an odorous compound, or a soup of odorous compounds, to become odorous, it must first volatilize, become airborne and escape into the environment. Then, it must be transported to a person, remaining in concentrations sufficiently high enough to be detected and to be considered objectionable by that person. Thus the necessary set of conditions that leads to an odor impact on the neighboring community includes:

- Odor source (in which odorous compounds)
- Odor emissions
- Odor transport
- Odor persistence and detection

The previous chapters of this report discussed the formation, volatilization and nature of odorous compounds associated with sources at composting facilities. This section focuses on the sources, emissions, transport and fate of these odorous compounds in the environment. The succeeding chapter concerns how people perceive and react to odors.

Odor Sources

Any location within a composting site that harbors organic compounds is a *potential* odor source including raw feedstock piles, active composting piles and windrows, curing piles, finished compost piles, grinding areas, biofilters, runoff storage ponds, puddles on the site and even surfaces where organic materials have been stacked. Some of sources present a much greater risk than others and these sources tend to be the primary

contributors to odors. In general, materials in the early stages of decomposition present the greatest risk of odors because they generate greater quantities of natural and intermediate volatile compounds and they need more oxygen to remain aerobic. Therefore, raw feedstock piles and relatively “young” composting windrows and piles are usually the sources of most concern, and deserve the most scrutiny. However, other sources cannot be ignored and may even emit a greater amount of odorous compounds than composting piles. Much depends on the specific conditions.

Epstein (1997) reports data from a study by Toffey et al. (1995) of odors from an aerated static pile from a biosolids composting facility. The study reports that the mass of odors released from biofilters and curing piles were comparable, and in some cases greater, than the mass emitted from composting piles (aerated under negative or suction air flow). In part, the contribution of odors from the biofilter and curing piles were due to air flow patterns and exposed surface area of these sources.

Elitzer (1995) shows collective emissions data of numerous volatile organic compounds at various points in several MSW composting facilities (some including yard trimmings or biosolids). Although the trends differ slightly among the various compounds, the highest emissions tend to come from the feedstock tipping floor, the output of composting digester drums (first stage of composting) and from newly formed composting piles. For some compounds, emissions were higher from “mid-aged” and “old” piles than fresh piles but generally emissions decreased with pile age and were lowest in the curing piles.

As indicated by the Toffey study, odor treatment devices like biofilters, and chemical scrubbers as well, can be relatively prominent contributors to site odor emissions, where they are used. This fact does not imply that they are ineffective, though poor design and operation would certainly increase the emissions. On the contrary, biofilters and scrubbers have been found to substantially decrease total odor emissions (Kuter, 1990; Williams and Miller, 1993).

However, because exhaust air from piles, buildings and other enclosures is delivered to these treatment devices, they become points of concentration for odor emissions, even after they substantially remove and treat odorous compounds. At the same time, the odor emissions decrease from the other sources. In a sense the treatment devices become a point source of odors. This situation is especially true for scrubbers that discharge treated air through an exhaust stack (as opposed to the broad surface of a biofilter).

Scrubbers, and even some biofilters, act like point sources of odor. Buildings and in-vessel exhaust outlets are other possible point sources. However, most other potential odor sources at a composting facility are considered area sources. Area sources emit volatile compounds over a broad area without a distinct and continuous air current (as in an exhaust stack). Emissions from area sources are more difficult to measure, quantify, predict and control.

The emissions from area sources tend to be inconsistent and more dependent on ambient conditions than point sources, although computer models often assume a constant average emissions rate (Brant and Elliott, 2004). Prominent area sources include storage piles, windrows, open aerated piles and bins, curing piles, processing and handling areas, water bodies (e.g. ponds) and the site itself.

Water storage ponds can emit odors if they become overloaded with organics to the point that oxygen is depleted and the water body becomes anoxic and anaerobic. Volatile

odorous intermediate compounds form within the water just as they do within the solid composting mass, perhaps even more readily. The same situation exists for small puddles and water-soaked soils that remain on site.

It has been suggested that the site itself can become a large area source for odors as organic liquids and small solid particles seep into the soil and pad surfaces overtime, more so at locations where feedstocks and composting piles are placed. Thus, the site can conceivably acquire a “resident” odor as the embedded organics decompose and volatile compounds are continually formed and emitted. This situation might explain the increase in odors occasionally reported following rain at some facilities (Rynk, 2004). The contribution of site surfaces to facility odors has not been reported in literature so the concept remains a matter of conjecture. Given the other large areas of actively decomposing material at most facilities, the site itself is probably a relatively small contributor to the total odor.

How much odor a given source contributes to the overall odor condition depends on many factors, including process conditions, oxygen, aeration, volume and exposure (e.g. agitation, surface area). In addition, while the odor produced by any single source may be inconsequential, the combined emissions from several sources on a site may bestow the facility with an “ambient” odor that can periodically lead to off-site problems. Such odor problems may occur only during unfavorable weather conditions and/or when activities at the facility raise the ambient odor level above some critical threshold.

Odor Emission

Once formed within a mass of decomposing organic feedstocks, an odorant can continue to decompose, remain within the mass to decompose later or escape into the environment. Its escape may come relatively slowly through exposed surfaces via passive mechanisms, typically diffusion or thermal convection. Or, active forces like agitation and forced aeration can hasten its liberation. Any factors that either accelerate or retard the decomposition of the odorant also play a role in the potential for the odorant to become an odor. Odor problems do not occur when an individual molecule of an odorous compound escapes the facility. The problems occur when odorant molecules leave in huge numbers.

Volume/Mass

Another relevant factor in the release of odors from a facility is the amount of material on site, whether the amounts is expressed as volume (e.g. cubic yards) or mass (e.g. tons). Odor problems have been attributed to facilities increasing the amount of feedstock accepted (Rynk, 2003). There are several reasons that the amount of material influences odors.

First, a greater amount of material potentially generates a larger inventory of volatile compounds. Second, more material translates to a larger surface area for the potential release of odors. Third, as the material volume increases so does the workload and pressure on management to keep the operation running well. How much a factor the resident mass/volume depends on the nature of the facility (e.g. enclosed vs. open; isolated vs. populated area) and the composting methods employed (e.g. large piles vs. small piles).

No rationale exists for determining volume (or mass) limits that would minimize odors. Furthermore, there are no universally accepted standards. Nevertheless, some jurisdictions have established guidelines for the purpose. For example, Massachusetts

Department of Environmental Protection (MDEP) professionals use an unofficial benchmark of 3,000 to 6,000 cubic yards per acre (Martinson, 2003). This range is drawn from the experience of the DEP's composting program staff, considering the size of windrows and piles that can be comfortably managed by facility operators. The Michigan Compost Operator Training Manual (Michigan Composting Coalition) suggests the following maximum annual throughputs (volumes accepted per year) as reasonable to avoid odors:

- Low intensity management: 3,000 cy per acre per year
- Medium intensity management: 5,000 cy per acre per year
- High intensity management: 8,000 cy per acre per year

In this case, "management" refers to the type of composting method used and the level of oversight and manipulation. The manual does not provide for either a technical or historical basis for the foregoing volume limits. Again, there is no rational or data to support volume limits for odor control. One can establish maximum sizes for windrows and piles and then calculate the corresponding volume per acre. However, setting maximum windrow and pile sizes is arbitrary and does not take into account the site conditions, process management and feedstocks and other conditions that can vary among facilities.

Surface Area

Volatile compounds escape from surfaces of windrows, piles and bins. Therefore, the amount of surface area exposed to the environment is a very important factor in the odor equation. All of the area sources identified earlier, including water and soil surfaces, release volatile compounds roughly in proportion to the exposed surface area. However, the geometry of piles and aeration patterns affect the emissions as well. For example, in passively aerated piles and windrows, more volatile compounds tend to escape with the air flow through the ridge than the sides. Exposed surfaces are especially critical for sources that generate a large amount of volatile compounds.

Thus, an expansive feedstock pile is worse than an expansive pile of finished compost. Small piles (i.e. short piles) have a greater surface area to volume ratio than large piles (i.e. tall piles). Thus, one can argue that odors are better contained by large piles. In fact, some composters do make this argument.

However, large piles are more difficult to effectively aerate and anaerobic conditions are more pervasive. Thus, very large piles of actively decomposing materials are generally discouraged. Forced aeration is one means to increase pile size, limit surface area and maintain acceptable aeration within the pile (see forced aeration section below). Another alternative is to limit the exposure of surfaces by containing materials within bins, buildings, vessels or flexible envelopes.

As Haug (1993) describes, the "surface odor emissions rate" or SOER is a useful technique for conceptualizing, measuring and modeling odor emissions from surface area sources like windrows, piles and biofilters. The SOER encompasses both the concentration of the "odor" and its rate of emissions per unit area. The SOER can be measured using an enclosed sampling hood and drawing air off the surface at a known rate and capture the sample in a tedlar bag or canisters. The procedure is not as straightforward as described.

The technique can be confounded by several factors, including variations in emissions rates over the surface. Therefore, several standard procedures have been established, although these procedures continue to be refined. For example, the South Coast Air Quality Management District (AQMD) uses a flux-chamber method that was originally developed by the U.S. Environmental Protection Agency to collect air pollutant emissions from contaminated lands.

Agitation/Turning

As noted above, volatile compounds escape from exposed surfaces. To do so, these compounds must first find their way to the surfaces from the interior of the pile. Otherwise, they remain trapped within the confines of the mass and eventually transform into innocuous forms (e.g. are metabolized or oxidized).

Compounds can migrate to the surface by diffusion or be carried in air currents and physically transported by agitation. Diffusion is a slow process that allows ample opportunity for the volatile compounds to be adsorbed and degraded within the mass. In contrast, agitation of the materials abruptly exposes the compounds to the surrounding. At that point, the volatile compounds that have accumulated within, volatilize and escape abruptly and in high concentrations. However, the emission of odors decreases quickly soon after the immediate exposure and then gradually returns to a relatively constant level (Lacoboni et al. 1980).

In composting, turning is a prime example of such agitation but materials are also disturbed during mixing of feedstocks, grinding, screening and simply materials handling. For this reason intense odors are typically experienced following turning and other means of agitation. The amount and character of the odors released by agitation depends on the nature and state of the materials. Raw feedstocks, actively decomposing materials and/or materials in an anaerobic state release more volatile compounds, and more odor, upon being disturbed than materials that are relatively stable or well aerated.

Because turning also introduces air, improves the distribution of water and nutrients and may improve porosity in some cases, it advances the composting process and improves odors in the long run. However, there is some debate about whether the frequent release of moderate odors from frequent turning is more damaging than the infrequent release of strong odors from infrequent turning. Composting operators have expressed contrasting opinions. Research provides little guidance on this point.

Lacoboni et al (1980) measured odors released from six windrows containing biosolids at different turning regimes (Table 4). Looking at only the averages among the pairs, there is a trend that shows more odor and stronger (i.e. peak) odor *per turning* as the frequency of turnings decreases. However, as the number of turnings increases, the *total* amount of odors released due to turnings (over all turnings) is slightly greater. Also, total emissions from the windrows (turning plus passive surface emissions) are nearly the same for all windrows. On the other hand, the variability of the results for individual windrows defies generalizations.

Therefore, from Lacoboni et al.'s results it is difficult to say whether more frequent turning has a positive or negative effect on odors. It very likely depends on the specific situation of the composting operation and whether the facility has flexibility in scheduling turnings. For example, the peak odor emission after turning may be the most important parameter if odor complaints tend to occur from periodic strong odors while the total emissions are more important for facilities that are plagued by a constant border

line odor. It should also be noted that the number of turnings of the biosolids windrows monitored by the Lacoboni study are greater than those for the typical green waste and agricultural composting windrows. Five or six turns are more typical in the latter cases (Rynk, 1994).

Table 5: Odor emissions from turned windrows composting biosolids

Windrow Number	Ambient Odor Emissions (ou/m ²)	Peak Odor Emissions after Turning (ou/min./m ²)	Odor Emissions per Turn (ou/m ²)	Number of Turns	Odor Emissions as a Result of Turning (ou/m ²)	Total Odor Emissions for a 6-Week Composting Cycle (ou/m ²)
1	2809	0.798	23.97	30	719	3528
2	2809	0.985	29.54	18	532	3341
3	2809	2.5053	61.59	12	739	3548
4	2809	0.502	15.05	30	451	3261
5	2809	1.133	34.00	18	612	3421
6	2809	0.771	23.13	12	278	3087

Source: from Lacoboni et al, 1980, after Epstein, 1997.

Aeration

Aeration ventilates the composting material. It brings in fresh oxygen-rich air and removes air that contains the products and by-products of decomposition, including volatile and odorous compounds. The air stream leaving the composting windrow/pile releases those odorous compounds into the surrounding environment unless it is captured and treated (e.g. in a biofilter). Again, the type and amount of odorous compounds in the exiting air stream depends on the feedstocks, their stage of decomposition and the aerobic/anaerobic state. There are two mechanisms of aeration in composting, passive and forced. Both carry odors into the environment.

Passive

Passive aeration relies on natural convection, wind and diffusion to move air in and out of the pile. Natural convection is largely driven by the tendency of warm air to rise up and out of the top of windrow piles and bins. Cool fresh air enters along the sides and edges to fill the vacuum. The air flow into the pile is determined by the temperature difference between the internal pile and the ambient air plus the porosity of the matrix of materials within the pile.

Passive aeration occurs naturally in any standing pile of materials (feedstocks, composting, curing and stored compost) and exposed surfaces in bins. The exiting air rises unevenly from the surface of the material, but more prominently near the peaks and ridges. The exhaust and potentially odorous air cannot be captured unless the material is totally contained in a building, vessel or other envelope (e.g. covers, plastic pods).

In general, strong passive aeration should be encouraged to manage odors because it reduces anaerobic conditions. Composters promote passive aeration primarily by establishing a porous matrix of materials. It also helps to build piles to a moderate size that strikes a balance between retaining heat and promoting air exchange. Smaller piles

limit the depth that the air must penetrate and also increase the exposed surface area per unit volume of material.

Although more aeration is generally better, passive air movement does carry odorous compounds out of the pile. The emission of odors is most critical at the early stages of composting when highly degradable feedstocks quickly consume the available oxygen and high temperatures encourage strong air movement. To minimize the odors carried with the exiting air, the exposed surface of piles and bins are often covered with a layer of porous and adsorbent amendments, such as wood chips. The amendment layer tends to adsorb many of the odorous compounds yet it is porous enough to permit strong aeration.

Forced

Forced aeration uses fans to push or pull air through the composting mass. It is used for composting material in freestanding piles (e.g. aerated static piles), partially enclosed bins and in many in-vessel composting techniques including aerated containers, rotating drums and agitated beds. In addition, forced aeration is employed for biofilters and sometimes used to aerate curing piles.

Compared to the passive alternative, forced aeration is a more certain approach to insuring that the materials remain aerobic. The use of fans to drive aeration removes the reliance on natural mechanisms. Thus, composting can take place in a larger pile, with a smaller surface area to volume ratio. However, steady and vigorous airflow from forced aeration can engulf and transport a large amount of volatile chemicals with it. Hence, the exhaust air can become an odor source in itself. For that reason, many composting facilities pass the exhaust through treatment devices like biofilters and chemical scrubbers. A greater airflow than necessary is a disadvantage, because it leads to either more odor release or greater demands on the treatment device.

There are several modes of forced aeration—positive or negative, intermittent or continuous. In the positive mode, a fan forces air outward from the base of the composting materials. The exhaust air discharges through the outer surfaces. It cannot be captured unless the material is contained in a building, container or vessel. In the negative mode, the fan draws or sucks air from the outside through the materials and into a collection pipe, vent or plenum at the base of the material. The exhaust air is concentrated in the collection system and this can be directed to a treatment device and/or discharged in a controlled manner. (Note: there are other variations to the geometry and layout of the ventilation networks).

In most actively composting materials, the amount of air moved through a composting mass is determined by temperature that is the need to remove heat to maintain favorable temperatures. Less air is needed to supply oxygen and remove moisture. Thus, forced air is typically turned on and off based on temperature. Another option is to run the fan continuously at a low rate and increase the rate when greater air flow is required for cooling.

Researchers at Ohio State University (OSU) have published a strong body of work describing the effects of forced aeration on odor formation and emissions in addition to nitrogen loss and other composting parameters (Elwell et al 2002a; Elwell et al., 2002b). In general, the OSU team has shown that, at the aeration rates typically employed for composting, a greater level of aeration leads to faster destruction of anaerobic compounds.

However, the greater aeration also produces a greater release of odorous compounds into the environment due to the increased air flow through the pile. Thus, odors tend to be reduced by strategies that minimize aeration (within limits), such as a lower air flow rate and/or intermittent rather than continuous fan operation. The OSU research demonstrates that *over aerating* a pile increases odor emissions. Thus, after the process oxygen and temperature needs are met, aeration should be kept to a minimum. Although odorous compounds may persist longer, only small amounts escape into the surroundings.

Containment

A lot can happen to an odorant molecule before it becomes an “emission.” Most odorants are intermediate compounds that contain energy and nutrients that microorganisms can use under the right conditions, and if time avails. Therefore, given time and the right conditions, most odorants can be decomposed within the mass of materials in which they are formed.

The vast majority of potential odorants that form likely meet this fate. It is in the interest of a composter to slow the escape of odorants, retaining them within the pile as long as possible, thereby giving the microorganisms time to further decompose the molecules of odorants. This situation not only minimizes the emissions of odors, it also conserves nutrients within the compost. There are two primary means of retaining volatile odorant molecules – (1) capturing them on their way out via adsorption and absorption; adsorption and (2) blocking their escape with covers.

Adsorption and absorption

Unless it is formed at the pile surface, or physically transported to (e.g. turning), a given odorant molecule faces a tortuous path to liberation into the ambient environment. In that path there are road blocks in the form of particle surfaces (adsorption) and pools of moisture (absorption) that can attract molecules via electrostatic or chemical forces. Once trapped or delayed on particle surfaces or in moisture, the odorant molecules are subject to decomposition.

On a molecular scale, organic materials have large internal surface areas that are good for adsorbing molecules. Various electrochemical mechanisms work to attract molecules to these surfaces. While many composting feedstocks, and compost itself, are good adsorbents, it can be an advantage to include materials that are especially effective adsorbents. Activated carbon is well known for this quality. Others include peat moss, wood ash, coal ash and finished compost. Ash that retains more organic carbon is more effective than ash that is completely combusted (BioCycle 2004). Highly adsorbent inorganic materials, like zeolite, have also been investigated for this purpose.

Numerous researchers have investigated including adsorbent organic materials into the feedstock mix as amendments for the purpose of odor control. Examples include peat moss (Mathur et al, 1990), wood ash (Rosenfeld and Suffet, 2003), coal ash (Das, 2000) and compost (Buyuksonmez et al., 2006) Often, the adsorbent provides other qualities in addition to the adsorbing surfaces.

For example, peat moss lowers the pH, wood ash increases pH and finished compost provides a diverse pool of microorganisms. In general, the research demonstrates a noticeable reduction in odor emissions due to these amendments. Their value and utility depends on the feedstocks, how critical odor control is and other economic factors like the cost of the amendments. While it is not the norm, compost and wood ash are used in practice as odor-reducing amendments. (BioCycle, 2004)

Moisture is critically important for the composting process but it also plays a role in retaining volatile compounds. Many volatile compounds, like ammonia, exist in equilibrium with soluble forms, like ammonium. As the amount of moisture decreases, soluble forms are converted into volatile forms, which are subject to escape. In addition, the pools of moisture provide hospice for the microorganisms working to decompose the odorants. In short, there are many reasons not to let composting materials become dry just as they should not become too wet.

Covers

Odorous compounds escape from the exposed surfaces of piles, windrows and bins. This condition holds even for forced aeration systems (and also to some extent for negatively aerated piles and bins). One approach is to block or hinder the escape of odors by covering the exposed surfaces. In doing so, the odorants remain within the composting mass and eventually decompose. Of course, because composting relies on the exchange of air with the ambient environment, the covers must be somewhat permeable to air or oxygen.

The primary way that covers are used in practice is by applying a somewhat porous material to the exterior surface. Typically, the material used is a relatively porous amendment like wood chips, woody screen overs or chipped brushy green waste. Less porous materials like compost, sawdust and straw are also used. In these cases, the cover materials physically hinder the path of the escaping odorants.

However, they also, and perhaps more importantly, serve as adsorbents that remove the volatile compounds from the exiting air stream. In a sense they serve as pseudo-biofilters. Wood chips have long been used for this purpose in composting biosolids (Rynk, 1992). Compost also is used as a cover at facilities because it is readily available and because it is an excellent adsorbent and medium for decomposition. In research associated with this C-CORP project, Buyuksonmez et al. (2006) found compost covers to be an effective measure for reducing odor emissions.

In addition to porous covers of organic amendments, synthetic membrane covers are also used to contain odorants within piles and windrows. In the past ten years, several innovative woven fabric membrane materials have been introduced that are relatively permeable to air and oxygen but impermeable to moisture and molecules of larger molecular weight. These membranes simply block the movement of many volatile molecules. Much of their effectiveness occurs because moisture tends to condense on the underside of the membranes. The moisture helps to trap and absorb odorant molecules. When the moisture drips back onto the pile below, it returns the odorant molecules back into the composting process.

Enclosures

Once odorants leave the surface of an open windrow, pile, bin or other surface (e.g. pond, puddle, tainted soil), their fates are subject to the whims of the natural environment (e.g. weather, geography, atmospheric chemistry). Those whims can deliver the odorants to unwelcoming neighbors. However, composting facilities have another line of defense—enclosures. Enclosures include buildings, composting reactors and vessels, containers and other envelopes that isolate the composting system from the surroundings. Enclosures differ from covers in that the emissions are not retained within the composting system but captured and contained by the facility. Typically, the air within the entire enclosure (e.g. building) is captured and then treated in a biofilter or other treatment device. Another

approach is simply exhausting the captured air after diluting it with copious volumes of outside.

A building may enclose an entire facility (Accortt et al, 2001) or just the most odor-critical components of the facility (e.g. receiving and mixing areas, first stage of composting). Other options include aerated containers and aerated plastic bags or pods. Enclosures are an expensive but potentially effective means of odor control. They do not eliminate odors altogether but through engineering and design, make odor management more controllable. Most passive odor emissions and area sources either become point sources (e.g. building exhaust) or are transferred to a single area source like a biofilter that can be more actively managed.

Odor Treatment—Biofilters *et al.*

As already stated, odor emissions can be captured through enclosures or negative aeration. Once captured, a number of treatment alternatives can be used to greatly reduce the amount of odorous compounds released into the environment. Options include biofilters, soil filters, chemical scrubbing, thermal oxidation and, more recently, non-thermal plasma oxidation.

The composting industry has primarily adopted biofiltration as its favored odor treatment technology. In part, the appeal of biofiltration is that it is similar to composting itself. Like a composting pile, biofilters require management and attention to nutrients, moisture, microbiology, porosity and aeration. Biofilters can go bad and become a source of odors.

However, biofilters can be a prominent source even when they are working correctly because all other odor emissions tend to be funneled there. When facilities are completely enclosed, the outside biofilter can be the primary source of potential odors at the site. Again, this situation does not imply that the biofilters are ineffective, just that they need to be managed and remain a source that deserves attention. Biofilters have a large surface area, usually open to the outside environment. They constitute an area odor source and should be modeled and managed as such. Many excellent references discuss the design, operation, management and performance of biofilters including Kuter, 1990, Haug, 1993, Wililams and Miller, 1993, Epstein, 1997, Das, 2000, Michel et al., 2002, and BioCycle, 2004.

Other treatment devices have found application at composting sites and other facilities that generate odors from organic materials (e.g. wastewater treatment plants). Scrubbers that employ chemicals to react with and neutralize odorants have been installed at several of the larger composting facilities (Haug, 1993). Often, they are preferred where a specific compound requires treatment (e.g. ammonia or hydrogen sulfide). Non-thermal plasma technology has been recently introduced. It employs electrical energy to generate free radical ions that react quickly with many odorous compounds. This approach is promising because it can be adapted for a smaller scale (Paul, 2006).

Transport and Fate in the Environment

Odor emissions *at* composting facilities are not particularly worrisome. The critical worry is odors *beyond* the composting facility, and primarily only when the odors reach people who object to them. Of course, the two issues are related, linked by the transport of odorous compounds to sensitive receptors and their fate in the environment beyond the boundaries of the composting facility.

Most volatile compounds released into the atmosphere are eventually “eliminated” by chemical reactions within the atmosphere and/or fall to the earth with precipitation and other forms of atmospheric deposition. However, much more quickly, they mix with, and become diluted by, the air within the atmosphere. The latter phenomenon—dilution—is how emitted odors practically “disappear.”

While the mixing and dilution is taking place, an intact “plume” of odorous air can be transported beyond the sources of the odors to neighbors. At that point, if the mixing has not diluted concentrations below human detection limits, the odors can impact the surrounding community. How quickly the odors are diluted depends on atmospheric conditions, especially wind and temperature, which in turn determine the stability, or conversely the turbulence, of the atmosphere and thus the degree of mixing. Topography and the landscape also play a role. All of these factors also influence *where* the odors travel. The proximity of neighbors is a very important factor in determining whether or not an impact occurs.

Transport Patterns—of Plumes and Puffs

When odorous compounds, or any other pollutants, are released into the air, the surrounding air effectively assimilates these compounds. Although it is an oversimplification, it can be said that the odors do not move independently from the air but travel within the assimilating air parcels and only gradually diffuse, decompose or wash out. In a sense, a moving parcel of air retains its identity (and embedded odors) but its character erodes over time and distance. How quickly that erosion takes place depends on the presence and strength of the forces that tend to diffuse, dilute, disperse and chemically alter the compounds within the air. With little wind or other disturbing forces, the air travels intact for some distance while progressively mixing into the surrounding ambient air.

In air pollution terms, this intact but eroding contaminated air stream is called a *plume*. It is well represented by the vapor plume from the exhaust stack of a power plant. The plume from the stack trails on for a distance, spreads out and eventually disappears. The wind, atmospheric temperature profile and also the surrounding landscape determine the plume’s direction, shape and longevity. If the plume remains warmer than the surrounding air, the plume continues to rise. While exhaust from a stack typifies a plume, area sources of odors can also be considered to travel and disperse in relatively intact plumes. An area source can be treated as a plume that has already spread to the width of the area source (Lui, 1997).

Plumes break apart by the action of a combination of diffusion, wind and rising air currents. Because wind and air currents change constantly and instantaneous so do the plumes. However, under relatively calm conditions, and on average, the plumes tend to gradually disperse, principally by diffusion (de Nevers, 2000). The diffusion causes the plume to spread out along its length. It spreads horizontally and vertically. At any instant in time the plume is actually twisted in a disorderly shape by random turbulence (de Nevers, 2000). However, the spreading pattern represents the net effect over time—and can be considered a steady state.

The way in which a plume spreads—its spreading shape—is commonly described by a mathematical relationship known as a Gaussian distribution. The Gaussian distribution is the familiar “bell shaped” curve that widens symmetrically around a centerline. When applied to plume spreading, the curve is turned on its side with the point of the bell at the odor source (e.g. stack outlet) and the curve spreads horizontally and vertical, although

not necessarily in the same way. To predict how a plume will behave, air pollution professionals use mathematical equations that define the plume's Gaussian spreading pattern. The spreading pattern in turn correlates with the movement, concentrations and dispersal of pollutants within the plume. The equations are used in computer models (e.g. the Gaussian model) to predict pollutant concentrations, like odor, at various directions and distances from the source.

A plume is an idealized way to envision odor emissions. It represents a continuous stream of emissions at a constant strength and rate. However, odors are rarely emitted as a continuous stream at composting sites. The strength of the concentrations of odor compounds change and their rate varies. A good example would be the odors emitted upon turning.

In such situations, the plume model does not work well. It also does not work well when the air does not disperse in the normal plume-like fashion that is spreading uniformly in a single direction. For instance, under very stable atmospheric conditions (e.g. temperature inversions, see below), the odorous air may hardly disperse at all (Haug, p 607). In these cases, odor emissions are sometimes modeled as a series of discrete puffs – a brief burst of odor release. Each puff can differ in odor concentration and character, although many computer models assume each puff is the same odor concentration (Brant and Elliott, 2004).

Proximity

The proximity of neighbors (distance and direction) to an odor source is a huge influence in odor impacts. It determines whether there is sufficient distance (or time) available, in nearly all situations, to dilute the odors below the detection limits. The number of odor incidents that neighbors are willing to forgive is usually small, so the distance must be large enough for odor to effectively disperse under all but the worst case conditions. There is nothing more effective at preventing odor problems than an isolated site—a long distance from the nearest neighbors (Miner, 1995). The next best situation is a long distance to neighbors in the direction that odors usually to migrate. However, since wind and weather conditions at any site usually vary, there is rarely a “safe” direction.

Publications offering composting guidance and regulations have specified minimum buffer distances between the boundaries of a composting facility and the nearest residential or commercial neighbors. Such recommended or specific minimum buffer distances range from 150 ft. to over 500 ft. (Epstein, 1997). The basis for these recommendations is not clear in most cases. They may develop from odor modeling, guidance in earlier publications or round numbers that represent practical best guesses. Overtime, the recommended minimum distances have tended to increase as the neighbors located at further distances have lodged complaints.

For general situations, it is impractical to establish a buffer distance that will eliminate all odor complaints. Odors have been known to travel a few miles in large enough concentrations to elicit complaints. Buffer distances of multiple miles are impractical for most composting facilities because workable remote sites are few (or few remain remote).

The most reasonable approach is to set a practical distance that limits the odor impacts to a minimal number per year. For specific facilities in specific locations, odor modeling can be used to predict the number of impacts on neighbors. However, it must be emphasized that the nature, topography and management of the specific facility, plus the

attitude and expectation of neighbors, determine the frequency and distance of odor complaints. Some composting facilities operate successfully within a few city blocks of residential neighborhoods. Some facilities in seemingly remote locations have been plagued by odor complaints from neighbors miles away. In summary, although setting a minimum buffer distance provides some degree of protection from odor impacts, it is very difficult to establish a good general standard. Furthermore, meeting recommended buffer distances will not in itself eliminate odor impacts nor guarantee that odors won't impact neighbors beyond the buffer distance.

Urban Encroachment

In numerous cases, composting facilities that were initially sited in well-buffered, seemingly isolated locations eventually had to struggle with odor complaints (Rynk, 2003a, 2003b). The incessant march of urban and suburban development has impacted farms, factories and composting facilities alike. In some cases, the encroaching development has forced composting operations to manage better or upgrade technology to minimize odor impacts on developing communities. In other cases, the changing landscape has led to facility closures. The "Preliminary Odor Assessment" component of the C-CORP project found encroachment to be a major factor, if not the major factor, in the odor problems plaguing the ten facilities examined by the preliminary assessment. Four of these ten facilities have closed.

A long distance to neighbors continues to be the best defense against impacting the community. However, since land is expensive to purchase as buffer space, and undeveloped space continues to disappear, composters and community planners need to find other ways to preserve odor-generating facilities in the light of encroaching development.

In addition to tighter facility management, better technology and best management practices, communities can look to creative zoning practices and community education to make sure that citizens are aware of the presence of the composting facility, its operation and its potential to occasionally impact the community with odors. Establishing an understanding of the facility and its operation plus realistic expectations of its odor performance are important steps (Goldstein, 2006).

The burden of public relations should fall on both the community leaders and the composting facility. However, the personal experiences of the authors suggest that communities are at best slow to take on this task, and more often reluctant to do so. Therefore, the composting facility should enlist, but not wait for, the support of local communities and the regulatory agencies (Goldstein, 2006.)

Wind

Wind has a dual effect. Wind carries odor-laden air from the odor sources to the neighbors. It also disperses and dilutes odors within the atmosphere. The speed, direction and consistency of the wind influence odor impact. The worst case is a slight wind (e.g. 2 to 5 mph) in the direction toward the most sensitive neighbors such that odors are continually carried to the neighbors with little dilution.

The best case is a strong turbulent wind (e.g. >10 mph) that frequently changes direction, which disperses the odor and causes only fleeting impacts, if any. In general, a brisk wind is usually good; that is, it usually helps to avoid odor impacts by diluting odor emissions. However, the specifics of the site and situation determine whether that statement holds true.

In general, wind direction and speed are influenced by the following factors, in order of their influence (de Nevers, 2000):

1. Storms and weather fronts: The relative proximity and difference between high- and low- pressure centers primarily determine wind directions and speed, over and above other factors.
2. Land features, including mountains valleys and canyons: In absence of overriding influences from storms and weather fronts, winds tend to follow valleys and canyons and locally blow up and down mountain slopes as the land surface heats and cools. In these situations, the wind typically reverses direction from morning to night, and between cold and warm seasons. The effect is greater with deeper or steeper features.
3. Onshore and Offshore breezes: When other effects are small, winds blow on- and off-shore of water bodies, with the direction depending on the relative temperatures of the land and water. When the water body is cooler (summer and/or afternoons) the breeze blows onshore (replacing warm air over the land that has heated and risen). When the land surface is cooler (winter and/or at night), offshore breezes occur.
4. General wind patterns: When the other effects are not present, winds tend to be light and follow the dominant wind patterns on the earth's surface due to general atmospheric air circulation (e.g. trade winds, westerly's).

Guidance for siting composting facilities routinely advises composters to consider prevailing wind direction. The guidance states that it is best to avoid situations where the prevailing winds blow toward neighbors. This advice is sound and prudent but it can be difficult to implement in practice. Because a facility can have neighbors in all directions, the guidance should state that prevailing winds should not blow toward the most sensitive neighbors.

Secondly, urban/suburban expansion has a way of filling in the vacant spaces around a facility with sensitive neighbors. Thirdly, prevailing wind direction is the direction that winds blow most often. It says nothing about wind speed or how frequently the wind blows in the prevailing direction. In fact, the wind blows in the "prevailing" direction only a percentage of the time, and typically less than 25% of the time (Natural Resources Conservation Service, 2006), especially if NNW and WNW are considered different than NW). In short, prevailing wind direction is an important factor but a favorable prevailing wind does not in itself preclude odor impacts on neighbors in other directions.

The direction of prevailing winds is largely determined by local topography including valleys and canyons, mountains and large water bodies (e.g. lakes, oceans). Where these features exist, the prevailing winds are more prominent and predictable. Where they are absent, such as on broad inland plains, wind direction tends to be more variable. For a given location, prevailing wind direction, and wind direction patterns generally, can be ascertained from wind data collected at nearby weather stations. Such data is usually available from the federal and state public agencies that regularly collect weather data.

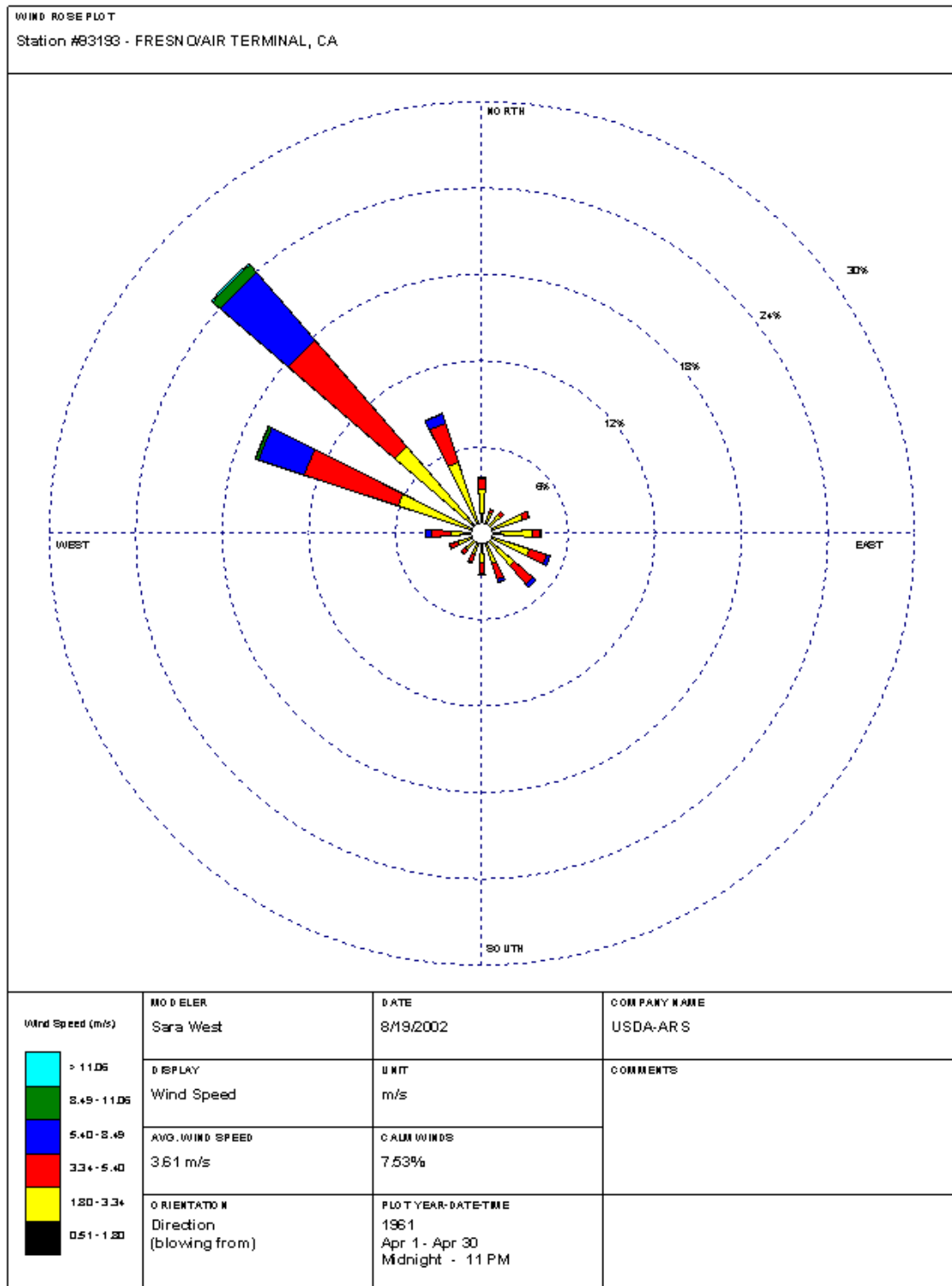
Wind roses are particularly helpful in evaluating the wind characteristics of a given location. An example wind rose is shown in Figure 2 (Natural Resources Conservation Service). The wind rose is a circular graph with 16 wind direction divisions. The spokes of the graph show the frequency (i.e. percent of the time) that the wind is blowing *from* the direction indicated by the strokes. The spokes emanating from the center of the wind rose correspond to the frequency of the winds in that direction. (The wind direction identifies

the direction that the wind is coming from. Hence, a west wind is blowing from the west and towards the east)

Many wind roses, including the one in Figure 2, also present information about the distribution of wind speed at the location. Usually the wind speed range is indicated by the color and/or thickness of the corresponding section of the spoke. The length of a wind speed section indicates the frequency that a particular range of wind speed occurred in the direction of the spoke. Wind roses provide a good visual representation of the wind characteristics of a given location. Wind roses for many weather stations can be obtained from: <http://www.wcc.nrcs.usda.gov/climate/windrose.html> (Natural Resources Conservation Service, 2006).

One problem with using wind roses is that they are developed from data collected at weather stations. Wind characteristics can vary greatly among specific sites, even sites that are relatively close together (e.g. within a mile). The differences can be due to landscape features, buildings, topography and simply local variations in the weather conditions. For this reason, it is helpful to have a weather station on the composting site, especially if odor impacts are a concern, and more so if the odor impacts are disputable. Wind roses and other weather data from nearby weather stations remain good resources for planning, managing and troubleshooting composting sites.

Figure 2: Example of wind rose for a specific location and time of year (Fresno, April).



Source: <http://www.wcc.nrcs.usda.gov/climate/windrose.html> (Natural Resources Conservation Service, 2006.)

Atmospheric stability

Winds generally mix the atmosphere near the earth's surface in the horizontal plane—east, west, north and south. Vertical mixing also occurs, from rising and falling air. The atmosphere is considered *unstable* when conditions are such that vertical mixing readily takes place. When conditions hinder vertical mixing, the atmosphere is *stable*. Vertical mixing is good for composting facilities because the plume of odors is carried upwards, where it is very unlikely to encounter an objecting human nose. When it rises, it is also likely to be diluted and dispersed by the more vigorous winds aloft.

In the lower atmosphere, up to about 6,000 ft. above the ground, vertical air movement occurs because of temperature differences at different altitudes (de Nevers, 2000). The vertical temperature profile, that is the change in temperature with altitude, is referred to as the *lapse rate*. When it refers to the actual temperature gradient of the ambient atmosphere, it is also called the *ambient lapse rate* (Lui, 1997).

“Normally,” the air temperature decreases moving from the ground upward (technically, the lapse rate is said to be positive when the temperature decreases with increasing altitude). When air near the earth's surface is heated by the sun's energy, it becomes less dense, and therefore buoyant, compared to the cooler air above. The warm air rises and the cool air falls, creating vertical mixing. However, if the air near the ground (e.g. at the composting facility) is cooler than the air aloft, it does not rise and no vertical mixing occurs. Conditions routinely arise that cause the atmosphere to increase in temperature with altitude. This situation is known as a temperature inversion (i.e. negative lapse rate).

In fact, the situation is more complicated than this description. Vertical air movement can be prevented even when inversions are not present. Because air expands and subsequently cools as it rises, the vertical movement of air also depends on its rate of cooling relative to the temperature of the surrounding air. As air rises, it expands and cools at a constant rate. If the assumption is made that the air loses no moisture as it rises, and thus no energy is lost or gained, then the air decreases in temperature at a predictable rate, known as the *adiabatic lapse rate* (de Nevers, 2000).

When the air remains unsaturated, the *dry* adiabatic lapse rate applies and air temperature decreases by 5.4°F per 1000 ft. (10°C per km) of elevation gain. Air that becomes saturated follows a different and lower lapse rate – the *moist* adiabatic lapse rate, which can vary approximately between 4 and 6.5°C/km (Lui, 1997; de Nevers, 2000). A given parcel of air is likely cool at a rate between the dry and moist adiabatic lapse rates because of the moisture it contains (and loses) and varying air pressures but the dry adiabatic lapse rate provides a reasonable approximation.

In order for a parcel of air to rise, it must be *more* than just warmer than the parcel of air above it. The rising parcel must *remain* warmer than the surrounding air along the way up. This condition depends on the rising air parcel's lapse rate (e.g. 5.6°F/1000 ft.) and the vertical temperature profile—that is, the ambient lapse rate of the surrounding air. If the vertical temperatures of the surrounding air do not fall as fast as the rising air's lapse rate, then vertical mixing stops. This situation can happen even when the air temperature decreases with height. A temperature inversion is just an extreme case.

This phenomenon is better explained by Figure 3. The figure shows the adiabatic lapse rate that a rising parcel of air tends to follow plus the ambient lapse rates for three different atmospheric conditions. Again, the ambient lapse rate is simply the vertical temperature profile of the air. The two temperature profiles to the right of the adiabatic

lapse rate (dotted line) are stable conditions in which no vertical mixing would occur. The far right profile is a temperature inversion. The temperature profile to the left of the adiabatic lapse rate is unstable and conducive to vertical mixing. In the unstable case, the rising air remains warmer than the surrounding air because the adiabatic lapse rate is less than the ambient lapse rate.

The lapse rate of a rising parcel of air is essentially fixed and approximately equal to the adiabatic lapse rate. Therefore, it is the ambient lapse rate that determines the stability (i.e. vertical mixing) of the atmosphere at any time. The ambient lapse rate is largely determined by wind, sunlight, radiational cooling at night and cloud cover. Using these meteorological conditions, atmospheric stability classes have been established (Table 6). Composting facilities should hope for conditions that create more atmospheric instability (e.g. A, B), which encourage dispersion of odors. Haug (1993) mentions that the stability categories are more applicable to open and rural areas. Trees, urban “heat islands” and rough terrain tend to confound the conditions. Also it is interesting to note that increasing wind speed tends to make the atmosphere more stable during the day but less stable at night.

Figure 3: Ambient lapse rates for three different atmospheric conditions

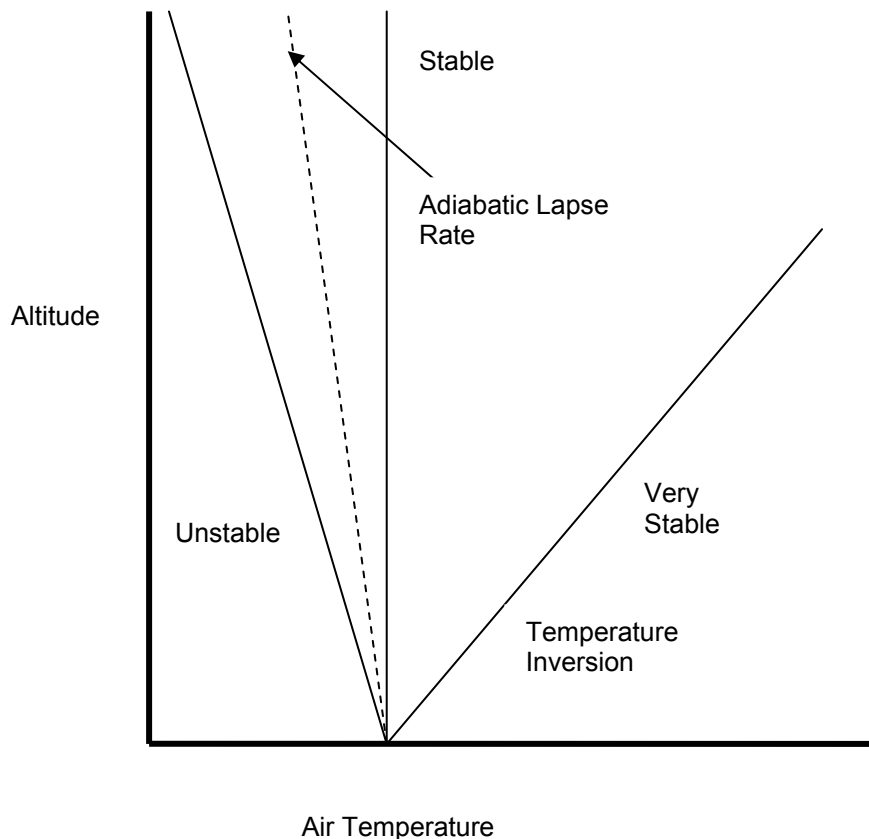


Table 6: Atmospheric stability categories

		Day		Night	
Surface Wind Speed	Incoming	Solar	Radiation	CloudCover1	
_ (m/s)	Strong	Moderate	Slight	≥4/8 Low Cover	≤3/8 Cover
<2	A	A - B	B	--	--
3-Feb	A - B	B	C	E	F
5-Mar	B	B - C	C	D	E
5 - 6	C	C - D	D	D	D
>6	C	D	D	D	D

A = extremely unstable D = neutral;
 B = moderately unstable; E = slightly stable
 C = slightly unstable; F = moderately stable

Assume neutral condition D for all overcast conditions, day and night

Source: adapted from Haug, 1993

Temperature Inversions–Diurnal Patterns, Other Factors

A temperature inversion is the condition when warm air sits above a layer of cooler air. Temperature inversions are not welcome occurrences for composting facilities. They prevent air from rising, dampen vertical mixing and keep potentially odor-laden air near the ground. The odor-laden air may then travel at ground level to neighbors, carried by light winds or air drainage (see following sections).

An inversion can take place through the entire profile of the lower atmosphere as shown in Figure 3, or only to a certain height, as depicted in Figure 4 below. In any case, the warm air aloft prevents vertical air movement and keeps the air near the ground from moving and mixing upwards. Odorous air remains near ground level and either accumulates at the site and/or migrates off site at “neighbor-level.” Temperature inversions are often correlated with numerous odor complaints and severe odor complaints (Haug, 1993). Therefore, composting facilities should recognize and anticipate the conditions that lead to inversions.

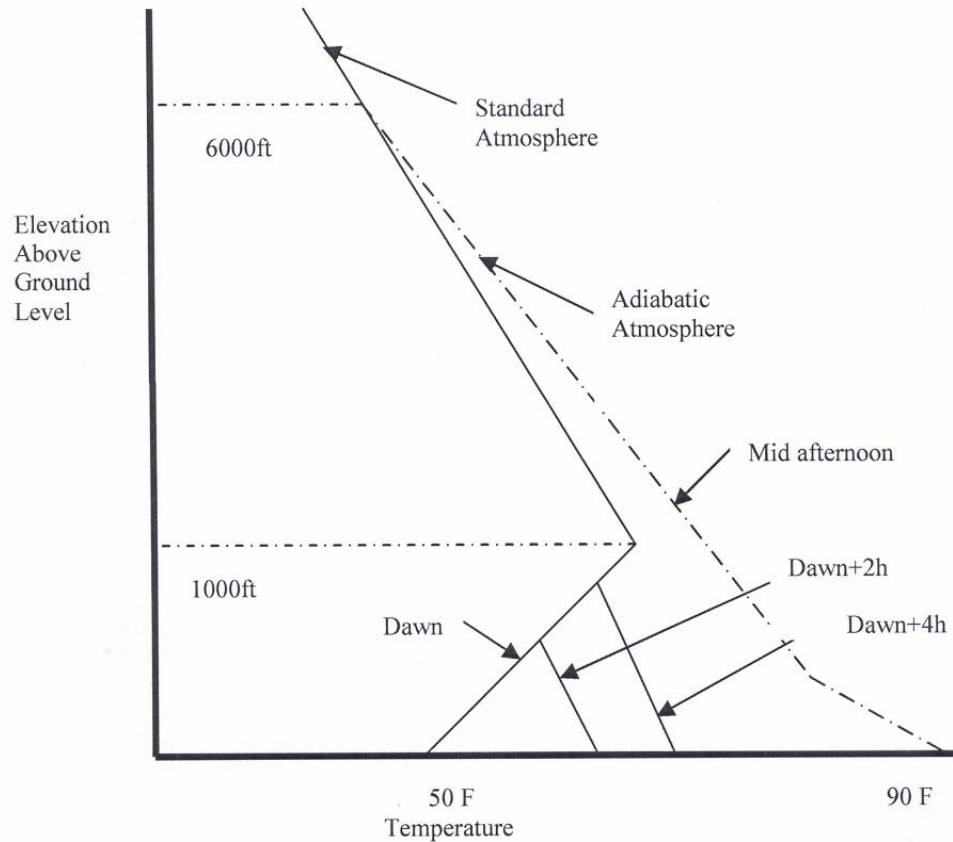
Air temperatures are not constant so Figure 3 represents a snapshot of conditions at one point in time, and a simplified snapshot at that. Atmospheric temperature profiles and stability conditions change—with daytime solar heating, nighttime cooling, winds and weather fronts. Temperature inversions come and go.

Among the more predictable patterns of change are those that evolve through the cycle of a day. These can result in stable conditions during some parts of a day and unstable conditions during other parts. Typically, radiational cooling of the earth's surface on a clear night lowers the air temperature near the surface while the air above remains warmer (because, compared to the earth, air is a poor radiator of heat, and also a poor absorber of it).

A temperature inversion develops during the night, at least in the lower levels of the atmosphere, as shown in Figure 4. After sunrise on a clear day, solar radiation begins to warm the earth and the air temperature near the surface increases. As the morning lengthens, the air temperatures near the ground increase and the temperature inversion breaks up the lower layer, although an inversion persists at higher elevations. By afternoon, the inversion is gone and a "normal" unstable temperature profile develops, generally matching the adiabatic lapse rate. Near sunset, the ground and the air around it begins to cool and a temperature inversion may reestablish itself near the ground and grow stronger and higher through the night. Clouds, winds and changing weather are among the factors that moderate the changes that work to establish and disperse temperature inversions.

The diurnal patterns described above help to explain why many composting facilities receive more odor complaints in the early morning and early evening. The low level temperature inversions at the beginning and end of the day, combined with typically low winds during these periods, hinder mixing and dispersion at ground level.

Figure 4: Vertical temperature distribution at various times on a cloudless day with low or average winds in a dry climate



Source: adapted from de Nevers, 2000

Air Drainage

An air mass is subject to gravity. Thus, if left undisturbed, air follows the same drainage patterns as water (Brant and Elliot, 2004). As cool air displaces less dense warm air, it flows down slopes and into valleys and along stream and water channels just as water does. Wind and vertical turbulence mix the air and overwhelm the tendency of air to drain downhill. However, if winds are light, cool air tends to follow the “lay of the land” and collect in low spots. The draining air carries with it whatever odorous compounds are embedded. As described above clear nights tend to be accompanied by diurnal temperature inversions, which dampen vertical air movement. Furthermore, winds tend to be lower during the night, setting the stage for air drainage.

Air drainage occurs when the air near the earth’s surface cools due to nighttime radiational cooling of the earth. If the air at higher elevations cools more than at lower elevations, the air flows down the slope. Only a slight slope is necessary. Cooling occurs faster in wide-open expanses with a clear “view” of a cloudless night sky. In contrast, areas cool less rapidly at night when shielded from the sky by trees, steep slopes, canyon walls or buildings. In a given region, these radiation-blocking elements may be more common to lower elevations. Furthermore, in developed areas, the ground, and adjacent

air remain warmer due to the heat retained by the thermal mass of the developed landscape (e.g. asphalt parking lots, concrete buildings). Because development normally occurs first in valleys and along waterways, on clear nights cooler air from uphill and less developed areas readily drains into the developed areas, displacing the warmer air down slope. Note that when an open area warms faster than its surroundings on sunny days, the direction of the air flow reverses from the cooling phase. However, there are many complicating factors at work, including cloud cover (often greater over higher elevations) and the more intensive daytime heating and greater temperature rise that occurs in developed areas.

A composting site is typically an expansive area of cleared land, open to radiational cooling. While not all composting sites are located uphill of development, those that are may discover that early-morning odor complaints come from downhill neighbors after clear relatively calm nights. Neighbors, located in a nearby low spot, or bowl, are most susceptible if winds are not active. If possible, it is wise to avoid siting a facility that is located in a natural air drainage “channel.” As described in the next section, physical barriers and a rough and changing topography help to disturb air drainage patterns by offering resistance to the air movement and increasing turbulence and dispersal of odors.

Topography

Topography is determined by natural features and man-made ones. Natural features include hills, mountains, valleys, water bodies, trees and vegetation, undulating surfaces and simply sloping ground. Manmade features include buildings, roads, bridges, fences, powerlines and planted landscapes.

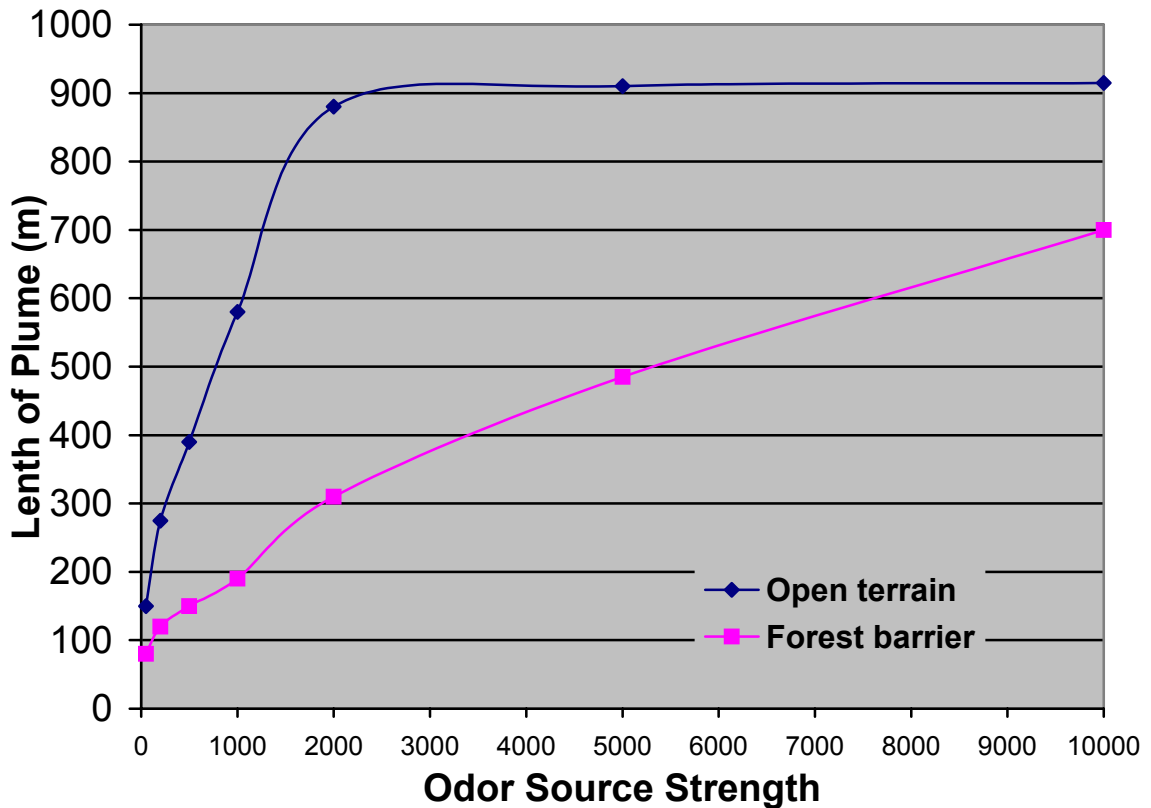
The topography can greatly affect air movement in a number of respects. The topography may provide barriers to air flow and slowing winds (e.g. wind breaks), establish airflow channels (e.g. valleys), increase turbulence (e.g. trees) and generally creating local –scale air circulation patterns (Lui et al., 1997). For a composting facility, desiring to minimize off-site impacts, the effect of topography can be negative or positive. The effects are negative when the topography directs air flow from the facility to sensitive neighbors before the odorants in the air are effectively dispersed. The effects are positive the predominant local air patterns are directed away from neighbors and when the topography hinders air movement and creates turbulence, which enhances dispersal.

A facility can use latter effects to its advantage. For example, retaining a row of trees around the site can interfere with air drainage and create turbulent eddies when the wind is blowing. Where trees do not exist, a soil berm, tall fence or hedge can have a similar but lesser effect, and fast-growing tree species can be planted for the longer term. In addition to the enhanced turbulence and odor dispersal, trees, fences or soils berms along the perimeter provide a visible barrier that shields the facility from the public, and vice-versa.

Figure 5 illustrates the effect of a forest stand on the concentration of an odor plume with distance. The figure was generated by computer simulation under assumed conditions (Chastain and Wolnak, 2000). It shows the distance required to dilute a plume of odorous air to 1 *odor unit* (OU) from odor sources of various strength (an odor unit is a measure of the strength of an odor, see following section for additional description). For instance, assuming a source is emitting odorous air at a strength of 2000 ou, Figure 5 shows that the plume requires about 3000 ft. (900 m) of open terrain to decrease to 1 ou. However with a forested barrier, the plume reaches 1 ou in less than 1000 ft. (300 m).

The forested boundary clearly reduces the chance that a neighbor will be impacted under the conditions assumed.

Figure 5: Effect of terrain on length of odor plume at various odor strengths



Source: adapted from Chastain and Wolak, 2000.

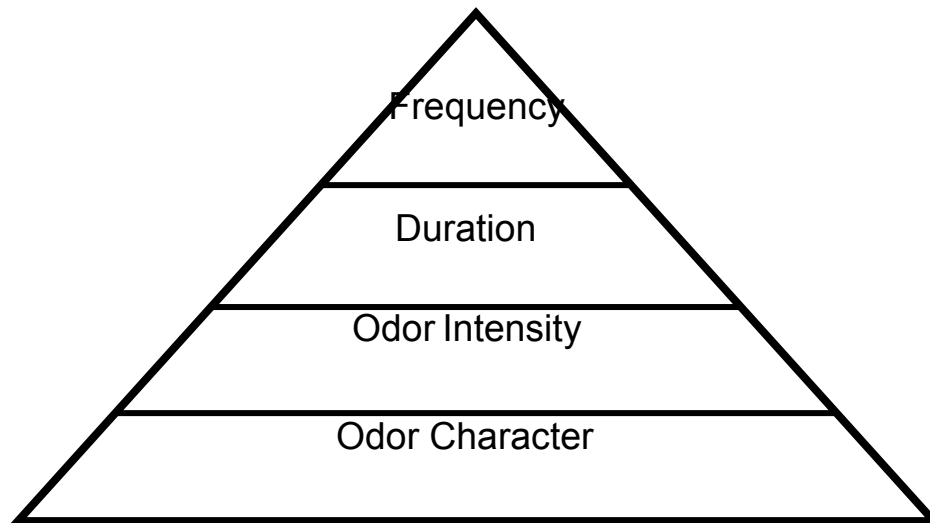
What Determines the Severity of Off-Site Impacts?

Potential odor impacts are influenced first by conditions surrounding the site – conditions that affect the transport and fate of odorous compounds in the conveying air plume (e.g. weather, topography, distance to neighbors). However, an odor will not endure beyond the facility, unless there is a discerning person in the path of the air plume. The discerning person must first detect the odor, then find it objectionable and become sufficiently annoyed to react negatively. This chain of events depends on the attributes of both the odor episode and the discerning individual.

Dalton (2003b) uses the acronym FIDO to represent the factors that determine the severity associated with an odor episode. FIDO stands for *frequency*, *intensity*, *duration* and *offensiveness*. The latter factor, offensiveness is where the human factor enters. McGinley et al. (2000) depict the same factors as a pyramid (Figure 6) substituting “odor character” for offensiveness.

If the odor dissipates relatively quickly and doesn't return, then the odor has no effect, in most cases. However, if it remains long enough to be bothersome or reoccurs repeatedly, then odor complaints are likely, either with the present odor occurrence or the next one. The severity and the force of the odor complaint depends a great deal on the person sensing the odor – his or her sensitivity, expectations, understanding of the situation and the health risks, feelings about composting and history, especially his or her history with the facility. These psychological and social factors are important determinants of whether or not a nuisance odor passes without controversy or becomes a problem. In fact, the expectations and attitudes of people can lead to odor complaints when the odors are fleeting, and even in the absence of odorous compounds.

Figure 6. Citizen Complaint Pyramid



Source: McGinley et al., 2000.

Detection—Attributes of the Odor Episode

For an individual to detect an odor, an odorant (or mix of odorants) must be present in a high enough concentration for the individual to detect the resulting odor. That condition is necessary but not sufficient to yield an odor complaint. To reach the complaint level, the odor also must be sufficiently annoying, which is largely determined by its intensity and quality.

Furthermore, the odor must persist, either continually for an uncomfortable duration of time or repeatedly for even short periods. Brief and occasional odor episodes are usually excused. Finally, the timing of the incident is a factor. A neighbor will have little tolerance for odor incidents that occur during a June graduation picnic. The sensitivities, expectations and attitudes of the discerning individual influence whether or not these conditions combine to yield an odor complaint, and how forceful that complaint is (see following section).

Concentration

Certainly, the concentrations of odorants in the air decrease as they travel from the source. Composting facilities rely on and hope for atmospheric mixing and brisk winds in

the right direction to odorants that might leave the site. However, if the atmospheric and geographic conditions do not disperse the odorants enough when the air plume reaches the site boundary, the odor might be detected by a potentially-objecting person (sometimes called the “receptor”). The actual pollution concentration, in ppm, at which an odor is detected (i.e. the detection threshold) varies with the nature of the odorants, as shown earlier in Table 1. Furthermore, individuals vary in their sensitivities so the detection thresholds represent the average person.

As described earlier, the concentration at which an individual recognizes an odor is usually two to ten times higher than the detection threshold (Haug, 1993). Concentrations that elicit annoyance, intolerance and irritation can be several times greater than the recognition threshold. For odors in general, Das (2000) states that odor complaints tend to occur at concentrations that are 5 times the detection threshold. Therefore, an odor concentration of 5 D/T at the location of a sensitive receptor seems to be a reasonable target for minimizing odor impacts off site. Achieving the 5 D/T concentration, or any other target, does not guarantee the elimination of odor complaints. It is simply a target for managing.

Intensity

Like concentration, odor intensity relates to the strength of the odor. While the intensity is strongly affected by the concentration, the nature and quality of the odor is also a factor. Thus, strength is a better indication of the acceptability of an odor than concentration (Dravnieks and O’Neil, 1979 after Haug, 1993). Intensity reflects an odor’s *staying power* or pervasiveness.

Some evidence suggests that odor complaints begin at odor intensities above 3.5 on the butanol intensity scale. Ratings from 4 to 6 correspond with a possible to probable nuisance and 6 to 8 would definitely be a nuisance (Haug, 1993).

Duration

In general, people become less tolerant of an annoying odor the longer that the odor lingers. The duration required to push a person over the tolerance line depends on the intensity and character of the odor. The odor science and composting literature reviewed provide no numerical guidance about duration and odors. For example, the literature suggests no data to indicate how long the average person will endure an odor of given strength and hedonic tonic tone before she/he takes action or lodges a complaint.

There is an effect in which a long duration of odor can increase tolerance. When exposed to a constant odor level, people tend to adapt to it. Their sensitivities and perceptions of the odor decrease (Dalton, 2003a). This adaptation is one explanation for why the last people to recognize an odor are often the operators at landfills, farm composting sites and wastewater treatment facilities.

Frequency

Frequency has a similar influence as duration on odor tolerance. People are less tolerant when odors that come-and-go frequently come. Again, there is no data in the literature to suggest what frequency levels are critical to triggering an odor complaint or how the interval between incidents affects the situation. Intuitively, one would suspect that shorter intervals stress a person’s tolerance. However, the intervals may be less important than the number of incidents that have occurred.

Repeated odors also appear to have a cognitive effect. In fact, the effect of repeated odors is the opposite of the adaptation that occurs with the extended duration of a continual odor. When an odor disappears and then returns, an individual recognizes the returning odor more readily than the initial odor of the same strength. A learned recognition occurs. This effect is much more prominent in females than males, possibly due to evolutionary influences concerning the need to identify offspring (Dalton, 2003a).

Timing

People are upset by odors when the odors interfere with their lives. Odor episodes that intrude at critical times bring quicker and stronger reactions. Examples of bad timing for bad odors include holidays and weekends during nice weather, mornings while children are waiting for school buses, during school recess periods, dinner hours and generally any time that people are enjoying activities outdoors. Awareness in scheduling composting activities can go a long way toward avoiding problems during some key periods, like weekends. Unfortunately, several of these critical times coincide with the worst atmospheric conditions, such as temperature inversions and slight winds (e.g. mornings and early evenings).

Reaction—Attributes of Odor Sensing Individual

Individuals differ greatly in their perceptions of odors. However, the differences in people's reactions to odors go well beyond their olfactory perceptions. People also interpret and respond to odors according to their historic associations, attitudes and expectations. In an excellent article in BioCycle magazine (Dalton, 2003b), Pamela Dalton, psychologist with the Monell Chemical Senses Center, writes the following. "Research has shown that people's reaction to odor and their beliefs about the effects from odor are influenced by a diverse set of factors including personality traits, personal experience and information or social cues from the community and media. These factors can increase, or in some cases decrease, a person's sensitivity and awareness of environmental odors." In short, what an individual feels and believes about an odor influences his/her response.

Dalton's research, described in the BioCycle article, demonstrates the influence of two psychological factors on odor perception—expectations and social cues. In one experiment, three different groups of volunteers were exposed to 20 ppm of n-butyl alcohol, which is not pleasant smelling but not an irritant at that concentration. Beforehand, one group was given a positive bias by telling them that the chemical was a natural plant extract. The second group was told that the chemical was a standard laboratory odorant (neutral bias). The third group was told that it was an industrial degreasing chemical (negative bias). All three groups were exposed to the same concentration of the same chemical. Nevertheless, the group given the negative bias reported significantly greater symptoms of throat, eye and nose irritation than the neutral bias group. The positive bias group reported significantly fewer symptoms.

In another experiment in Dalton's lab, three groups of volunteers were asked to smell an unidentified odorant (acetone was used). Planted within each group was a "confederated subject"—a paid actor who was instructed to orally respond either positively (e.g. increases alertness), negatively (e.g. irritates eyes) or in a neutral manner. The volunteers were asked to rate the odor intensity every minute over the 20-minute exposure duration. The odor intensity ratings for the groups hearing the positive and neutral biases generally decreased during the experiment. The decrease was due to adaptation, which typically occurs during continued exposure to a constant odor. However, the odor intensity ratings

This document contains excerpts of the subject report.
The full report is available online at www.calrecycle.ca.gov/publications/Organics/44207001.pdf

of the negatively biased group increased over time. The negative comments of the confederate subject influenced the other volunteers that the odor was getting more intense. In addition, the negatively biased group reported significantly more nausea, drowsiness and eye and nose irritations.

Negative expectations are likely to prompt a negative response. When neighbors are already conditions to expect malodors from a composting facility they are more likely to notice them. Furthermore, they will perceive more serious consequences when they believe the odors present risks. They may even feel ill in the absence of harmful chemicals. Whether they know it or not, an activist neighbor protesting a facility is conditioning other neighbors to perceive the situation in a negative manner.