

CHAPTER 7

Aeration Requirements

INTRODUCTION

Air must be supplied to a composting material for three basic purposes. First, air must be supplied to satisfy the oxygen demand from organic decomposition (stoichiometric demand). Second, air must be supplied to remove water from wet substrates to provide drying (drying demand). As air is heated by the composting material, it picks up moisture and thus dries the remaining material. Drying is an important benefit to be achieved during composting, particularly with wet substrates. Third, air must be supplied to remove heat generated by organic decomposition to control process temperatures (heat removal demand). If not controlled, process temperatures can reach such high levels that biological activity is actually impeded. The aeration rate can be used to control the rate of heat removal and thereby adjust the system temperature.

The aeration system is an important feature of all modern composting systems. The ability to control aeration is one of the key points of process control and is an important consideration in process selection. Simplified procedures for calculating aeration demands for various process conditions and feed substrates are presented in this Chapter. More exact estimates can be made using the simulation models presented in Chapters 11 to 14. Fundamentals of aeration manifold design are presented in Chapter 15.

The reader may have noted that this chapter on aeration is presented between Chapters 6 and 8, both of which deal with feed conditioning. The reason for this is that the requirements for energy conditioning covered in Chapter 8 depend on the aeration supply. Therefore, a short recess from feed conditioning is necessary to first discuss the aeration demands imposed by composting.

STOICHIOMETRIC DEMANDS

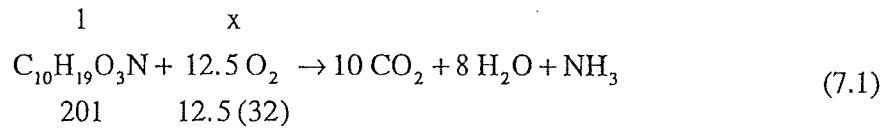
The stoichiometric oxygen requirement can be determined from the chemical composition of the organic solids and the extent of degradation during composting. Representative chemi-

mol vikt
 H = 1
 C = 12
 N = 14
 O = 16

Table 7.1. General Chemical Compositions for the Organic Fraction of Various Organic Materials

Waste Component	Typical Chemical Composition	Reference
Carbohydrate	(C ₆ H ₁₀ O ₅) _x	
Protein	C ₁₆ H ₂₄ O ₅ N ₄	
Fat and Oil	C ₅₀ H ₉₀ O ₆	
Sludge		
Primary	C ₂₂ H ₃₉ O ₁₀ N	
Combined	C ₁₀ H ₁₉ O ₃ N	McCarty ¹
Refuse (total organic fraction)	C ₆₄ H ₁₀₄ O ₃₇ N	Haug et al. ²
Wood	C ₉₉ H ₁₄₈ O ₅₉ N	Corey ³
Grass	C ₂₉₅ H ₄₂₀ O ₁₈₆ N	Corey ³
Garbage	C ₂₃ H ₃₈ O ₁₇ N	Corey ³
Food wastes	C ₁₆ H ₂₇ O ₈ N	Corey ³
Mixed paper	C ₁₈ H ₂₆ O ₁₀ N	Kayhanian and Tchobanoglous ⁴
Yard wastes	C ₂₆₅ H ₄₃₄ O ₂₁₀ N	Kayhanian and Tchobanoglous ⁴
Bacteria	C ₂₇ H ₃₈ O ₁₆ N	Kayhanian and Tchobanoglous ⁴
Fungi	C ₅ H ₇ O ₂ N	
	C ₁₀ H ₁₇ O ₆ N	

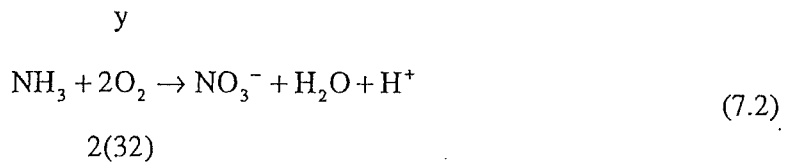
cal compositions of various organics and organic mixtures are presented in Table 7.1. Using municipal sludge as an example and assuming an average composition from Table 7.1 of C₁₀H₁₉O₃N, the carbonaceous oxygen demand can be determined as



Based on the assumed substrate composition, the oxygen demand can be estimated as

$$x = 12.5(32) / 201 = 1.99 \text{ g } O_2 / \text{g substrate BVS}$$

Ammonia released as a result of organic decomposition can be oxidized according to the following nitrification reaction:



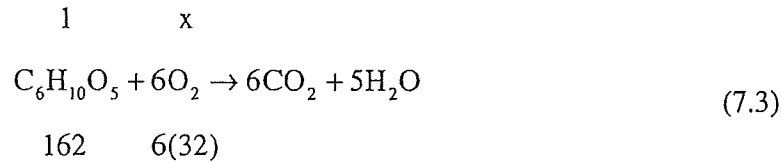
Assuming all ammonia is oxidized, the maximum nitrification demand for the above substrate can be estimated as

$$y = 2(32) / 201 = 0.32 \text{ g } O_2 / \text{g substrate BVS}$$

The nitrification demand is significantly less than that required for organic oxidation. Also, most of the produced ammonia will not be oxidized. Some will be used directly for cell

synthesis, but the largest fraction will probably be lost from the compost by volatilization. Therefore, oxygen demands for nitrification generally are not considered when developing aeration demands for composting.

Many other composting substrates, sawdust for example, are largely cellulosic in nature. Their decomposition reaction can be estimated by assuming a carbohydrate composition:



The oxygen demand for cellulosic substrates can be estimated as

$$x = 6(32)/162 = 1.185 \text{ g O}_2/\text{g BVS}$$

The stoichiometric demand for oxygen varies from a low of about 1.0 g O₂/g organic for highly oxygenated substrates such as starch and cellulose to a high of about 4.0 g O₂/g organic for saturated hydrocarbons (refer to Table 3.2). A value of 2.0 g O₂/g organic is typical for many complex substrates, such as sewage sludge, which are composed of mixtures of protein, carbohydrate, and fats.

For cases where a mixture of substrates are input into the process, the total oxygen demand can be determined from the assumed composition of the individual fractions and their weighted average oxygen demands. For example, refer back to Figure 6.13 where both sludge and a sawdust amendment are the input substrates. Assuming that Equation 7.1 applies to the sludge BVS component and Equation 7.3 to the sawdust BVS, the total oxygen demand can be estimated as

$$\begin{aligned} & [(0.375)(1.990) + (0.247)(1.185)] / (0.375 + 0.247) \\ & = 1.67 \text{ g O}_2/\text{g feed BVS} \end{aligned}$$

Air contains 23.2% oxygen by weight. Therefore, the weight requirement of air for the above mixture of sludge and sawdust is determined as

$$1.67 / 0.232 = 7.20 \text{ g air/g feed BVS}$$

This is a total *quantity* of air which must be supplied over the composting cycle to meet the stoichiometric demand. The quantity of air supply (i.e., lbs, kg, ft³, or m³) must be distinguished from the *rate* at which the air is supplied (i.e., kg/min or m³/min). The rate of air supply is considered in later sections of this Chapter.

It is usually more convenient to express the stoichiometric demand on the basis of total dry weight of the feed substrates. This requires that we know the biodegradable fraction of the volatile solids. Substrate degradability is the subject of Chapter 9. For the present purposes we will assume reasonable values for degradability coefficients and leave the more in-depth discussion to Chapter 9.

Example 7.1

100 metric tons of sludge cake are to be composted. The sludge cake is conditioned with sawdust amendment and product recycle with the proportions shown in Figure 6.13 (see also Figure 7.3). The sludge has the composition given by Equation 7.1 and the sawdust given by Equation 7.3. Determine the quantity of air that must be supplied to meet the stoichiometric demand.

Solution

1. From Figure 6.13 the following values apply:

$$S_s = 0.20$$

$$V_s = 0.75$$

$$k_s = 0.50$$

$$S_a = 0.65$$

$$V_a = 0.95$$

$$k_a = 0.20$$

Solid content
VS content
degradability

Also from Figure 6.13, the 100 metric tons of sludge are blended with $100(2/5) = 40$ metric tons of sawdust.

2. The stoichiometric demand for the sludge cake is determined as

$$100(0.20)(0.75)(0.50)(1.99) = 14.93 \text{ metric ton of O}_2$$

$$14.93(1000) = 14,930 \text{ kg O}_2$$

3. The stoichiometric demand for the sawdust amendment is determined as

$$40(0.65)(0.95)(0.20)(1.185) = 5.85 \text{ metric ton of O}_2$$

$$5.85(1000) = 5,850 \text{ kg O}_2$$

4. The total stoichiometric demand is the sum of the individual substrate demands:

$$14,930 + 5,850 = 20,780 \text{ kg O}_2$$

5. The quantity of air required to meet the stoichiometric demand is determined as

$$20,780 / 0.232 = 89,570 \text{ kg air}$$

$$89,570 / 1000 = 89.57 \text{ metric ton air}$$

6. Air at 25°C and 1 atm pressure has a specific weight of 1.20 kg/m³ (0.075 lb/ft³). The volume of air required to meet the stoichiometric demand is determined as

$$89,570 / (1.20) = 74,640 \text{ m}^3$$

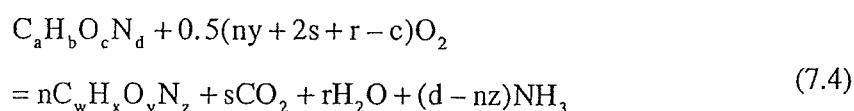
7. The stoichiometric air quantity on a dry weight basis can be determined as

$$89.57 / [100(0.20) + 40(0.65)] = 1.95 \text{ kg air / kg ds mixed substrates}$$

The above example points out the importance of air supply to the composting process. The weight of air required to just meet the stoichiometric demand is almost twice the dry weight of the feed substrates. Air is usually the largest term in the mass balance for any composting system.

In any practical composting system, it is necessary to supply an excess of air over the stoichiometric requirement to assure fully aerobic conditions. The excess air ratio (EAR) is defined as the ratio of actual air supplied to that required to just satisfy the stoichiometric demand.

Another approach to estimating oxygen requirements during aerobic composting is based on the composition of feed substrate and final product. This approach is useful if bench-scale composting studies can be conducted to estimate final product composition. Degradability of the feed substrate is thereby included in the analysis. Rich⁵ suggested the following stoichiometric equation:



where

$$\begin{aligned} r &= 0.5[b - nx - 3(d - nz)] \\ s &= a - nw \end{aligned}$$

The terms $C_aH_bO_cN_d$ and $C_wH_xO_yN_z$ represent the compositions of feed substrate and final product, respectively. An elemental analysis is required for evaluation of the subscripts in these terms. Use of this approach is illustrated in the following two examples adapted from Rich.⁵

Example 7.2

Bench scale tests of aerobic composting were conducted on a substrate with starting composition $C_{31}H_{50}O_{26}N$. Tests indicated that 1000 kg ds of the substrate were reduced to 200 kg ds at the completion of composting. Final product composition was determined to be $C_{11}H_{14}O_4N$. Determine the stoichiometric oxygen requirement per 1000 kg of feed.

Solution

1. Molecular weight of the substrate is

Carbon	31(12)	=	372
Hydrogen	50(1)	=	50
Oxygen	26(16)	=	416
Nitrogen	1(14)	=	14
			<hr/>
Total		=	852

$$\text{kg-mol of organics entering the process} = 1000/852 = 1.173$$

2. Molecular weight of the compost product is

Carbon	11(12)	=	132
Hydrogen	14(1)	=	14
Oxygen	4(16)	=	64
Nitrogen	1(14)	=	14
			<hr/>
Total		=	224

The kg-mol of compost leaving the process per kg-mol entering the process = $n = 200/(1.173)(224)$
 $= 0.76$

3. The following values apply:

a = 31	w = 11
b = 50	x = 14
c = 26	y = 4
d = 1	z = 1

Using these values, r and s can be determined as

$$r = 0.5\{50 - 0.76(14) - 3[1 - 0.76(1)]\} = 19.33$$

$$s = 31 - 0.76(11) = 22.64$$

4. From Equation 7.4, the quantity of oxygen required by the process is

$$W = 0.5[0.76(4) + 2(22.64) + 19.33 - 26](1.173)(32) = 783 \text{ kg}$$

5. Check with a materials balance using Equation 7.4:

In	
Substrate	1000
Oxygen	783
Total In	<hr/> 1783 kg
Out	
Compost	200
Carbon dioxide 1.173(22.64)(44)	1170
Water 1.173(19.33)(18)	408
Ammonia $[1 - 0.76(1)](1.173)(17)$	<hr/> 5
Total Out	1783 kg

6. The air required is $783/0.232 = 3375 \text{ kg}$. This is equivalent to $3375/1000 = 3.375 \text{ kg air/kg ds}$ substrate. As was the case in Example 7.1, the stoichiometric air demand is several times the dry weight of feed substrates.

Example 7.3

Estimate the energy released as heat in the bench tests described in Example 7.2.

Solution

1. The percentage elemental composition of organics in the substrate and compost are

In

$$\%C = 31(12)/852 = 43.6$$

$$\%H = 50(1)/852 = 5.9$$

$$\%O = 26(16)/852 = 48.9$$

Out

$$\%C = 11(12)/224 = 59.0$$

$$\%H = 14(1)/224 = 6.3$$

$$\%O = 4(16)/224 = 28.6$$

2. From Equation 3.26, the R values of the substrate and compost are

$$\text{Substrate } R = 100[2.66(43.6) + 7.94(5.9) - 48.9] / 398.9 = 28.6$$

$$\text{Compost } R = 100[2.66(59.0) + 7.94(6.3) - 28.6] / 398.9 = 44.8$$

3. From Equation 3.27, the unit heats of combustion of the organics are

$$\text{Substrate } Q = 127(28.6) + 400 = 4030 \text{ cal/g VS}$$

$$\text{Compost } Q = 127(44.8) + 400 = 6100 \text{ cal/g VS}$$

4. Total energy released as heat is

$$\text{Energy in: } 1000(1000)4030 = 4030 \times 10^6 \text{ cal}$$

$$\text{Energy out: } 200(1000)6100 = 1220 \times 10^6 \text{ cal}$$

$$\text{Energy release: } \frac{4030 \times 10^6 - 1220 \times 10^6}{1000} = 2810 \times 10^6 \text{ cal}$$

AIR DEMAND FOR MOISTURE REMOVAL

Determination of the air requirement for drying requires further analysis of the composting process. Referring to the mass balance diagram shown in Figure 6.7 and neglecting any amendment or bulking agent addition, the quantity of water to be evaporated daily, W , is given by

$$W = (X_s - S_s X_s) - (X_p - S_p X_p) \quad (7.5)$$

Considering the ash fraction to be conservative, a mass balance on the inert fraction yields

$$(1 - V_s)S_s X_s = (1 - V_p)S_p X_p \quad (7.6)$$

Solving Equation 7.6 for X_p , substituting into Equation 7.5, and rearranging gives

$$W = [(1 - S_s) / S_s] - [(1 - V_s) / (1 - V_p)][(1 - S_p) / S_p] \quad (7.7)$$

Equation 7.7 was solved for various substrate and compost solids contents. Results and other assumptions are presented in Figure 7.1. Conditions appropriate to a digested sludge cake were used to obtain the results shown in Figure 7.1. However, similar analysis for other substrate

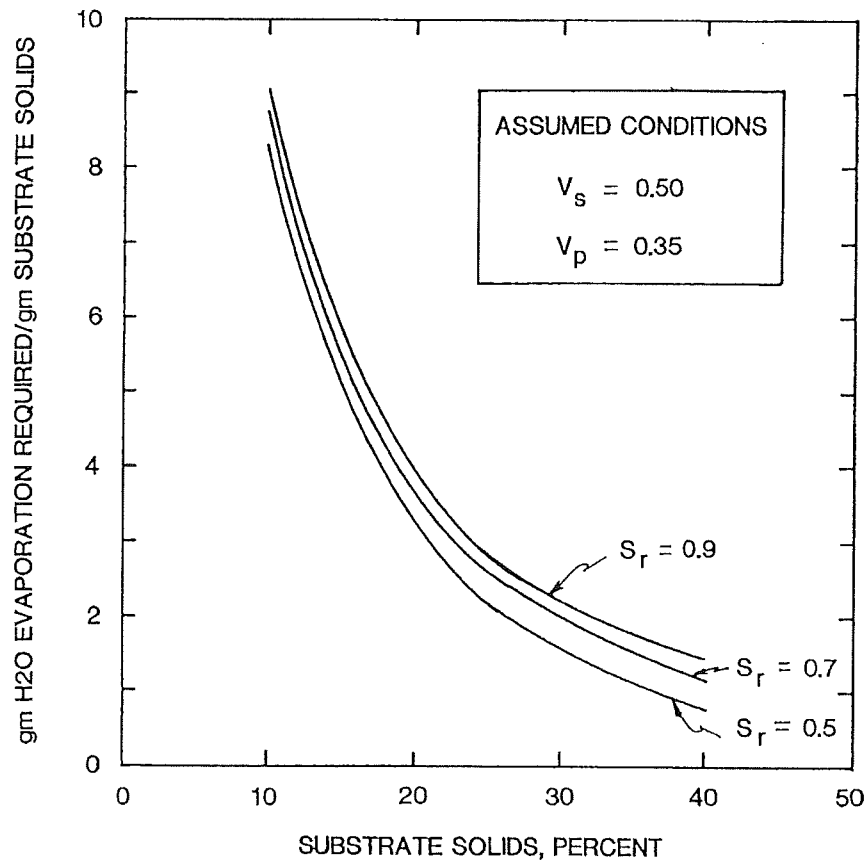


Figure 7.1. Effect of substrate solids and compost product solids on required moisture evaporation. From Haug and Haug.⁶

conditions results in very little change from the values indicated. The quantity of moisture to be evaporated is determined primarily by the input solids at substrate solids below ~30%. Above 30%, both feed solids and the final compost solids are important in determining the quantity of moisture to be evaporated. Rates of biological activity begin to decrease below moisture levels of about 40 to 50%.⁷ Therefore, drying to a moisture level below ~30% with the heat supplied by composting is difficult.

The quantity of water vapor that can be carried in saturated air at different temperatures is shown in Figure 7.2. The curve was constructed from standard psychrometric charts and steam tables⁸ for a total atmospheric pressure of 760 mm Hg. The quantity of moisture in saturated air increases exponentially with increasing air temperature. Gas that leaves a wet composting material will be near saturation and about the same temperature as the composting material. If thermophilic temperatures are maintained, considerable moisture will be removed with the exhaust gases.

If the temperature difference between inlet and outlet air is greater than ~25°C (45°F), relative humidity of the inlet air will have a minor effect in determining the overall moisture removal. This means that drying can occur even in climates with high ambient humidity in the feed air.

The specific humidity, w , is defined as the weight of water carried per unit weight of dry air, i.e., g water/g dry air. Values of specific humidity can be read from Figure 7.2. However, the following algorithm for calculating specific humidity is useful and is incorporated into

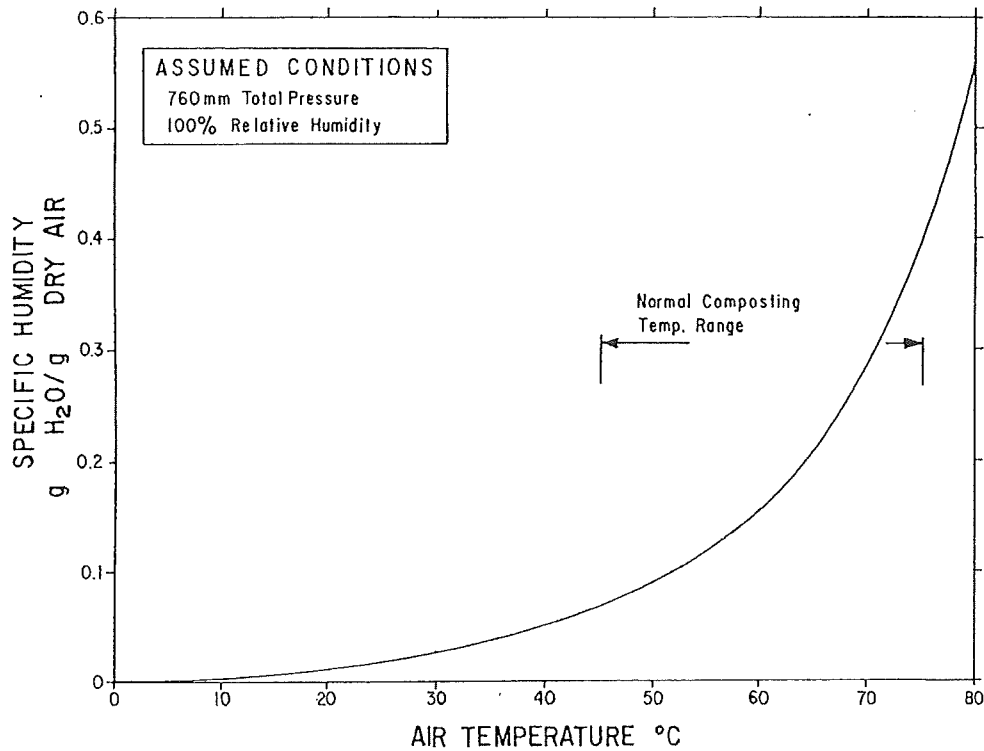


Figure 7.2. Specific humidity as a function of air temperature under conditions of 100% relative humidity and 760 mm Hg total pressure.

later simulation models. Saturation vapor pressure (PVS) is a function of temperature and can be mathematically modeled by the Antoine equation:⁹

$$\log_{10} PVS = a / T_a + b \quad (7.8)$$

where

PVS = saturation water vapor pressure, mm Hg

a = constant equal to -2238 for water

b = constant equal to 8.896 for water

T_a = absolute temperature, °K

The actual water vapor pressure (PV) is determined as

$$PV = RHAIR(PVS) \quad (7.9)$$

where

PV = actual water vapor pressure, mm Hg

RHAIR = relative humidity, fraction of saturation vapor pressure

Specific humidity can be determined from the water vapor pressure and the molecular weights of water (18.015) and dry air (28.96):

$$W = (18.015 / 28.96)[PV / (PAIR - PV)] \quad (7.10)$$

where w = specific humidity, g water/g dry air
 $PAIR$ = atmosphere pressure, mm Hg

Example 7.4

A wet organic substrate at 25% TS is to be composted and dried to a final solids content of 65% TS. The substrate has a VS content of 75% with the chemical composition given by Equation 7.1. The compost is expected to be 45% VS. Ambient air to the process is 20°C with 75% relative humidity and total pressure of 760 mm Hg. Exit gas temperature is 55°C saturated. Determine the weight and volume of air and the excess air ratio (EAR) required to remove the required moisture.

Solution

1. The requirement for water evaporation can be determined from Equation 7.7:

$$W = [(1 - 0.25)/0.25] - [(1 - 0.75)/(1 - 0.45)][(1 - 0.65)/0.65]$$

$$W = 2.76 \text{ g water/g dry substrate}$$

2. Determine the moisture-carrying capacity of the exit gas as follows. From Equation 7.8 the saturation vapor pressure is determined as

$$\log_{10} PVS = -2238 / (273 + 55) + 8.896 = 2.073$$

$$PVS = 118.3 \text{ mm Hg}$$

Because the exit gas is saturated, the relative humidity is 1.00. The actual vapor pressure is then determined from Equation 7.9 as

$$PV = (1.00)118.3 = 118.3 \text{ mm Hg}$$

The specific humidity is determined from Equation 7.10 as

$$w = (18.015/28.96)[118.3/(760 - 118.30)]$$

$$w = 0.1147 \text{ g water/g dry air}$$

Note that this value corresponds with that from Figure 7.2 for a temperature of 55°C.

3. The specific humidity of the inlet air at 20°C and 75% relative humidity is determined in the same manner:

$$\log_{10} PVS = -2238 / (273 + 20) + 8.896 = 1.258$$

$$PVS = 18.10 \text{ mm Hg}$$

$$PV = (0.75)18.10 = 13.6 \text{ mm Hg}$$

$$w = (18.015/28.96)[13.6/(760 - 13.6)]$$

$$w = 0.0113 \text{ g water/g dry air}$$

The above value cannot be read from Figure 7.2 because the latter figure applies only to saturated conditions.

4. Net moisture removed with the exhaust gases is

$$0.1147 - 0.0113 = 0.1034 \text{ g water/g dry inlet air}$$

Note the relatively small moisture contribution of the inlet air if the temperature difference is about 20°C or greater.

5. The weight of required air is determined as

$$2.76/0.1034 = 26.7 \text{ g dry air/g ds substrate}$$

Note that the air required for drying is significantly greater than that required for biological oxidation as determined in Example 7.1.

6. From Example 7.1, the specific weight of air at standard temperature and pressure (STP) is 1.20 g/L. Therefore,

$$26.7/1.2 = 22.25 \text{ l dry air/g ds substrate}$$

Again, the air weight and volume are total quantities that must be supplied during the composting cycle to remove a given quantity of water.

7. The EAR is calculated as follows: from Equation 7.1 the stoichiometric demand is 1.99 g O₂/g BVS. One g ds of substrate contains 0.75 g VS. Assuming the 0.25 g ash to be conservative, the final compost will contain $0.25/(1 - 0.45) - 0.25 = 0.205$ g VS. Therefore, about $(0.75 - 0.205)/0.75 = 72.7\%$ of the VS are degradable. Therefore, the stoichiometric demand can be converted to units of g air/g ds as follows:

$$1.99(1/0.232)(0.75)(0.727) = 4.68 \text{ g air/g ds}$$

The EAR is determined as

$$\text{EAR} = 26.7 / 4.68 = 5.7$$

Another approach to determining the quantity of water that must be removed is to use the bar diagrams introduced in Chapter 6. Referring back to Figure 6.13 for the case of wet substrate conditioned with amendment and recycle, the bars for substrate and amendment are repeated in Figure 7.3. The right bar represents the compost product assuming 60% TS and loss of all BVS during the composting process. Recycle is not shown in Figure 7.3 because it is within the system boundary and does not add new water to the process. For this case, 3.581 g water must be removed per g ds of the substrate. Using the same inlet air exhaust gas conditions from Example 7.4, about 34.6 g air/g ds substrate are required for drying. The bar diagrams provide visualization of the problem and are particularly useful when multiple substrates or amendments are involved.

Using the procedures of Example 7.4, the quantity of air required for moisture removal was determined as a function of substrate solids content. Inlet air was assumed to be 20°C and 100% relative humidity. Exit gas temperatures were assumed to be 40°C or greater. Thus, inlet

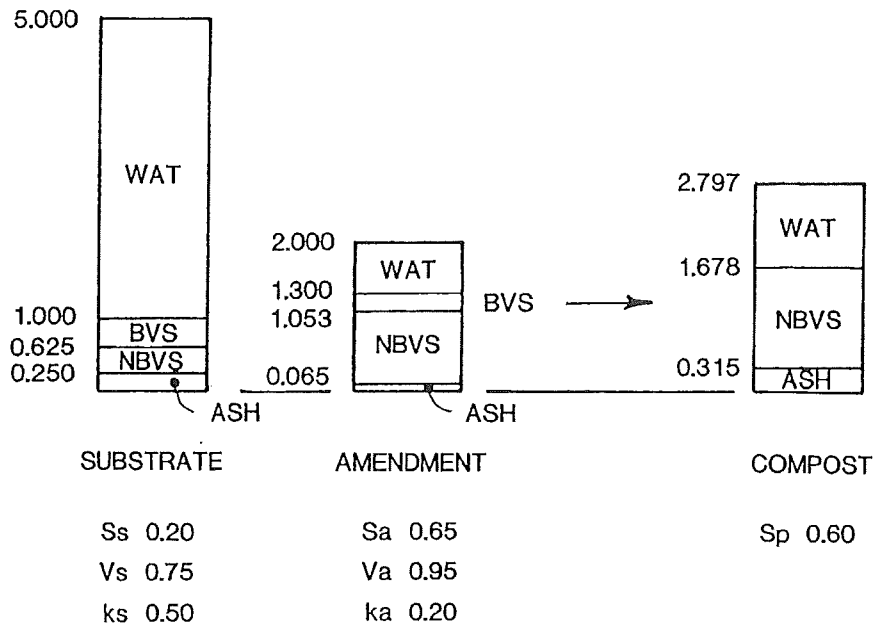


Figure 7.3. Bar diagrams from Figure 6.13 for the case of a wet substrate at 20% TS conditioned with amendment and recycle. Recycle is not shown because it is within the system boundary and does not contribute new water to the system.

air conditions are not critical to the problem. A final compost moisture content of 30% was assumed. Results and other assumptions are presented in Figure 7.4. The typical range of stoichiometric air requirements for complex substrates such as digested and raw municipal sludge is also shown. With wet substrate, the air required for moisture removal is significantly greater than the stoichiometric demand for biological oxidation and is influenced largely by the substrate solids content and exit gas temperature. At substrate solids of 20%, the air requirement for drying can be 10 to 30 times that for biological oxidation. With dryer substrates, the air requirements for drying and biological oxidation become more equivalent. For example, at 40% TS substrate and 70°C exit temperature the two air requirements become essentially equivalent. This may be somewhat misleading, however, because water addition may be required in the latter case to prevent moisture limitations during composting. This will add to the evaporative burden and increase the required air supply over that shown in Figure 7.4.

Because the stoichiometric demand is generally less than the demand for drying, control of the air supply becomes an important factor in operation of the composting process. The extent of drying can be regulated by control of the air supply. It will be shown in Chapter 8 that composting can be divided into two distinct thermodynamic regions: one in which the energy supply is sufficient for both composting and drying, and one in which energy is sufficient for composting with only limited drying. The air supply can be used to control the thermodynamic region of operation. Thus, the air supply is one of the operator's most important tools for process control.

AIR DEMAND FOR HEAT REMOVAL

Rates of biochemical reactions generally increase exponentially with temperature. However, process temperatures can elevate to the point of thermal inactivation of the microbial population. Temperature then becomes rate limiting. To control process temperatures in a

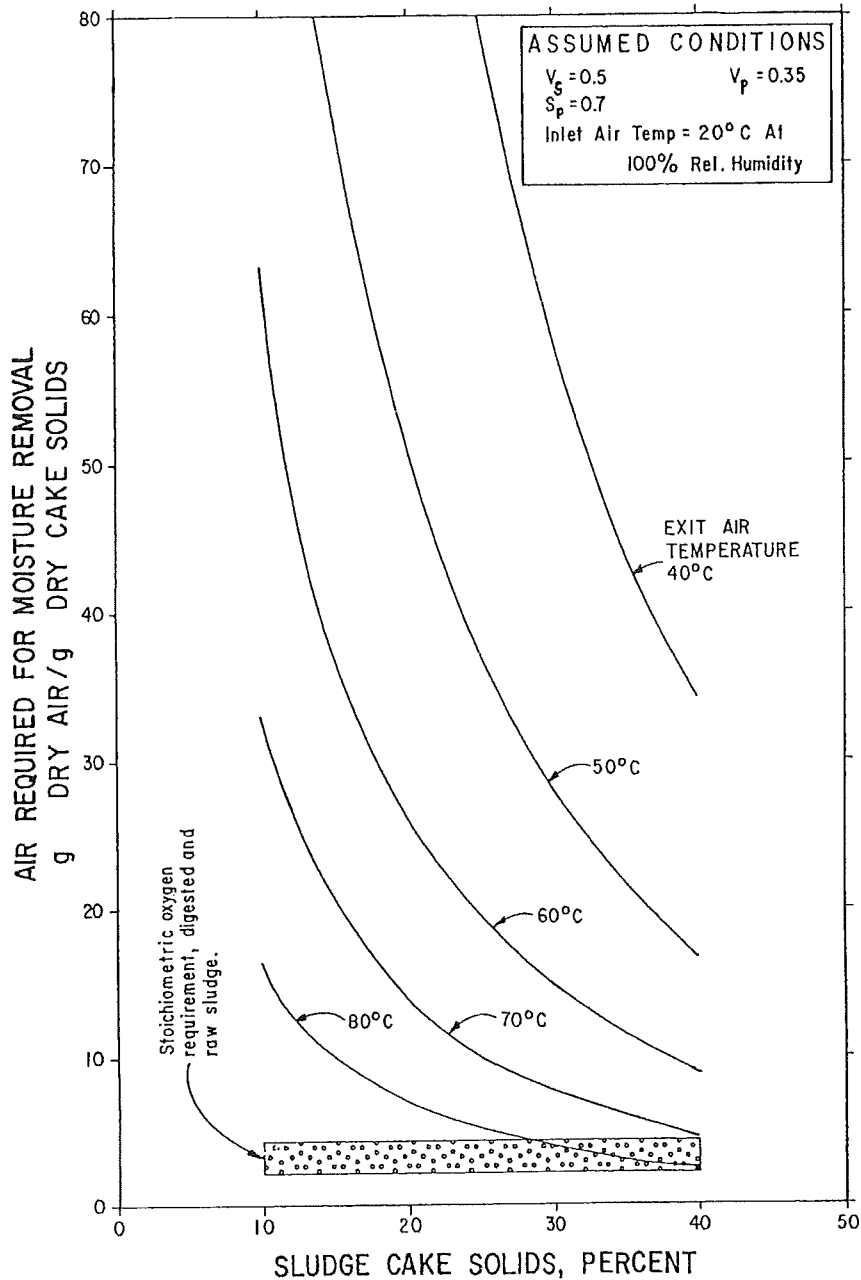


Figure 7.4. Effect of substrate solids and exit air temperature on air requirements for moisture removal to a compost solids content of 70%. From Haug and Haug.⁶

more optimum range for the microbial population, air supply can be increased to remove more heat.

Referring to Chapter 3, the heat of combustion per electron transferred to a methane-type bond is essentially constant at ~26.05 kcal per electron transferred or, since O₂ accepts four electrons, 104.2 kcal/mol O₂. This equals 3260 cal/g O₂ or 5870 Btu/lb O₂. Thus, heat release can be estimated from the stoichiometric demand for oxygen.

Example 7.5

Using the oxygen demands determined by Equations 7.1 and 7.3 and the mixture of substrate and amendment shown in Figure 7.3, estimate the heat release for 1 g ds of feed substrate.

Solution

1. From Equation 7.1 the oxygen demand of the substrate is 1.99 g O₂/g BVS. From Figure 7.3, 1 g ds of substrate contains 1.000 - 0.625 = 0.375 g BVS. Oxygen demand and the corresponding heat release for the substrate is

$$0.375(1.99) = 0.746 \text{ g O}_2 / \text{g ds}$$

$$0.746(3260) = 2430 \text{ cal/g ds}$$

2. From Equation 7.3, the oxygen demand of the amendment is 1.185 g O₂/g BVS. From Figure 7.3, 1.300 - 1.053 = 0.247 g BVS are contained in the amendment. Oxygen demand and heat release from the amendment is

$$0.247(1.185) = 0.293 \text{ g O}_2 / \text{g ds}$$

$$0.293(3260) = 955 \text{ cal/g of substrate ds}$$

3. Total heat release is the sum of the above,

$$2430 + 955 = 3385 \text{ cal/g of substrate ds}$$

Heat released during composting will be removed primarily by the hot, moist exhaust gases leaving the process. Some heat will be removed in the output solids and some lost to the surroundings. However, these are relatively small compared to that contained in the exhaust gases. Heat released by organic decomposition will heat the incoming dry air and water vapor to the exit temperature, supply the heat of vaporization, and heat the evaporated water vapor to the exit gas temperature. Considering only these major heat demands and neglecting other minor losses allows a closed solution to the problem of determining the air demand for heat removal.

Example 7.6

Estimate the air demand to remove the heat generated in Example 7.5. Assume the gas conditions of Example 7.4, namely ambient air at 20°C and 75% relative humidity and exhaust gases at 55°C saturated.

Solution

1. Let x = the lb dry air required to maintain the compost temperature at 55°C. Then,

$$\begin{aligned} \text{Heat of vaporization at } 20^\circ\text{C} &= (x)(0.1034)(585.8) \\ \text{Heat inlet water vapor and evaporated} &= (x)(0.1034 + 0.0113)(0.44)(55 - 20) \\ \text{water vapor to } 55^\circ\text{C} & \\ \text{Heat dry air to } 55^\circ\text{C} &= (x)(0.24)(55 - 20) \end{aligned}$$

2. For the above equations, 585.8 is the heat of vaporization at 20°C and 0.44 and 0.24 are the specific heats of water vapor and air in cal/g-°C, respectively.
3. Heat release from Example 7.5 is 3385 cal/g ds. At steady state, heat release must balance heat demand. Therefore,

$$(x)(60.57 + 1.77 + 8.40) = 3385$$

$$x = 47.9 \text{ g air/g of substrate ds}$$

4. From Example 7.1 the stoichiometric air demand is 1.95 g air/g substrate ds. The EAR is determined as

$$\text{EAR} = 47.9 / 1.95 = 24.6$$

For the examples based on Figure 7.3, the air quantity required for heat removal is greater than that required either for stoichiometry or for moisture removal. Therefore, in this case the requirement for heat removal governs. The reader should note that this conclusion is valid only for the above example. Requirements for moisture removal could govern under other process conditions, such as a wetter feed substrate. Because the heat of vaporization is generally the largest term in the energy balance, moisture removal and heat removal are related and the requirements for each should not differ by much for wet substrates. With dry substrates the air demand for heat removal will be greater than that for moisture removal. Requirements for moisture and heat removal are significantly greater than that required by stoichiometry and will usually be the governing conditions.

Composting has often been described as a problem of materials handling. If so, one should be aware that input air and exhaust gases are usually the dominant terms of the mass balance. In some cases the weight of air moved through the process can be 30 to 50 times that of the dry weight of substrates. The significance of the air movement is sometimes overlooked because the gases are not visible. The reader is cautioned to always remember that materials handling includes both solids and gases.

AERATION RATES

The air demands estimated above for stoichiometry, moisture and heat removal represent total *quantities* which must be supplied over the composting cycle. Converting these quantities to actual *rates* of air supply requires knowledge of the type of composting system and the kinetics of microbial oxidation.

Batch Processes

For a batch process, such as the windrow and aerated static pile, the total air *quantity* can be converted to an aeration *rate* by considering the time duration of the process. Assume a batch process with a total air demand based on heat removal from Example 7.6 of 47.9 g air/g of substrate ds. Assume that this quantity is supplied at a constant rate over a 25-day composting cycle. Then the *average* rate of aeration can be estimated as

$$\begin{aligned} & (47.9)(10^6) / [1.2(25)(24)(10^3)] \\ & = 66.5 \text{ cmh / dmt (cu. meters per hour per dry metric ton)} \\ & = 2135 \text{ cfh / dt (cu. feet per hour per dry ton)} \end{aligned}$$

where 1.20 g/L is the density of air at standard conditions.

A number of factors can cause the *peak* rate of aeration to exceed the average rate calculated above. First, the rate of organic oxidation, and therefore the rate of heat release, will vary throughout the composting cycle. Second, the type of aeration control may increase the peaking factor. An on/off aeration control logic is used in some systems. Obviously, the total air demand can be supplied only during the "on" sequence. Temperature feedback logic is popular with many composting systems and can also result in high peaking factors.

The peak rate of air supply can be estimated from data developed by Wiley,¹⁰ Jeris and Regan,¹¹ Schulze,^{12,13} and Snell.¹⁴ These researchers observed that the rate of oxygen consumption is a function of temperature. Peak rates of about 4 to 14 mg O₂/g VS-h were observed in the temperature range of 45 to 65°C (see Figure 10.17). For the feed mixture presented in Figure 7.3, this is equivalent to 0.0035 to 0.0121 g O₂/h per g ds of mixed substrate and amendment. Using 3260 cal/g O₂ consumed, the heat release rate can be estimated as

$$(0.0035 \text{ to } 0.0120)(3260) = 11 \text{ to } 39 \text{ cal/h per g of feed solids}$$

$$20 \text{ to } 70 \text{ Btu/h per lb of feed solids}$$

Using the same assumptions and calculation procedures for heat removal presented in Example 7.6, the aeration rate required to maintain 55°C is about

$$(x)(60.57 + 1.77 + 8.40) = 11 \text{ to } 39$$

$$x = 0.15 \text{ to } 0.55 \text{ g air/h per g feed solids}$$

Assuming an air density of 1.20 g/L, the peak aeration rate becomes

$$(0.15 \text{ to } 0.55)(10^3)/1.20 = 125 \text{ to } 460 \text{ cmh/metric ton of feed solids}$$

$$4000 \text{ to } 14,700 \text{ cfh/ton of feed solids}$$

Using simulation models of the aerated pile process operated with temperature feedback control logic, Haug¹⁵ predicted peak aeration rates of 3800 to 4800 cfh/dt of sludge for raw sludge blended with wood chips. Murray and Thompson¹⁶ reported that peak aeration rates of 4000 to 5000 cfh/dt were sometimes insufficient to keep process temperatures below 60°C when composting a raw sludge/wood chip mixture. Williams and North¹⁷ reported a peak aeration rate approaching 10,000 cfh/dt during static pile composting of a raw sludge/wood chip mixture. Both the theoretical and measured values compare favorably with the estimate based on oxygen consumption data. The subject of peak aeration rates is addressed again in Chapter 14.

It should be noted that the peak aeration rate may be maintained for only a short period until the peak demand has passed. In the model presented by Haug,¹⁵ the required aeration rate exceeded 4000 cfh/dt for about 2 days, 3000 cfh/dt for about 4 days, and 2000 cfh/dt for about 8 days. Thus, there is a time duration associated with any peak demand. We might speak of the instantaneous peak, the 1-h peak, or the 24-h peak. The oxygen consumption data presented above is probably on the order of 1-h peak data, whereas most of the reported field data represent 24-h peak demands.

If the aeration system cannot meet the peak demand, process temperatures will exceed the desired set point. The designer must make a tradeoff between aeration system capacity, and

hence capital cost, and the needs for process temperature control. It may be more cost-effective to size the system for less than the peak demand and accept process temperatures above setpoint for a short period. The simulation models in Chapters 11 through 14 are useful to develop statistical information on which to base such decisions.

Aeration systems for batch processes take many forms. Some aerated pile and windrow systems use a single blower connected to a single pile. In this case, the peak demand is carried by the blower. Other systems use a central blower facility connected to many individual piles. In this case, the peaking factor can be "shaved" because it is unlikely that all piles simultaneously would be at the point of maximum oxygen consumption.

Minimum aeration rates should also be considered because the system must be capable of operating over the turndown range from peak to minimum rates. For an individual pile or windrow the minimum average rate usually occurs at the very beginning or end of the batch cycle and may be as low as 200 to 500 cfh/dt.

Continuous Processes

Many reactor systems operate on a continuous or semicontinuous feeding schedule. Typically, substrate is conditioned and loaded into the reactor on a daily basis. Reactor residence time is usually greater than 10 days, so the daily feeding schedule can be modeled as a continuous process. For a continuous feed process, the quantity of required air can be converted to an *average* rate of aeration by considering a daily unit weight of feed substrate. Again using the air quantity for temperature control determined in Example 7.6, the aeration rate becomes

$$47.9 \text{ g/day of air per g/day of substrate ds}$$

This is equivalent to 1660 cmh/dmtpd of substrate (m^3 per hour per dry metric ton per day) or 53,000 cfh/dtpd (ft^3 per hour per dry ton per day). This is typical of the range of values predicted from simulation modeling of continuous processes as presented in Chapter 13.

With continuous feeding, the *peak* aeration demand should not exceed the average demand over the composting cycle, i.e., (peaking factor = 1). With semicontinuous feeding, some peaking might occur between feed periods. However, the 15 to 20% contingency normally applied to blower design capacity and the usual practice of providing standby capacity appear adequate to handle most above average aeration demands.

The designer should consider that feed quantity and composition will vary throughout the life of the project. The process should be examined under all expected conditions to determine whether seasonal or periodic peaking factors should be applied. Similarly, minimum flow conditions should be considered. This is particularly important if the process will operate below design loadings in early years. There is a tendency to focus attention only on average or peak design loadings. However, the full range of operation should be considered to avoid control problems during minimum turndown conditions.

CONTROLLING THE AERATION RATE

Once minimum, average, and peak aeration rates have been determined, the designer must select a control system to regulate the aeration rate. There are a number of control strategies which have been used in practice. These can be summarized as follows:

1. **Uncontrolled** — Windrow aeration by natural ventilation is an example of this approach. Such an approach is not applicable to aerated pile or reactor systems.
2. **Manual** — Throttling valves can be used to manually control the aeration rate. This is a common practice where lateral ducts are tied to a manifold which in turn is connected to a central blower system. Throttling valves can also be used with a single blower/manifold system. Flow through each lateral or single blower is manually adjusted by the throttling valve throughout the composting cycle.
3. **On/Off Sequencing by Timer** — With a single blower design, the average rate of air supply can be controlled by regulating the blower "on-time" by means of a timer control. This approach is often used with the static pile system and some reactor systems. Timer control can be used in conjunction with throttling valves to allow adjustment of both on-time and flowrate.
4. **Feedback Control Based on O₂ or CO₂ Content** — Oxygen or carbon dioxide probes inserted into the composting mixture or the exhaust gas ducts can generate a control signal used to modulate air supply and maintain a setpoint O₂ or CO₂ content. O₂ or CO₂ is the *controlled* variable and aeration rate the *manipulated* variable. This control strategy is only usable with dry substrates and where temperature control is not used because the aeration supply is then near the stoichiometric demand. With wet substrates or where temperature control is used, the aeration demands for moisture and heat removal are so high that the O₂ content often differs only slightly from that of ambient air (21% by volume).
5. **Feedback Control Based on Temperature** — Thermocouples inserted into the composting mixture can generate a control signal used to modulate air flowrate or blower on-time to maintain a setpoint temperature. Temperature is the *controlled* variable and aeration rate the *manipulated* variable. This control approach is used in many static pile and most reactor systems and is considered well proven.
6. **Air Flowrate Control** — If the daily quantity of feed material remains reasonably constant, it is possible for the operator to control air flowrate to a fixed value by either manual adjustment of fan dampers or by a setpoint flowrate control loop. This approach is used in some reactor systems where conditions are not expected to change rapidly.

Where a control signal, temperature for example, is used for regulation, the air supply can be adjusted by a number of techniques. The on-time can be controlled in a timer system. Throttling of inlet guide vanes or inlet dampers is commonly used with fixed speed aeration blowers. Outlet dampers can also be used, but the possibility of fan surging at low flow conditions should be considered. A variety of variable speed drives can also be used to adjust the aeration rate. Speed control becomes more cost-effective in large systems where the power savings can offset the added capital cost. Again, it is important to consider minimum, average, and peak aeration rates to define the range of system operation. Flow measuring devices and throttling valves must operate over the entire range of expected conditions.

MECHANISMS OF AERATION

For the aerated static pile and most reactor compost systems, the mechanism for supplying oxygen is obvious: air exchange is provided by forced ventilation using blowers to pull or push air through the material. In other systems, particularly the non-aerated windrow process, the

mechanisms of aeration are not so obvious. On first impulse one is tempted to assume that windrow turning is the primary method for oxygen replenishment within the free airspace. As will be seen, however, this does not appear to be the principal mechanism. The purpose of this section is to explore the factors responsible for supplying oxygen to pile or windrow systems that do not use forced aeration.

Exchange Volumes

For any substrate the air volume required to supply the stoichiometric oxygen demand can be estimated using the procedures of Example 7.1. Once the total air volume is estimated the number of exchange volumes can be calculated provided the free airspace in the mixture is known. The number of exchange volumes is defined as the number of times the mixture free airspace must be renewed with air to supply the stoichiometric oxygen demand. Knowledge of the number of required exchanges can provide insight into the mechanisms responsible for aeration.

Example 7.7

A yard waste consisting of grass and leaves is to be windrow composted. No recycle is used. The mixed yard wastes are estimated to be 80% VS with a degradability of 50%. Initial moisture content in the windrow is adjusted to 50%. If unit weight of the mixture is 0.65 g/cm^3 , estimate the number of volume exchanges required to satisfy the stoichiometric oxygen demand during composting.

Solution

- Specific gravity of the mixture can be calculated from Equation 6.1:

$$1/G_s = (0.80/1.00) + [(1 - 0.80)/2.5]$$

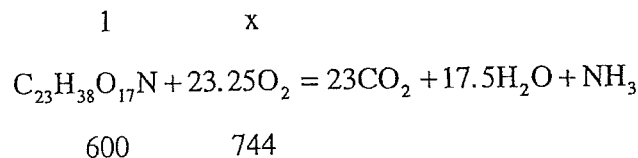
$$G_s = 1.14$$

- Determine the mixture FAS from Equation 6.11:

$$f = 1 - [0.65(0.50)/(1.13)(1.00)] - [0.65(1 - 0.50)/1.00]$$

$$f = 0.387$$

- The stoichiometric air requirement for composting can be estimated assuming the chemical composition for grass from Table 8.1:



$$x = 744/600 = 1.24 \text{ g O}_2/\text{g substrate BVS}$$

$$x = 1.24(0.80)(0.50)/(0.23) = 2.16 \text{ g air/g ds}$$

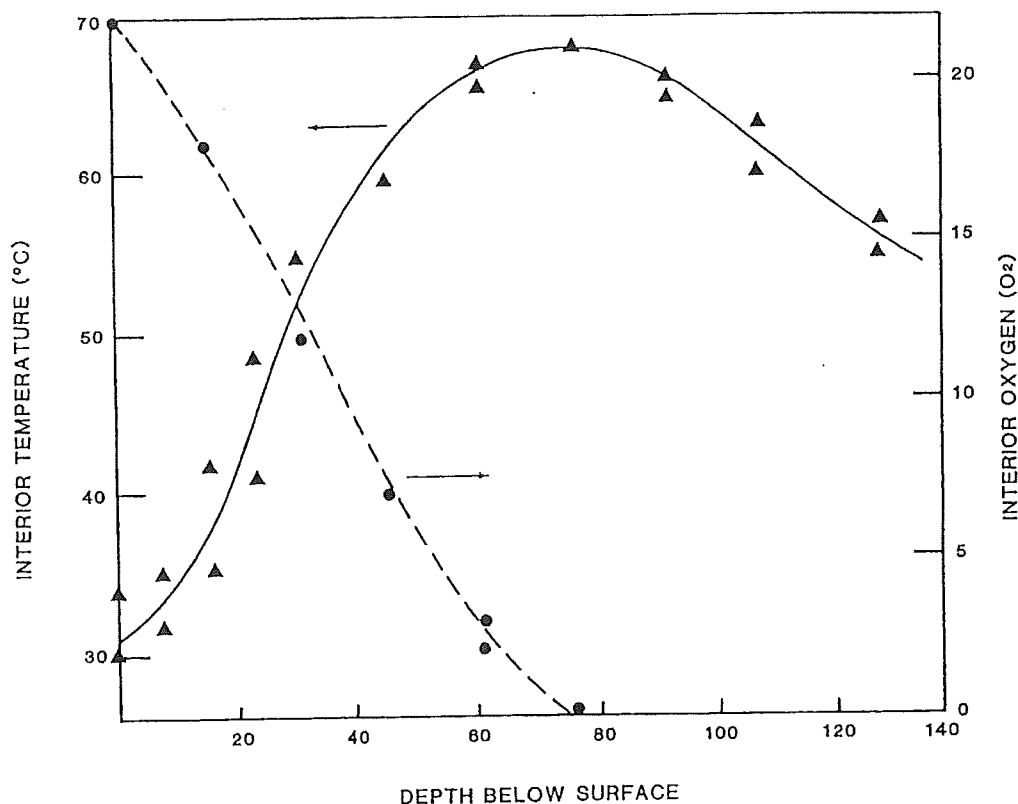


Figure 7.5. Profiles of oxygen concentration (%) and temperature with depth (cm) into a windrow composed of digested sludge cake and recycled compost. Measurements were made 5 h after windrow turning. From Iacoboni et al.¹⁹

4. The volume of air to be supplied can be estimated assuming air density at 1.20 g/L:

$$x = 2.16 / 1.20 = 1.80 \text{ l/g ds}$$

5. Each cc of mixture contains $0.65(0.50) = 0.325$ g ds and contains 0.387 cc of free airspace. The number of void volume exchanges can be estimated as

$$\frac{0.325(1.80)(1000)}{0.387} = 1510 \text{ exchanges}$$

Suppose it is assumed that each turning of the windrow completely renews air contained in the voids and that no other aerating mechanisms are at work. With these assumptions, the number of windrow turnings must equal the number of required exchange volumes. Therein lies the problem. The number of turnings normally used in windrow composting is nowhere near the exchange volumes estimated in Example 7.7. Furthermore, no combination of reasonable values for the variables used in the analysis seems likely to reduce significantly the required number of exchange volumes.

Smith¹⁸ and Iacoboni et al.¹⁹ observed that oxygen concentrations in the interiors of non-aerated sludge windrows often decreased to undetectable levels within a few minutes to several hours after turning. A profile of oxygen content with depth into such a windrow is shown in Figure 7.5. The data were recorded 5 h after turning. Based on the windrow dimensions it was estimated that about 50% of the windrow volume was aerobic, while the rest was either slightly aerobic or anaerobic. Maier et al.²⁰ observed a similar phenomenon in

windrows composed of finely ground refuse (particle size <1.25 cm) and reported oxygen depletion in the bottom interior 4 to 5 h after turning. These observations seem reasonable in light of the analysis of required exchange volumes.

In discussing the turning frequency required for windrow composting of ground refuse, Golueke⁷ indicated that the windrow needed to be turned every other day for a total of only 4-5 turns. By the fourth or fifth turn the material should be so advanced toward stabilization as to require no further turning. More frequent turning would be beneficial if the material were very wet or compacted. Based on experience gained during windrow composting studies at the University of California, McGauhey and Gotaas²¹ and later Golueke²² recommended the following turning schedule as adequate for municipal refuse (2.5 to 5 cm probable particle size):

Moisture Content (%)	
>70	Turn daily until the moisture content is reduced to <70%
60-70	Turn at 2-day intervals (number of required turns is about five)
40-60	Turn at 3-day intervals (approximate number of turns is four)
<40	Add moisture

The question that remains is how such minimal turning as described above can result in the aerobic conditions desired during composting. Obviously, exchanging air contained in the FAS by windrow turning is entirely inadequate to supply the air quantities required. Other aeration mechanisms must be operating in the windrow process.

Molecular Diffusion

Assuming no forced aeration, there are two ways oxygen can be supplied through pore spaces into the interior of the windrow between turnings: (1) by molecular diffusion and (2) by mass movement of air through the pores in response to an energy gradient. Molecular diffusion results from constant and random collisions between molecules of a fluid. As a result of such collisions, there is a tendency for molecules to move from a zone of high concentration to a zone of lower concentration. If oxygen is depleted within the windrow, a net movement of oxygen from the surrounding air into the windrow will occur as a result of molecular diffusion. Similarly, carbon dioxide and water vapor will diffuse from the interior of the windrow where it is produced to the outside air where the concentration is lower.

The problem with molecular diffusion, however, is that the process is extremely slow compared to rates at which oxygen is required for composting. Shell²³ and Snell¹⁴ studied the diffusion of oxygen through composting refuse and concluded that diffusion alone supplied only a small percentage of the oxygen needed during composting. Furthermore, the rate of diffusion decreased as moisture content of the compost increased, a definite problem with wet substrates. Only when refuse was placed in thin layers (5 to 10 cm) did molecular diffusion become significant. Even in this case the rate of oxygen diffusion was estimated to be <5% of the maximum rate of oxygen demand.

Natural Draft Ventilation

Because molecular diffusion is not a practical transport mechanism, it appears that only a mass flow of air in response to an energy gradient can supply the required oxygen. Remember, forced ventilation or aeration by means of mechanical blowers is not considered here. The

question then is what forces are operating within a composting windrow or pile to produce a mass flow of air?

Referring to Figures 2.5 and 2.6, it is common to observe steam continually issuing from the top of windrows even if they are turned only infrequently. This implies a mass flow of water vapor and other exhaust gases from the pile interior. The movement is in response to the high temperature of gases within the windrow, analogous to hot flue gases drafting up a chimney. This effect is termed natural draft ventilation.

The density of dry and saturated air as a function of temperature is shown in Figure 7.6. As temperature increases, the density of dry air decreases. However, the degree of saturation can also affect the density, particularly at higher temperatures, because the saturation vapor pressure increases exponentially with temperature (Figure 7.2). The effect of water vapor on density is explained by the fact that the molecular weight of water is considerably less than that of the oxygen and nitrogen it displaces. Carbon dioxide produced from organic decomposition has the opposite effect because its molecular weight is greater than either oxygen or nitrogen.

The density difference between warm moist air within the interior of the windrow or pile and colder, less moist ambient air produces an upward buoyant force that induces a natural ventilation of the windrow. A schematic illustration of the natural draft ventilation process is presented in Figure 7.7. The concept of natural drafting is easily understood. However, the question is whether the rate of natural ventilation is sufficient to satisfy the actual oxygen demands.

Haug²⁴ developed hydraulic models to simulate the process of natural ventilation. Based on results of these models and observations of actual composting systems, it was concluded that natural drafting is the likely driving force for most oxygen transfer in a conventional (no forced aeration) windrow or pile system. The ventilation rate was found to be a function of the density difference between inside and outside gases, the particle size of the compost, and the free air space of the pile. It was also suggested that the ventilation rate is independent of pile height, all other factors being constant. As the height increases, the rate of natural ventilation should remain relatively constant whereas the rate of oxygen consumption per unit of ground area increases with height. Thus, there is a limit to the height of pile beyond which adequate oxygen cannot be supplied by natural ventilation. The Haug²⁴ model suggested that natural draft could supply adequate oxygen with pile heights from 1 to 3 meters, particle sizes about 0.1 cm and above, and a temperature difference of about 40°C. Maier et al.²⁰ observed that aeration of windrows composed of finely ground refuse was improved when the windrow was placed on elevated racks so that air could permeate from below and produce a natural upward draft. The natural draft was reported to successfully aerate windrows placed about 1.2 m deep.

With regard to aeration, the function of windrow turning is to assure that adequate free airspace is maintained. Ground refuse and grass, for example, are noted for their tendency to consolidate during composting. If left unchecked, FAS can decrease to the point where ventilation becomes inadequate. Periodic turning decreases the unit bulk weight of the mixture, increases free airspace and assures the highest possible ventilation rate for the particular particle sizes in the mixture. While turning itself does not supply adequate air quantities by the mechanism of volume exchange, the mechanical agitation produces conditions within the pile that enhance natural draft ventilation.

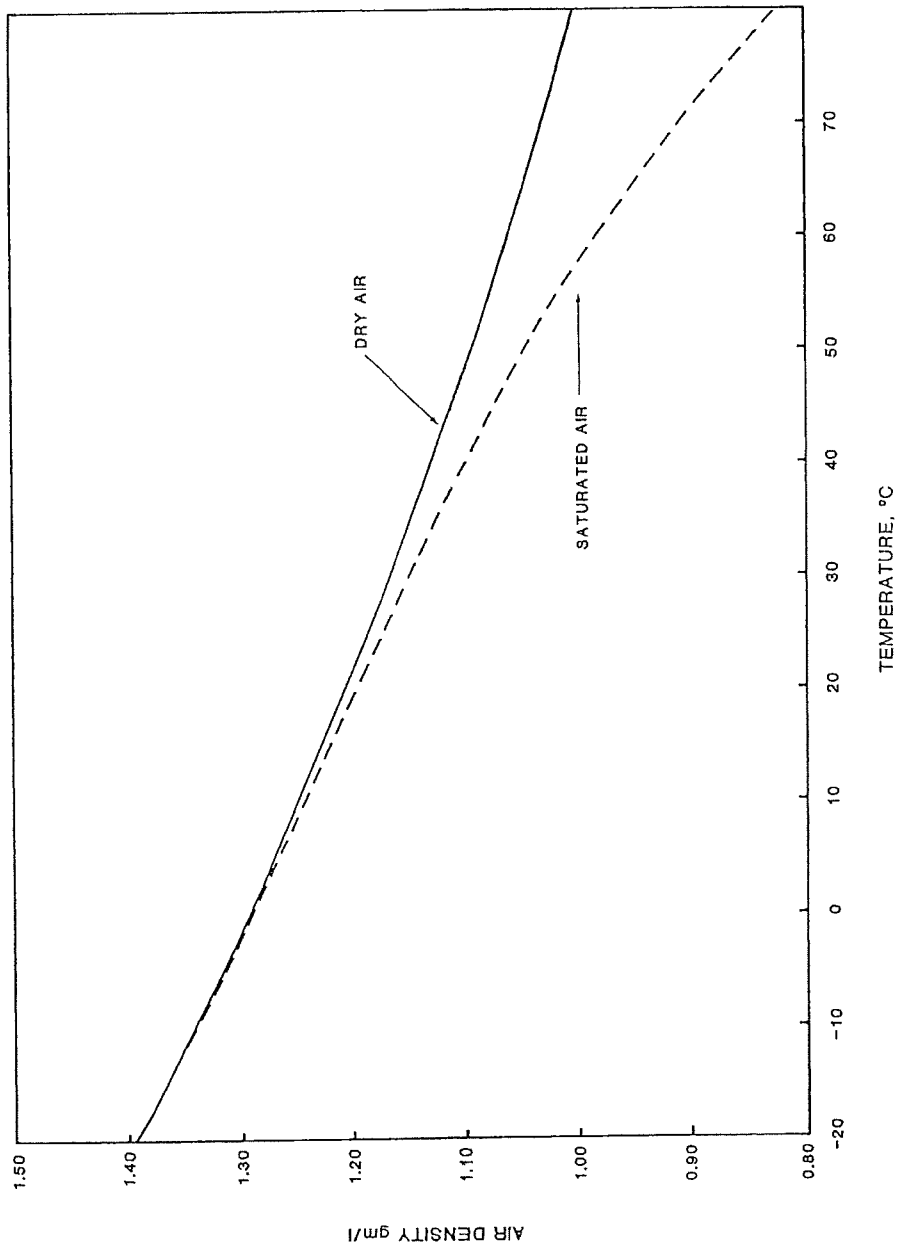


Figure 7.6. Density of dry and saturated air as a function of dry bulb air temperature at 760 mm Hg pressure.

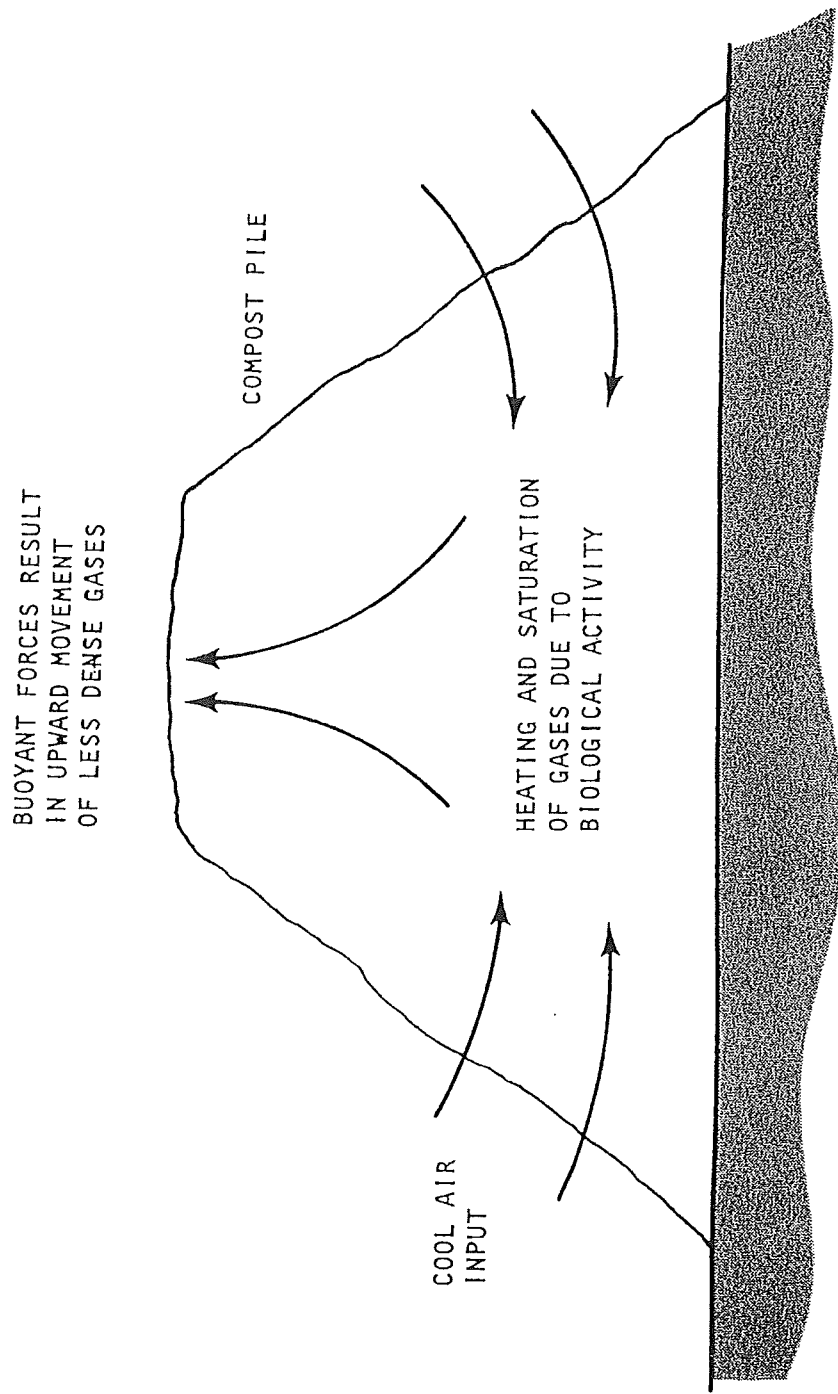


Figure 7.7. Schematic illustration of natural draft ventilation induced by buoyant forces acting on hot, moist air produced during active composting.

SUMMARY

Air is required during aerobic composting for three purposes: (1) supplying oxygen for biological decomposition (stoichiometric demand), (2) removing moisture from the composting mass (drying demand), and (3) removing heat to control process temperatures (heat removal demand). The stoichiometric demand depends on the chemical composition of the organics. Values ranging from about 1.2 to 2.0 g O₂/g BVS are typical for most composting substrates, but values as high as 4.0 g O₂/g BVS are possible with highly saturated organics.

The moisture carrying capacity of air increases exponentially with increasing air temperature. Relative humidity of the inlet air is not a significant variable affecting drying if the exhaust gas temperature is 25°C or more above that of the inlet air.

The air requirements for drying and process temperature control are usually much greater than the requirement for biological oxidation. Either drying or temperature control can govern the air requirement depending on process conditions. With very wet substrates the requirement for moisture removal will tend to govern, whereas the requirement for heat removal will become dominant with dryer substrates. Only with relatively dry substrates and high exit air temperatures do the air requirements for drying and biological oxidation become equivalent. With substrates solids of 20%, the air requirement for drying can be as much as 10 to 30 times that for biological oxidation. The different air requirements for stoichiometry and moisture and heat removal allow control over the extent of drying by control of the air supply. Control over the extent of drying has a significant influence on the thermodynamic balance achieved during composting.

For a batch process, the quantity of air required can be converted to an average aeration rate by considering the time duration of the process. Peaking factors are significant in batch processes. Peak aeration rates can exceed the average rate by a factor of 3 to 5 or more. Peaking factors are less significant with continuous feed processes. Procedures presented in this chapter allow the designer to estimate the quantity of air required and the minimum, average, and peak aeration rates for various process conditions and feed substrates.

A number of control strategies are available to regulate air supply to the process. These range from simple manual control systems to more sophisticated feedback control loops using temperature, oxygen or carbon dioxide as the controlled variables and air supply as the manipulated variable. Aeration supply and control systems must be designed to operate over the full range from minimum to peak flow conditions.

Forced ventilation by means of blowers or fans is the major aerating mechanism in the aerated static pile and most reactor systems. In nonaerated windrow or pile systems, however, the mechanisms of aeration are not as obvious. Required air volumes to supply the stoichiometric oxygen requirements are significantly greater than can be accounted for by periodic mechanical turning, even if practiced on a daily or more frequent basis. Theoretical modeling and field observations suggest that natural draft ventilation is the most significant aeration mechanism in the non-aerated windrow process.

Natural ventilation occurs as a result of the density difference between warm, moist gases contained within the windrow and cooler, less moist, ambient air. The rate of ventilation is a function of the density difference between inside and outside gases, particle size, and free air space of the composting mixture. Natural ventilation is enhanced by increasing the density difference (i.e., higher internal temperatures), increasing the free air space (i.e., reduced bulk weight and moisture content), and increasing the particle size. The role of mechanical turning is to increase the mixture free air space to assure the highest possible ventilation rate for the particular composting mixture.

