Chapter 14
Landfill Air Addition

Abstract Although less well-developed compared to anaerobic sustainable landfilling technologies, the addition of air as an extensive or just a portion of sustainable landfilling operations provides a series of distinct potential benefits compared to anaerobic systems. The fundamental system configuration and design approaches for aerobic systems are provided, along with operation, monitoring, and control techniques. Given the unique nature and relatively limited experience with full-scale aerobic systems (compared to anaerobic), a special series of case studies from Asia, Europe, and North America are provided to provide examples of how aerobic technologies can be incorporated into sustainable landfilling operations.

Keywords Landfill • Air addition • Aerobic • Temperature • Fire • Stabilization

14.1 The Role of Air Addition in Landfill Operation

Under normal waste disposal conditions at landfills, an anaerobic environment and biological stabilization process dominates. Aerobic microbial processes are present when waste is first disposed as oxygen exists in the pore spaces within the waste, but the oxygen is quickly consumed at a rate greater than it can be replenished from the outside environment. Thus, an anaerobic environment is maintained throughout the majority of the active phase of waste decomposition. As illustrated in Chap. 2, aerobic phases are limited to a short initial phase, and given time, a final phase after waste stabilization reaches completion.

The anaerobic pathway of waste stabilization, and the resulting landfill gas and leachate conditions, is the default environment encountered at disposal facilities integrating sustainable landfill practices. Efforts to create and maintain an environment of aerobic waste stabilization for some, and even a majority, of a landfill's operating life have been attempted. Aerobic composting of solid waste, whether for the bulk waste stream or an organic-rich fraction (e.g., source segregated food waste), is a commonly-employed method of biological waste treatment around the world (Haug 1993). Operators of composting systems promote aerobic conditions within the waste so that biological decomposition can occur in a relatively short time period (typically a matter of several months) compared to the lengthy process

T.G. Townsend et al., *Sustainable Practices for Landfill Design and Operation*,
Waste Management Principles and Practice, DOI 10.1007/978-1-4939-2662-6_14

of anaerobic decomposition. Ideally, this process results in an end-product that can be beneficially used as a soil amendment to provide nutrients for agricultural lands. The operation of landfills akin to large composting facilities has also been explored as a waste treatment technology.

In considering the potential benefits offered by adding air to landfills, it is useful to first assess the relative differences between aerobic and anaerobic biological treatment processes (see Table 14.1 for a summary of this assessment). Since aerobic respiration of the biodegradable waste more completely oxidizes organic matter (producing CO_2 and H_2O), more energy is released in the reaction, resulting in more rapid reaction rates and higher temperatures (Haug 1993; Palmisano and Barlaz 1996). While the anaerobic degradation pathway is also exothermic and energy is released, part of the organic matter's energy is conserved in the form of CH_4, which in turn can be collected and harvested for energy (see Chap. 19). Creating environments favorable for aerobic stabilization are theoretically easier to achieve and control, as the primary requirements are providing sufficient air and moisture. Because of the interdependence of microorganisms in anaerobic systems (see Chap. 2), it may take longer to reach a state of active CH_4 production and these systems may be susceptible to imbalance and upset (e.g., acid buildup and suppression of methanogenesis).

Because of these differences, aerobic operation provides conceptual advantages with respect to waste and leachate treatment compared to the anaerobic pathway, and since the amount of CH_4 produced will be reduced, aerobic operation offers benefits with respect to greenhouse gas (GHG) emissions in cases where landfill gas emissions are inefficiently controlled. The trade-off, however, is that aerobic operation is more expensive because of the need to mechanically add air to the waste (via either forced air injection or application of vacuum pressure to pull air into the waste mass). Anaerobic landfills take longer to stabilize but do not require mechanical energy other than that needed to add liquids and extract the gas, which itself can be converted to energy. Aerobic landfills also require a higher degree of monitoring to avoid potential issues with smoldering or fires and the formation of explosive gas mixtures.

In this chapter, we summarize and examine practices for employing air addition as part of sustainable landfill management. A review of existing experience finds that landfill researchers and operators have attempted to realize several of the benefits that can result from aerobic waste treatment, including providing better leachate treatment, conditioning the waste for further anaerobic treatment, providing rapid waste stabilization, and "curing" landfills near the end of their active life. Following a discussion of these different beneficial aspects, design and operational considerations, as well as challenges, are presented. The chapter ends with a description of air addition practices implemented at landfills around the world.

14.2 Achieving Benefits from Air Addition

In some aerobic landfill applications, the operator introduces air only during targeted periods of a landfill's operation as a means to meet specific objectives. In other applications, the operator attempts to maintain aerobic conditions throughout the

Table 14.1 Comparison of aerobic and anaerobic biological conditions

Feature	Comparison
Biological reaction	Biology in aerobic operations is thought to be more diverse, including bacteria and fungi. Anaerobic biology consists of a more defined set of microbial groups that are dependent on one another. The aerobic reaction pathway is generally viewed as more rapid and robust. Anaerobic pathway is sensitive to environmental conditions and may take time to become established
Energy released and temperature	Both reactions are exothermic, but the aerobic reaction releases more energy, due to the more favorable thermodynamics of micro-organism use of O_2 as an electron acceptor. Landfilled waste often reaches temperatures of 60 °C, while temperatures as high 70 °C or greater are often reached in aerobic composting processes. Greater temperatures result in more rapid reaction rates and pathogen destruction. High aerobic temperatures can contribute to smoldering, combustion, and fire issues at composting facilities and landfills
Exhaust gas	In anaerobic systems, the prime end-product gases are CH_4 and CO_2. In aerobic systems, the primary product gases are N_2, CO_2, and O_2, depending on the degree of oxygen utilization. Mixed systems may generate some quantities of all listed gases
Trace gases and odor	Chemicals found as byproducts in both systems may be malodorous, but the anaerobic environment tends to produce chemicals with strong, pronounced odors. These include volatile fatty acids, reduced sulfur compounds (e.g., H_2S), and ammonia. Presence of trace compounds that are either decomposition products or products of volatilization will depend on the initial waste composition
Final material product quality	At the end of waste stabilization, a mature product from either process will be of similar quality. The fate of some chemical species may differ (e.g., Nitrogen will be conserved in anaerobic systems as ammonia). Because of its more complete stabilization, aerobic treatment is often used as a post-treatment step for anaerobically produced products
Energy	Aerobic systems are net energy consumers (because of energy needed to introduce air). While some energy is required in anaerobic systems, the opportunity exists to harvest energy through CH_4 recovery and conversion

landfill's operational life. As a result of more rapid reaction rates and the ability to more completely transform some chemical constituents, landfill operators can utilize controlled air addition to meet a number of desired sustainable operation targets; see Table 14.2 for several of these potential applications.

Some landfill researchers and operators have attempted landfill air addition to utilize aerobic biological activity as the dominant waste stabilization mechanism, replacing the anaerobic pathway. Instead of CH_4 and CO_2 being the dominant gas-phase decomposition products, an aerobic landfill would have a gas composition consisting primarily of N_2, CO_2, and possibly O_2. Leachate quality differs in the rate at which organic strength (BOD, COD) is reduced, as well as other differences such as pH, nitrogen, and heavy metals.

Several researchers have compared performance and outputs of aerobic and anaerobic landfill operation in the laboratory and at pilot scale. Stessel and Murphy (1992) demonstrated in a set of laboratory lysimeter experiments that recirculating leachate through simulated landfilled waste while simultaneously adding air resulted in reduced leachate concentrations of organic compounds and more rapid waste degradation rates, measured by means of waste settlement. Optimal degradation (maximum waste settlement) was observed under the minimum moisture content, moisture addition rate, and air addition rates of 75 %, 0.09 m^3/m^2-day, and 40,000 m^3/m^3 water applied, respectively (Stessel and Murphy 1992). Similarly, Matsufuji et al. (2004) compared solid waste stabilization in semi-aerobic (often referred to as the "Fukuoka method"; discussed more later in this chapter) and anaerobic landfill cells at the laboratory scale, and found that leachate BOD concentrations decreased much faster in the simulated aerobic landfill cells, along with decreased BOD to COD ratios (<0.05 after 3 years of experimentation) and low NH_3–N levels as compared to anaerobic landfill cells. Using data gathered from large scale lysimeters where semi-aerobic, recirculatory semi-aerobic, and aerobic conditions were tested, Matsufuji et al. (1993) reported that aerobic landfill conditions metabolized 72.4 % of the organic waste mass within 10 years as compared with 56.7 % under anaerobic landfill conditions.

Bilgili et al. (2007) utilized four laboratory-scale systems to investigate the effect of leachate recirculation on aerobic and anaerobic waste degradation and leachate quality, and observed that conductivity, TDS, and chloride concentrations were greater under aerobic conditions due to the higher pH values; pH in the aerobic treatment remained between 8 and 9 after study day 100, in contrast to anaerobic cells where pH rose steadily from roughly 6 at day 100 to 7.5 on day 500. Air addition effectively reduced organic matter and ammonia leachate content (Bilgili et al. 2007). In laboratory columns containing a waste stream designed to represent the composition of fresh MSW, Sartaj et al. (2010) found that aerobic conditions were effective in reducing the concentration of heavy metals, attributing this to the adsorption of metals on waste materials and precipitation of metal oxides due to the increased pH. Kim et al. (2011) operated four waste-packed laboratory columns, two each under aerobic and anaerobic conditions for a period of 1,650 days, and observed differences in leachate heavy metal concentrations; some elements were greater in concentration under the aerobic environment, while others were greater under anaerobic conditions. Cr(VI) accounted for approximately 45 % of the Cr in

Table 14.2 Potential beneficial applications of air addition to landfills

Application	Description
Improving leachate quality	Introduction of air into the bottom layers of a landfill (the pipes and drainage stone of a LCRS) stimulates a leachate treatment zone, particularly for the organic matter
Primary waste treatment	Similar to an aerobic waste composting operation, adding sufficient air to landfilled waste will result in the bulk of waste decomposition to occur via the aerobic biological pathway
Waste conditioning	A brief period of air addition to newly-deposited waste may better prepare waste for subsequent anaerobic decomposition in that waste temperatures are increased (particularly beneficial in colder climates) and rapidly degradable organic matter can be stabilized to avoid uncontrolled acid production by anaerobic decomposition conditions
Waste curing	The addition of air following anaerobic waste treatment serves to stabilize the residual waste
Nutrient management	Air addition is used to biologically transform recalcitrant ammonia nitrogen to nitrate, which can be further denitrified in other anoxic areas of the landfill

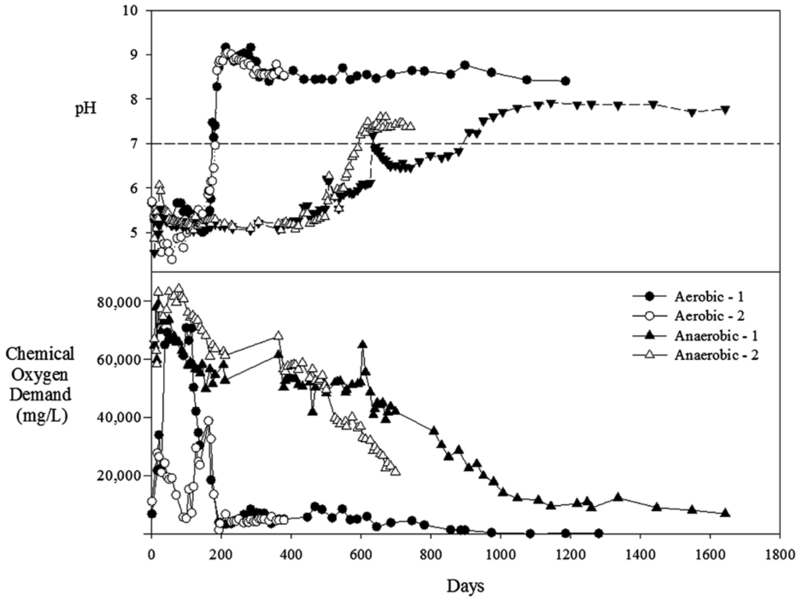


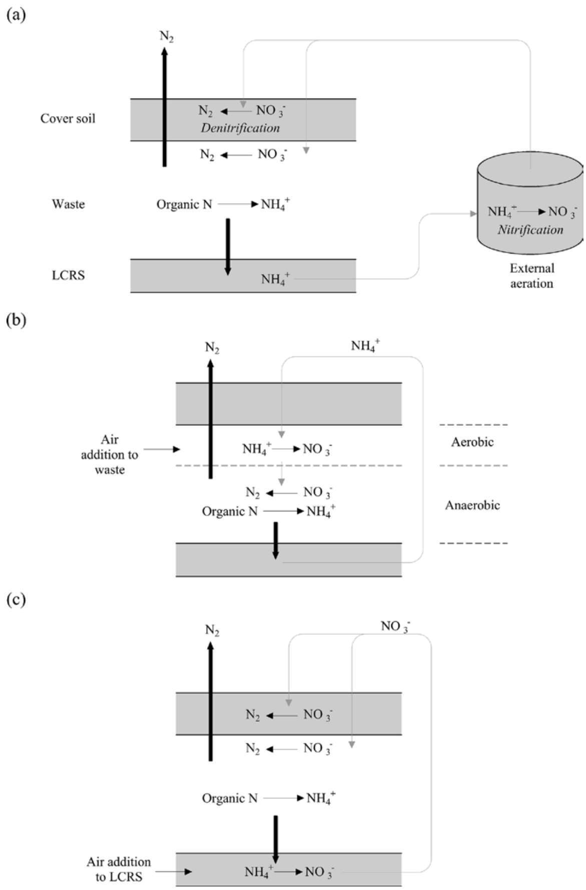
Fig. 14.1 Differences in pH and COD in landfill leachate from simulated bioreactor landfills (Kim et al. 2011). One pair was operated aerobically and the other was operated anaerobically

aerobic lysimeter leachate while chromium in the anaerobic lysimeter leachate was below the detection limit. Kim et al. (2011) found that metal leachate concentrations decreased significantly in leachate from the aerobic lysimeters as waste stabilized, while concentrations in the anaerobic columns remained stable. Figure 14.1 provides the pH and COD for this experiment and illustrates the difference between these two environmental extremes.

While most biodegradable organic matter can be equally treated through aerobic and anaerobic pathways (although reaction rates may differ), for some chemical constituents, aerobic treatment offers treatment capabilities not possible with anaerobic systems. For example, the dominant form of N in anaerobic landfill leachate is ammonia nitrogen (as discussed in Chaps. 2 and 11), and this constituent tends to be conserved in the landfill over time, and thus increases in concentration, presenting a treatment challenge (Berge et al. 2005). Using aerobic treatment, ammonia can be nitrified to nitrate, which denitrifies to N_2 gas in a subsequent anoxic step, thereby removing it from the system (Berge et al. 2006, 2007). This approach has been examined in several different configurations as illustrated in Fig. 14.2.

Some landfill operators practice external nitrification in tanks, and then recirculate the nitrified leachate back into the landfill to promote the anaerobic conversion of nitrate to nitrogen gas. This approach has been described by some as a hybrid bioreactor landfill. Other researchers have investigated the potential for adding air to specific regions within a landfill so that the nitrification step can occur within the landfill itself (i.e., in situ). Leachate treatment (including ammonia transformation)

Fig. 14.2 Alternative strategies for promoting leachate nitrogen removal by using air addition (**a**) external aeration (**b**) air addition into the waste mass (**c**) air addition into the LCRS



represents a major motivating factor in the decision to employ the semi-aerobic landfill approach, a technique where air is introduced into the LCRS using large diameter pipes to promote ventilation, thus creating an aerobic treatment layer at the base of the landfill; the semi-aerobic landfill approach is discussed in greater detail later in this chapter. Onay and Pohland (1998) conducted laboratory-scale experiments that demonstrated the ability for reactors (operated as either aerobic or anoxic) working in series with internal leachate recycle to achieve 95 % nitrogen conversion (nitrification and denitrification) to the end-product of N_2 gas. An investigation into the kinetics of in situ ammonia (NH_3–N) removal from landfill leachate showed the feasibility of simultaneous nitrification/denitrification in an aerobic landfill environment, with total N removal rates of 0.196 and 0.117 mg/day-g dry waste for acclimated and non-acclimated waste (acclimated waste had an established nitrifying microbial population), respectively (Berge et al. 2006).

Some landfill operators practice the addition of air early in the active life of the landfill for a limited period, allowing the bulk of biological treatment to occur through anaerobic conversion (Rich et al. 2008). Early air addition has been utilized as a method for increasing the temperature of the waste (a particularly valuable function of aerobic operation in colder climates), thereby conditioning the waste for subsequent conversion to an anaerobic environment, and as a means to provide treatment of readily degradable organic compounds that otherwise might result in rapid acid formation in anaerobic environments. An additional early-phase air addition strategy has included the induction of air into surficial regions of landfill (specifically, recently-added waste lifts) as a means to control CH_4 emissions to the atmosphere prior to LFG collection device installation (Hansen et al. 2002; Jung et al. 2011). In this system, LFG is extracted into a horizontal collection layer at the base of the targeted waste lift with the goal of inducing air from the surface of the landfill into the waste, thus minimizing anaerobic CH_4 production. Later, when additional waste is placed on top of this area, the devices are repurposed as horizontal collectors for anaerobic biogas; air addition piping can also serve a later purpose as liquids introduction devices for bioreactor landfills.

A common practice, especially in Europe, has been the addition of air to landfills toward the end of their active life as a method of promoting near-complete stabilization of waste that has already undergone anaerobic decomposition. In some cases, infrastructure for LFG extraction is reconfigured so airflow into the landfill can be induced. In other cases, wells are added to older landfills for the specific purpose of air addition. Low-pressure aeration projects have been undertaken extensively in Germany. The Milmersdorf landfill represents one such case where >90 % of biodegradable organic carbon was stabilized via oxidation with active aeration and active off-gas extraction through wells installed in the waste (i.e., the AEROflott® technique) (Ritzkowski and Stegmann 2012).

14.3 Air Addition System Configuration and Design

The design of an air addition system includes estimating the volume of air that must be added (or extracted in an induced system) to meet design objectives, selection of the type of air addition system (vertical wells and/or horizontal pipes), detailed specifications on sizing and configuration of the air addition devices, setting spacing between individual devices, and selection of materials for air piping. Finally, the design should include specification of other control and monitoring devices such as pressure and temperature measurement gauges and automated controls (e.g., emergency shut-off valves that engage at a high pressure threshold) as desired. This section reviews design objectives, methods for estimating air addition volume requirements and rates, and air addition system infrastructure.

14.3.1 Design Objectives

The engineer will consider multiple objectives in the design of a landfill air addition system. A primary objective will be the conveyance of air to the targeted area of the landfill. Infrastructure will be required to actively deliver (an active system) or passively encourage (a passive system) air to the landfill region of interest. In the case of active systems, mechanical blowers, fans, or compressors must be connected to a piping network capable of accommodating the desired flow rates to the targeted addition points. In the case of passive systems, infrastructure (e.g., vents, drains) must be located and appropriately sized to promote air entry into the landfill based on temperature gradients.

Integral to the design of the air conveyance system will be the identification of the target air volume and addition rate so that the infrastructure can be sized appropriately. This determination will depend on overall project objectives such as the purpose of air addition (e.g., primary waste treatment versus targeted waste heating or curing) and needed performance requirements. In addition to air volumes and flow rates, appropriate air addition pressures that promote necessary distribution of air into the waste mass must be considered.

As a result of concerns such as explosive gases and excessive waste heating, it is critical that the engineer maintain the objective of designing a system that can be monitored and appropriately controlled during operation. Important monitoring parameters include gas composition, gas temperature, and waste temperature. Coupled with monitoring must be a plan and equipment specification for addressing concerns that may be revealed as an outcome of monitoring. For example, if elevated temperatures create excessive waste temperatures, the monitoring and operations plan must include contingency procedures to slow or mitigate the high temperature conditions.

14.3.2 Air Addition Rate

In a similar manner as discussed in earlier chapters for liquids addition, a multitude of factors must be considered when calculating the amount of air that should be added to a landfill to meet a given design objective. The total amount of air added per volume or mass of waste will reflect the degree of aerobic treatment targeted; complete stabilization will require much more air than systems where the objective is to heat the waste prior to anaerobic stabilization or to cure the waste after anaerobic degradation has reached practical completion. The rate of air addition depends upon several factors, including the ability of the landfill to accept air, the number and size of the addition devices available, the ability of the blower system to deliver air, and the ability to add air while minimizing the potential to create excessive heat generation, explosive conditions, and related issues.

In a similar manner as the CH_4 potential (L_o) for waste undergoing anaerobic decomposition (see Chap. 13), an O_2 consumption potential for waste undergoing aerobic decomposition can be estimated. This may be measured in the laboratory or estimated using assumptions regarding waste composition and the fraction of waste potentially subject to aerobic decay. The following equation is commonly cited in design texts for solid waste and represents the O_2 demand as a function of a generic stoichiometric representation of waste's chemical composition (Haug 1993).

$$C_aH_bO_c + \left(\frac{4a+b-2c}{4}\right)O_2 \rightarrow aCO_2 + \left(\frac{b}{2}\right)H_2O \quad (14.1)$$

When this equation is simplified to the aerobic degradation of cellulose ($C_6H_{10}O_5$), we arrive at:

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O \quad (14.2)$$

A similar equation for the anaerobic decomposition of cellulose was presented in Chap. 13. Upon comparison of these two equations, the anaerobic decomposition of one molecule of cellulose results in three molecules of CH_4, while the aerobic respiration of one molecule of cellulose requires six molecules of O_2. Thus, as an approximation, the O_2 consumption potential for a cellulosic waste would be approximately twice as much as L_o, and given the composition of air (approximately 79 % N_2 and 21 % O_2), the air consumption potential (A_o) would be 9.5 times as much an L_o.

If the design target was 100 % aerobic stabilization, the volume of air needed would be large. Figure 14.3 provides an assessment of the magnitude of air that would be required by showing the amount of air needed (volume per time at steady state) to keep up with an incoming waste disposal rate (mass per time). The values presented assume a waste with a L_o of 100 m^3 of CH_4 per Mg (A_o = 950 m^3/Mg) where waste could be theoretically stabilized as effectively aerobically as anaerobically. In addition to a line representing 100 % aerobic target activity, lines corresponding to a 50 % aerobic treatment target (50 % anaerobic) and a 10 % aerobic treatment target (90 % anaerobic) are presented. As this figure illustrates, the large amount of air needed for complete aerobic treatment is one of the limitations of aerobic biostabilization as a primary waste treatment technique, particularly at larger landfills.

Calculating the design air addition rate depends on several other considerations beyond the desired addition rate. The desired rate must be achievable within the constraints of the system provided. For systems where air is injected under pressure, the flow rate achievable into a device (e.g., a vertical well) depends on the dimensions and construction of the device (e.g., the length and diameter of well, perforation or slot size and configuration) and the hydraulic properties of the waste (e.g., permeability, porosity). Jain et al. (2005) conducted a series of air pump tests using small (5 cm diameter) vertical wells at a landfill designed in part for aerobic operation

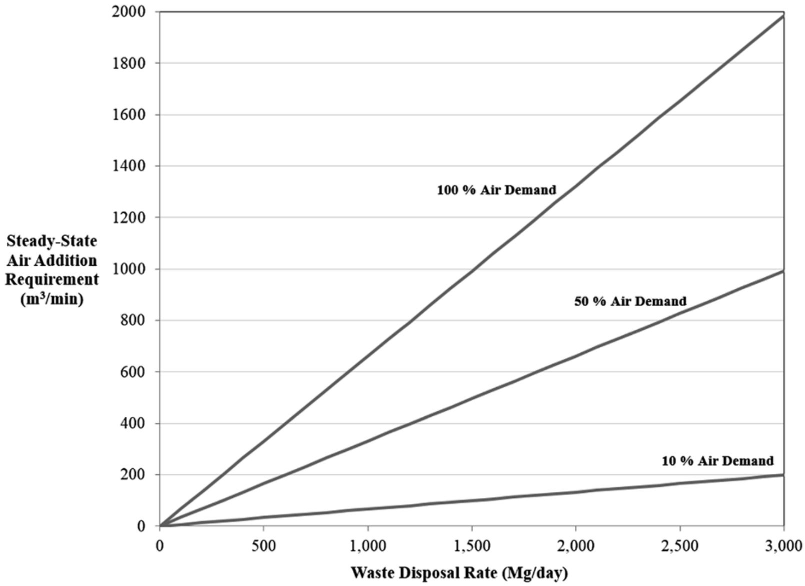


Fig. 14.3 Air addition requirement for complete aerobic waste stabilization as function of waste disposal rate

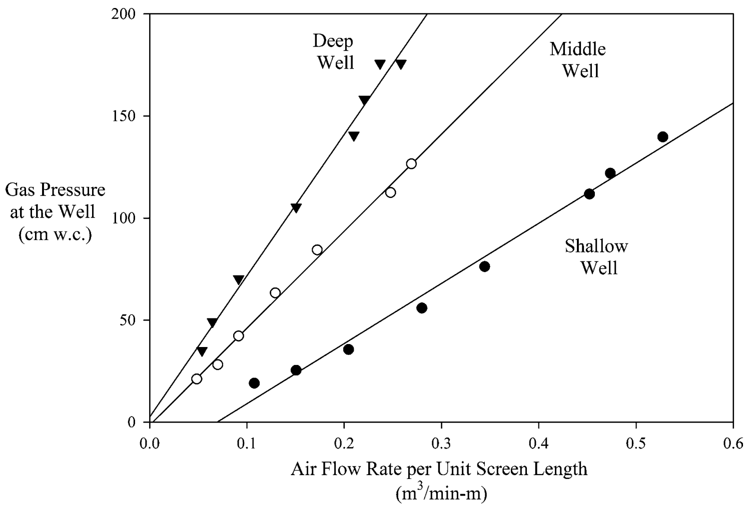


Fig. 14.4 Results of aeration pump tests at a MSW landfill: backpressure as a function of added flow rate (Jain et al. 2005)

(New River Regional Landfill, Florida, USA). Figure 14.4 shows a representative graph of pump test results, where the flow rate was measured as a function of injection pressure in wells installed at varying depths within the waste. Greater injection pressures resulted in greater air addition rates, and the achievable rates declined as the well construction depth increased, which was attributed to the greater overburden pressures in deeper sections, larger amount of moisture present, and increased gas pressures present from anaerobic decomposition.

Since pressurized air addition in landfills has not been practiced to a large extent, methodologies for the design and placement of air addition devices lag similar efforts for liquids addition and LFG extraction. Some basic concepts from modeling gas extraction in landfills, however, may be applied (e.g., the concept of radius of influence). Additionally, the large body of design information available for air addition and vapor extraction for soil/groundwater remediation systems can be consulted and adapted. Air injection system design (blowers, manifold, and injection wells) methodology takes into account the necessary air volume, air flow rate, air entry pressure for the surrounding media, constituent mass to be degraded, friction and minor pressure losses, and a factor of safety to decrease the potential for air flow backup due to high pressures within the media. In the case of a landfill, leachate surrounding an injection well may cause a need for increased injection pressure (Marley et al. 1995; Hudak 2000; Leeson et al. 2002). Air addition systems may also be designed with the intent of pulsed or periodic air injection, possibly necessitating a higher air addition rate while blowers are operating to achieve the overall air addition volume over a fixed time period. The unique challenge for designing these systems for landfills is the heterogeneity of the waste material and the potential for elevated temperatures and subsurface heat-generating reactions. When air is added to an injection well, aerobic decomposition activity will occur to the greatest extent in the area immediately surrounding the well. The rapid reaction rates associated with aerobic activity may result in large amounts of heat generation, and it has been observed that temperatures within the waste can increase beyond the upper range where aerobic microorganisms thrive (discussed in next section) (Stone and Gupta 1970; Powell 2005).

The selection of a blower depends on the volume of air required, desired flow rate, and anticipated pressures required to add the amount of desired air. There are several factors that can influence the effectiveness of the air addition system. Due to the heterogeneous nature of the solid waste placed in the landfill, a wide variation of achievable addition rates should be expected. Another consideration is the presence of higher moisture contents in the landfill waste; moisture acts as a physical barrier to air flow and can reduce the flow significantly (observed by Jain et al. 2005). In practice, it may be impossible to have a completely aerobic landfill, because waste in deeper sections of the landfill is dense and well compacted, and thus air permeability is very low (see Chap. 5). For aerobic landfills, the balance of air and water addition is critical. Sufficient water must be available to provide a suitable environment for microorganisms to thrive. If sufficient water is not available, excessive heat production can result in the combustion of the waste. However, if an excessive amount of water is present, hydraulic limitations make it difficult to add sufficient amounts of air evenly to the waste, resulting in short-circuiting and uneven treatment of the waste mass. Finally, with respect to heating of the waste, sufficient infrastructure must be in place to allow generated heat to escape, as discussed in the following section.

14.3.3 Air Addition System Infrastructure

The three primary components of air addition system infrastructure include a mechanical blower or fan, a conveyance system, and a network of air injection and gas handling piping. The conveyance system delivers air from the blower to the landfilled waste, and the air injection and gas handling network is used to distribute air to the landfilled waste mass (and, where applicable, remove gas from the landfill). The air injection network can be installed in different ways, depending on the site-specific conditions and design goals.

Landfills that have an LCRS can incorporate the LCRS infrastructure to add air to the waste mass. In this system, air is allowed to move passively through the headspace of the LCRS piping that is open to the atmosphere. The temperature differential between the interior of the landfill (high temperature) and the ambient temperature (generally lower) produces a "chimney effect" in which air is drawn into the pipes and brought into the waste mass (Leikam and Keyer 1997).

For landfills with no LCRS or when the LCRS is not chosen as the means for air introduction to the landfill, wells dedicated to air introduction are used. Air can be injected via retrofitted vertical injection wells that are drilled down into the waste from the landfill surface and connected to necessary piping infrastructure. This type of a system is more commonly employed at closed or abandoned landfills that have been targeted for enhanced stabilization or remediation for a variety of goals, including CH_4 mitigation, improvement of leachate quality, or perhaps as part of preparation for another land use (Heyer et al. 2005; Ritzkowski et al. 2006). Alternatively, for sites where air addition infrastructure is constructed as landfilling progresses to achieve aerobic decomposition of organic wastes earlier in the landfill's life cycle, horizontal wells, typically situated in trenches filled with permeable media, may be used (Hansen et al. 2002).

Air introduction to waste may be accomplished through an assortment of methods utilizing vertical wells. Ritzkowski and Stegmann (2012) detail four major vertical well aeration strategies, and these are summarized in Fig. 14.5. One method involves high pressure (i.e., compressed air forcing $\geq$30 kPa) aeration where positive pressure forces air deep into the waste mass, and where suction is applied to other wells which pulls injected air through the waste (Fig. 14.5a). Another method utilizes low-pressure aeration with parallel off-gas extraction via applied suction at additional injection wells (Fig. 14.5b). Low pressure aeration can also be applied without off-gas extraction (injected air migrates through waste eventually to the atmosphere; Fig. 14.5c) and with simple atmospheric venting (vents are drilled into waste to allow for low resistance pathways; Fig. 14.5d).

Pumping and extraction systems for aerobic landfilling operations are similar to those used in a GCCS in some respects. Both utilize blowers to move gases (see Fig. 14.6 for a picture of a blower used for air injection to landfilled waste), particularly in cases where air entry is achieved through induced vapor extraction.

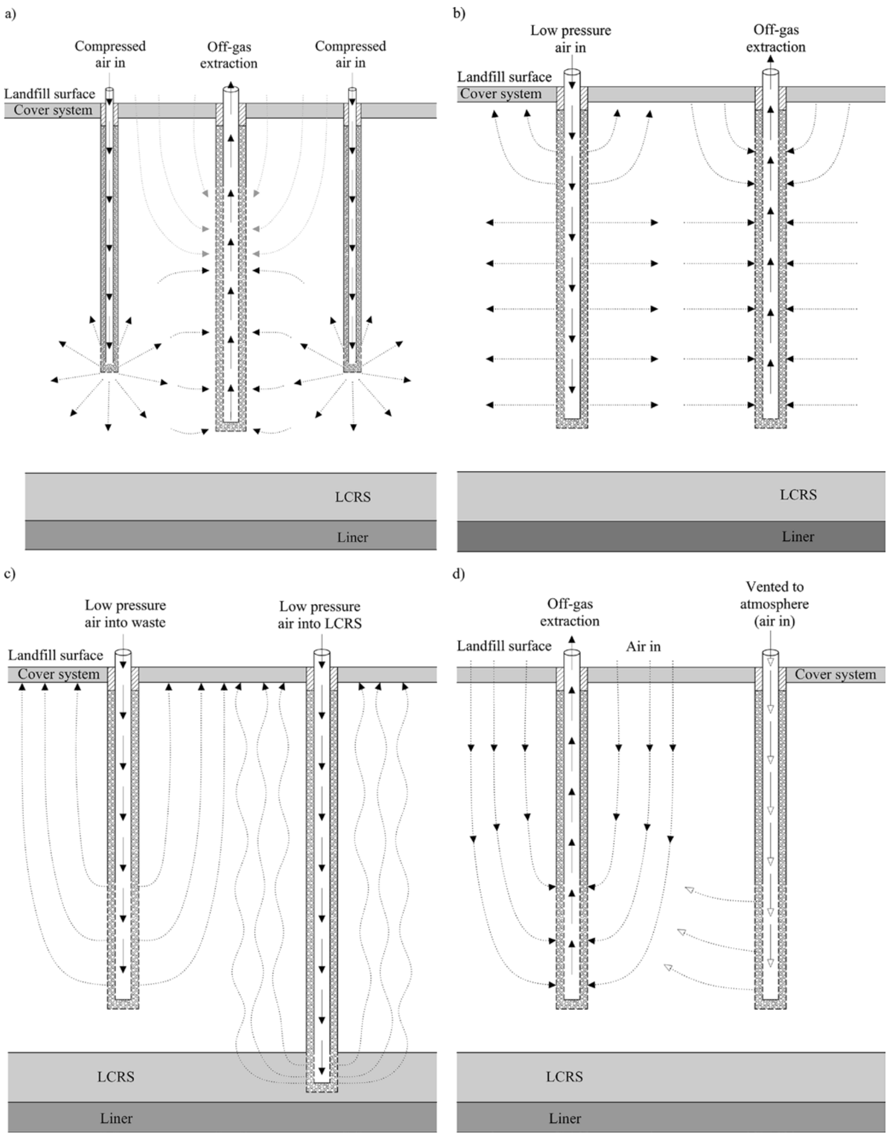


Fig. 14.5 Vertical well air addition strategies (**a**) (modified from Ritzkowski and Stegmann 2012) (**a**) addition of pressurized air (**b**) combined extraction-aeration system inducing low-pressure aeration (**c**) aeration into the LCRS and waste mass (**d**) extraction system allowing air introduction to a vent open to the atmosphere

Since the volume of air required to stabilize a unit mass of waste is greater than the volume of LFG produced under anaerobic conditions, the sizing of system infrastructure (blowers, pipes) will necessarily be larger. Aerobic systems may also be operated following a pulsed period so more effective oxidation for a larger radius of influence is achieved (Boersma et al. 1995; Bass et al. 2000; Yang et al. 2005).

Fig. 14.6 Variable speed positive displacement blower used for air addition at New River Regional Landfill (Ko et al. 2013)

14.4 Operation, Monitoring and Control

Because of the uncertainties related to air addition and the potentially dramatic consequences that might result from improper operation (e.g., excessive waste heating or smoldering conditions), proper operation, monitoring and control are critical. This section reviews these issues, including a focus on explosive gas control and fire prevention.

14.4.1 Operation

Aerobic waste degradation results in the release of more heat than anaerobic activity, thus leading to an increase in landfill temperature relative to typical anaerobic landfill environments. The rapid release of heat can increase the waste temperature and result in combustion or combustion-like conditions, referred to as landfill fires, subsurface oxidation events, subsurface exothermic reactions, or hot landfills. This must be controlled by careful monitoring of temperature and by installing a system to add water if needed. The explosivity range of CH_4 is from 5 to 15 % (volume) in air, thus the potential to create explosive conditions may exist when air is added. Furthermore, landfills (particularly larger facilities) are typically well-insulated, thus rapid heat increases within the landfill are often difficult to dissipate.

The primary operating constraints for an air addition system will include pressure, air or gas flow rate, gas composition, and temperature (gas or waste). The operating pressure (or the required injection pressure) will be based on limits or ranges established at the design stage. The design pressures are typically calculated using literature-reported values for waste properties (e.g., intrinsic permeability), possibly coupled with fluid flow modeling (see Chap. 5) and may be supported through limited field pump tests to establish site-specific constraints or conditions (see Fig. 14.4). In addition to the pressure considerations related to injecting air into the waste mass, another factor to consider is the backpressure experienced within the piping infrastructure—blower and compressor systems have an upper limit of backpressure that can be experienced before mechanical shutdown. Again, in this case it is useful to establish pressure profiles as part of pump testing prior to specification of mechanical blower equipment so that under- or over-design can be avoided. Given that pulsed or periodic air injection has been shown to be advantageous over continuous injection for aeration (Boersma et al. 1995; Yang et al. 2005), these techniques should be considered for landfill aeration systems and design flow rates should account for the possibility of operation as a pulsed system. Air channels (i.e., preferential airflow pathways) form within the surrounding media and pulsed operation increases mixing of aerated pore space with landfill gas or leachate through formation and collapse of these flow paths (Johnson et al. 1993; Yang et al. 2005).

Temperature monitoring and control are among the most critical factors in the operation of aerobic landfills. Landfills that are in a regulatory environment that requires extraction and monitoring of LFG [e.g., US landfills that are subject to the US EPA Emission Guidelines or New Source Performance Standards under the Clean Air Act (Code of Federal Regulations 1996)] may be required to monitor gas temperature. However, in aerobic environments, additional temperature measurement and monitoring is often warranted for multiple reasons, including within the waste mass itself. First, extracted gas temperatures can include the temperature of gas produced radially outward from a given gas extraction point, thus the measured gas temperature represents a combination of gases produced in all directions from the given extraction well. Second, gas temperatures are often lower than actual waste temperatures, thus the measurement of a given gas temperature may not accurately reflect the temperature conditions of the waste itself, particularly near areas where air is added. Finally, the frequency of gas temperature measurement in regulatory environments like those in the US EPA regulations is limited (monthly), which does not provide the operator sufficient data to understand whether air addition is effective or if excessive temperatures are occurring within the waste.

Gas composition is another key operating parameter that must be measured during air addition operations. Similar to waste temperatures, measuring gas composition provides an opportunity to understand the degree of effectiveness of air addition. The number of gas composition monitoring points must be balanced with cost; ideally, a larger number of monitoring points allows for more information on the landfill environment, but too many monitoring points (which could consist of piping comprised of stainless steel, carbon steel, PVC, or CPVC probes drilled vertically into the waste) could be cost prohibitive. Table 14.3 summarizes these key

Table 14.3 Summary of key aerobic landfill operating parameters and associated monitoring devices or approaches

Operating parameter	Monitoring devices or approaches
Pressure	Pressure should be measured at individual air addition devices, at the blower or compressor station, and possibly within header pipes. Dial pressure gauges may be appropriate, with the pressure range spanning the design pressures at a minimum. The injection pressures may be adjusted manually and monitored visually or they may be tracked and adjusted using a supervisory control and data acquisition (SCADA) system
Flow rate	Total system flow rate (at the blower station) and flow rate into individual wells should be monitored at a minimum. Rotameters have been shown to be effective devices to track flow rate and should be specified to include the range of anticipated design flow rates at a minimum. Similar to pressure measurement, flow rates may be adjusted manually and monitored through visual inspection, or flow may be controlled through a SCADA system
Temperature	Temperatures may be monitored by installing thermocouples within the waste (extension-grade Type T thermocouple wire has been successfully used in MSW landfill environments), either placed directly in waste or housed in a sheathing such as a small-diameter PVC pipe. The density of thermocouple placement depends on the number of air addition points and the design objectives, but a prudent approach would include providing thermocouples around air addition points and at different depths. At sites where a large number of thermocouples is desired, routing all thermocouple wiring to one or more central locations for data logging is preferred to reduce labor and provide a more robust dataset. Temperature can be read from thermocouples via manual readout devices or connected to a multiplexer and data logger for frequent, automatic measurements
Gas composition	Gas composition monitoring can occur at dedicated monitoring points, at LFG extraction wells, or within LFG extraction header pipes. A specialized meter designed to analyze LFG is recommended to reduce potential interference. These meters typically analyze CH_4, CO_2, O_2, and calculate a balance gas. LFG meters can provide frequent measurements. In some cases, the monitoring of certain trace gases may be required (e.g., CO or H_2), particularly in cases where high temperatures are observed. Order-of-magnitude measurement of CO in the field can be accomplished by collecting samples in non-reactive gas sample bags (e.g., Tedlar) and sampling the gas using a colorimetric detector tube (Powell et al. 2006). Confirmatory laboratory sampling may be achieved by collecting gas samples from monitoring points of interest in a Tedlar bag or a passivated stainless steel canister

operating parameters and provides information on monitoring devices or approaches that can be taken. More specific information on gas composition and temperature monitoring techniques are presented in Chap. 16.

The operation of the liquids addition system will require integrated planning with respect to air addition system operation. Moisture may be added prior to or during air addition, and liquids addition could occur concurrently or alternately with air addition events. Ultimately, the selection of these operating conditions must be incorporated into the landfill's overall design and operating plan so that the system can meet design goals.

14.4.2 Explosive Gas Control

A concern at all landfills is the formation of explosive gas mixtures, as CH_4 is flammable when mixed in a certain proportion with O_2. Locations at a landfill where LFG has the potential to mix with air, and thus CH_4 to mix with O_2 (such as pump stations, valve vaults, buildings near the landfill, and GCCS infrastructure) require periodic monitoring to assess whether potentially explosive conditions have formed (a spark or ignition source must be present for an explosion to occur when an explosive gas mixture is present). Landfill operators attempt to avoid explosions by minimizing locations where explosive gas conditions exist, and where they might exist, avoiding potential ignition sources (e.g., explosive proof switches at pumping stations, prohibiting smoking in or around active or closed landfill areas). Clearly, landfill operators that purposely promote air entry into the landfill must be extra vigilant with regard to avoiding explosive conditions.

When evaluating landfill gas for flammability, the most typically cited values are a 5 % lower explosive limit and a 15 % upper explosive limit, by volume (ATSDR 2001). These values refer to the percentage of CH_4 present in air. When the CH_4 content is less than 5 %, not enough fuel is present to sustain a flame (the mixture is too lean), whereas when the CH_4 is greater than 15 %, the mixture is too rich. These values, however, refer to the occurrence of CH_4 in air. In reality, CH_4 would almost always be accompanied by another gas such as CO_2, and other non-flammable gases act to dilute the CH_4. The presence of "diluent" gases therefore reduces the range over which CH_4 is flammable.

Given the impact of diluent gases, it is more helpful to describe CH_4 flammability in the form of a flammability chart, as opposed to a fixed set of CH_4 concentrations. Figure 14.7 presents a flammability chart, with O_2 shown as a function of CH_4, and zones delineated that express whether the mixture is flammable or not (following the procedure of Coward and Jones 1952). The relative concentration of the primary diluent gases expected, N_2 and CO_2, will vary depending on specific site conditions, thus the chart presents the flammability zone with N_2 treated as the diluent gas, as it provides a larger (more conservative) range.

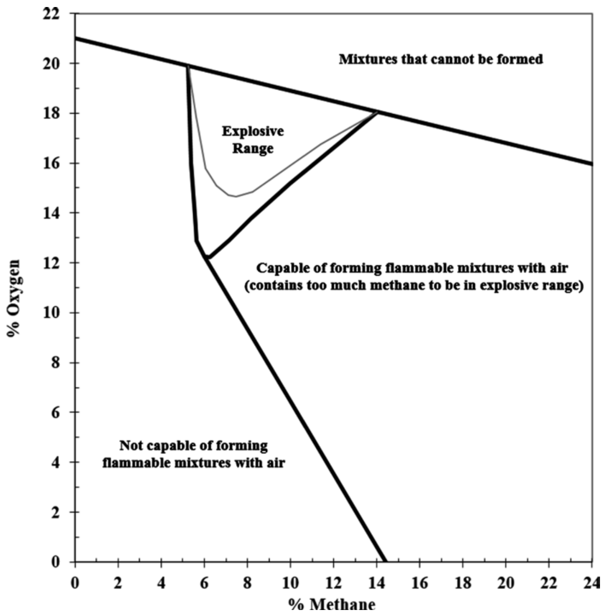


Fig. 14.7 Flammability chart (Ko et al. 2013)

14.4.3 Fire Prevention and Control

Heating events within the waste mass, which are also referred to as subsurface fires, subsurface oxidation events, subsurface exothermic events, or hot landfills, among other terms, are a concern at all landfills. Landfill fires on the surface are fairly common in the US and internationally, and the causes can vary widely (FEMA 2002). Generally, heating events can be caused by external factors (such as hot or smoldering materials delivered to the landfill) or caused by reactions within the waste itself (such as intrusion of atmospheric air that results in aerobic reactions). In anaerobic systems, temperatures as high as 55–60 °C are sometimes reached in the landfill interior, and this temperature becomes self-regulating since higher temperatures will limit the activity of the anaerobic organisms. With aerobic systems, however, temperatures can reach 70 °C or more; Powell (2005) reported waste temperatures increasing approximately 20 °C to more than 70 °C within 1 week of initiating air addition at an MSW landfill in the US. While the aerobic process may be self-regulating to a degree, the well-insulated conditions within a landfill may prevent the heat produced from aerobic reactions from exiting the waste. For example, waste temperatures following cessation of air addition as reported by Powell (2005) showed very slow temperature declines, which is in contrast to the rapid temperature increases brought about by aerobic operation. At this point, heating reactions may create smoldering or pyrolysis-like conditions within the waste (with temperatures ranging from 80 to 100 °C or more), which is supported by work reported by Moqbel (2009).

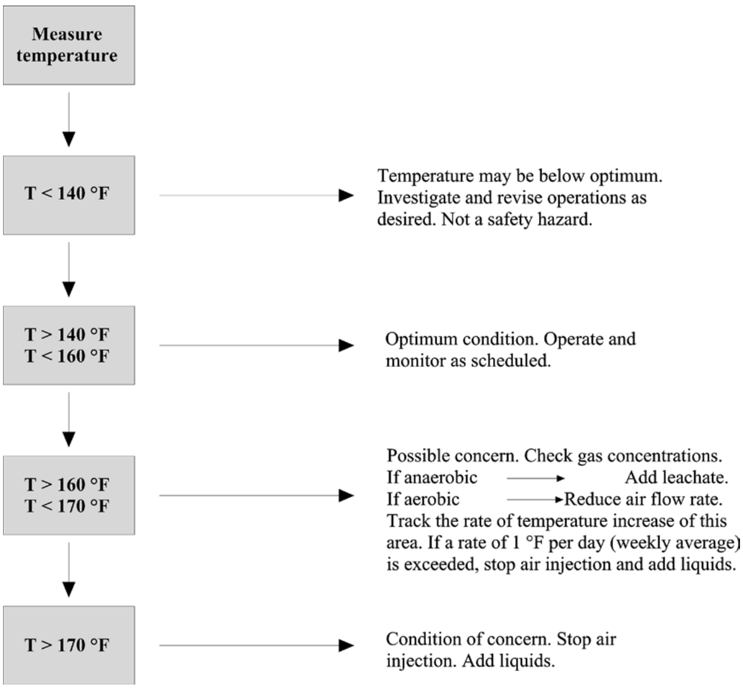


Fig. 14.8 Temperature control chart used as part of the NRRL Aerobic Bioreactor Research (Ko et al. 2013)

Given the complexities inherent with landfilled solid waste (and accompanying cover material), adding sufficient air to a full-scale landfill operation at a rate that meets air addition objectives but does not promote excessive waste heating, combustion, or pyrolysis conditions may be challenging. Landfill operators who add air must have monitoring points to measure in-situ temperature of the waste to understand subsurface conditions and to regulate air addition rates; methods for monitoring temperatures within landfills are summarized in Chap. 16. The engineer who develops a site's operations plan must establish monitoring equipment, methods, frequencies, and operating thresholds to maximize control over the system. Figure 14.8 presents the temperature threshold regime utilized as the New River Regional Landfill described in Chap. 4 (air addition was practical at this site as summarized by Ko et al. (2013).

When monitored temperatures reach a level of concern, the typical first course of action is to reduce or stop air addition. Given the insulating environment present within landfills, cessation or reduction of air addition may slow or stop the increase in temperatures within the waste, but that may not always occur, at which point other measures such as addition of liquids in the area of concern may be needed. The amount of liquid added must be balanced with the goal of future air addition, since hydraulic limitations to air addition will occur with excessive liquids addition.

14.4.4 Control of Fugitive Emissions

CH_4 and other gas-phase compounds produced in anaerobic landfills necessitate the installation of recovery and treatment systems, both to meet regulatory and environmental considerations, and for energy recovery. As stated earlier, one of the cited goals of some practitioners of air addition to landfills is the suppression of CH_4 generation. This raises the fundamental question of whether aerobic landfill exhaust requires collection and treatment. Even if a landfill were designed, constructed, and operated to be completely aerobic, because of hydraulic and other constraints already discussed, it is likely that CH_4 generation could not be completely suppressed. Thus, in a regulatory environment it is not likely that avoidance of active LFG collection would be possible. In this case, the addition of air would need to be balanced with the need to actively collect LFG produced anaerobically in the landfill. This leads to a complex situation where the goals of operating a landfill aerobically would need to be consistent with the requirements typical of active LFG collection systems. For example, US EPA Clean Air Act requirements for active LFG collection systems place a limit on the amount of O_2 (5 % by volume) or N_2 (20 % by volume) that may be present at LFG collection wells or devices. The obvious conflict can be seen when considering the composition of air that would be introduced into a landfill during aerobic operation. These regulatory considerations must be examined at the design stage and the approach to aerobic operation would need to be discussed with the appropriate regulatory officials to ensure the aerobic operation would be consistent with existing regulatory operating constraints.

14.5 Air Addition Experience

In recent years, aerobic bioreactor landfill technology has received increased attention due to the cited potential benefits (Matsufuji et al. 1993; Rich et al. 2008; Ritzkowski and Stegmann 2010). The concept of the aerobic bioreactor landfill has been applied—although with varying practices and techniques—in several countries, including Japan, Germany, and the US. These experiences and approaches are summarized in the following sections.

14.5.1 Asia

The semi-aerobic method of landfill operation was developed at Fukuoka University in Japan, and thus is frequently described as the “Fukuoka method” and has been used in Japan, China, Korea, and to some degree, in Malaysia (Matsufuji et al. 2004; Ritzkowski and Stegmann 2012). Developed in 1965, this approach has been presented as a technique well-suited for developing countries and has been implemented

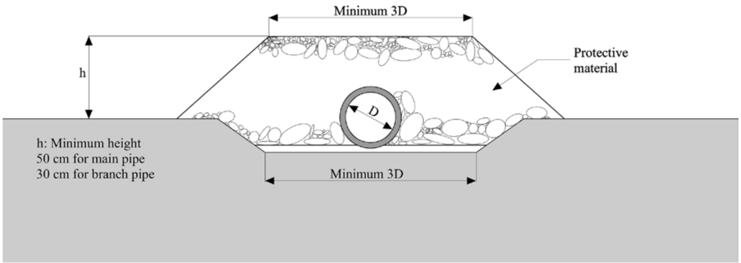


Fig. 14.9 Configuration of large diameter LCRS drain for the semi-aerobic landfill

Fig. 14.10 LCRS of semi-aerobic landfill after construction and before waste placement; connected rock drains are shown (Photo courtesy of Yasushi Matsufuji)

in several regions, particularly in Asia (Chong et al. 2005). The core fundamental of the Fukuoka method is to create as much of an aerobic zone as possible within the landfill by building an air introduction system in a manner that promotes natural ventilation into the waste. The method does not require the use of mechanical extraction systems (e.g., air pumps or blowers) and allows for locally-available and less expensive materials to be used.

Air entry into the semi-aerobic landfill is achieved through two means. First, a large leachate collection pipe, typically at least 0.45 m diameter and as large as 0.6 m, serves as the primary leachate drainage port for the landfill and extends outward to the point of discharge and open to the environment (Figs. 14.9 and 14.10). This pipe should be bedded in drainage rock and at least two-thirds of the pipe diameter should remain open to provide for passive air inflow to the bottom of the landfill. Deep aeration was observed in lysimeter experiments to provide the quickest degradation of organic carbon as well as enhanced nitrification compared to injection of air at shallower waste depths (Wu et al. 2014).

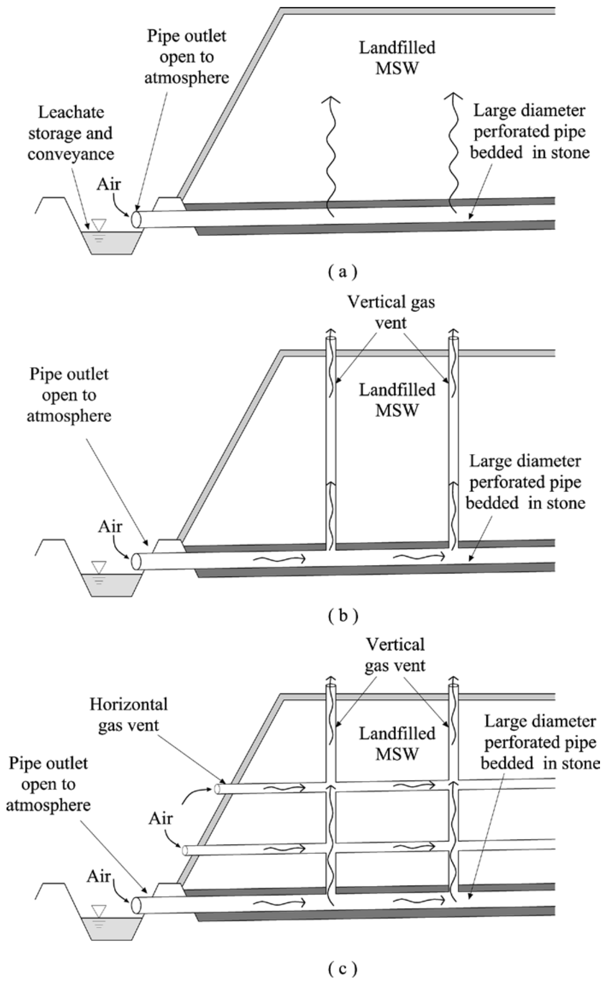


Fig. 14.11 Illustration of the semi-aerobic landfill concept (**a**) LCRS vents, (**b**) LCRS and vertical well vents, and (**c**) LCRS, vertical well, and horizontal vents

Figure 14.11a illustrates air entry into the semi-aerobic bioreactor from the LCRS. The second means of promoting air entry is the connection of vertical pipes to the leachate drainage pipes (Fig. 14.11b). The Fukuoka method recommends a spacing of the vertical pipes of 20–40 m, with closer spacing recommended for deeper landfills. These pipes (sometimes referred to as vents) serve as a means for heated vapor within the landfill to rise to the surface and thus draw air into the waste from the bottom. The vents can be constructed in a similar manner as LFG collection wells placed during waste filling (see Chap. 13), but the method encourages innovative use of construction techniques and less expensive construction materials (Matsufuji et al. 1993, 2004; Chong et al. 2005). Figure 14.12 shows a vent constructed for a semi-aerobic landfill in Thailand. The Fukuoka Method developers

Fig. 14.12 Vertical vent of a semi aerobic landfill after construction and before waste filling

describe the ability of the vents to draw air into the landfill as critical to the success of the technology, and if site-specific reasons preclude close spacing of vents, additional horizontal vents exiting the side of the landfill should be constructed (Matsufuji et al. 2004). The horizontal vents should be connected to the vertical risers and should slope downward toward the vertical wells to promote gravity drainage of liquids (Fig. 14.10c, Matsufuji et al. 2004).

14.5.2 Europe

Under current European Union directives, landfilling of unprocessed waste is discouraged or prohibited, and thus investigations and application of sustainable landfill technologies have not focused on landfills as a primary means of stabilizing solid waste (Ritzkowski and Stegmann 2012). The presence of old landfills in countries such as Germany, Italy, Austria, and the Netherlands, coupled with the desire to reduce CH_4 emissions from old waste, has led to active pursuit of sustainable landfill practices through landfill aeration, given the decreased potential for GHG release via aerobic landfills (Matsufuji et al. 1993; Rich et al. 2008). In this approach, landfills where the bulk of stabilization has occurred through anaerobic processes, and where biogas volumes are sufficiently small such that gas to energy is no longer feasible, are operated to encourage aerobic stabilization of the remaining biodegradable organic matter to reduce GHG emissions and environmental impact by replacing CH_4 emissions with CO_2 emissions (Ritzkowski et al. 2006).

Fig. 14.13 Inlet point for air addition and gas extraction at a closed landfill undergoing aerobic treatment (Photo courtesy of Marco Ritzkowski)

Several landfill aeration techniques, using a variety of well configurations, have been pioneered and patented in Europe, most notably in Germany, as profiled by Ritzkowski and Stegmann (2012). Many of these systems include the pressurized addition of air into vertical wells in the landfill combined with active extraction of off-gas (vapor) from other wells. Figure 14.13 shows the inlet of an air injection and gas extraction landfill at a German landfill. Some systems utilize filtration of off-gas (collected gas) through landfill soil cover or other filtration media (e.g., biofilters comprised of wood chips or compost) (Ritzkowski and Stegmann 2012), while others utilize passive aeration. Figure 14.14 gives an example of an aeration system at a closed landfill included the contained blower structures and the air treatment system. Figure 14.15 shows a passive aeration vent installed at a similar site. Many facilities repurpose formerly operated LFG collection systems such that much of the required infrastructure to operate aerobically is present. An additional beneficial effect of these aerobic treatment systems is odor minimization (Ritzkowski and Stegmann 2012), as it promotes oxidation of reduced compounds which tend to comprise the variety of malodorous compounds (e.g., mercaptans, volatile fatty acids).

14.5.3 North America

Air addition into landfills has received limited application in North America. In the 1960s, air addition was explored at a large landfill in California, where Merz and Stone (1966) added air through an access well in the center of a 20-ft deep landfill

Fig. 14.14 Blower housing and exhaust gas treatment system at a closed landfill (Photo courtesy of Marco Ritzkowski)

Fig. 14.15 Wind-powered air vent at a closed landfill undergoing aerobic treatment (Photo courtesy of Marco Ritzkowski)

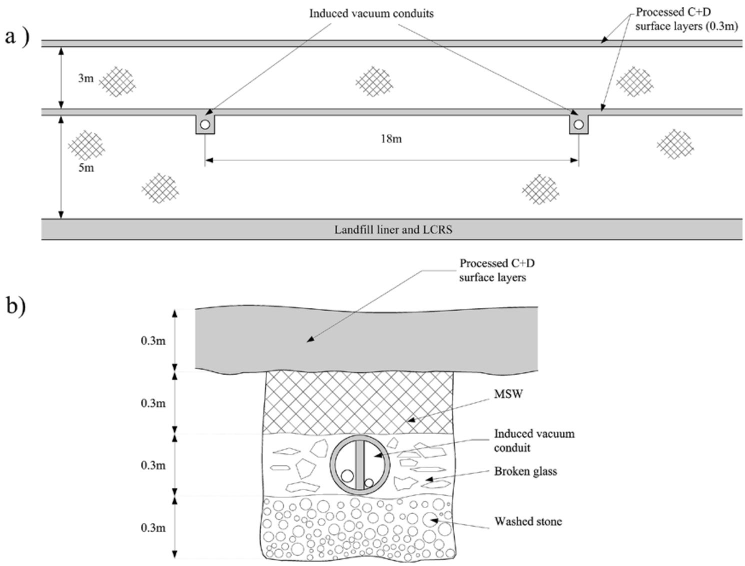


Fig. 14.16 Cross section illustrating construction of the VSA biostabilization technique

test cell using a mechanical blower. Aerobic conditions dominated within the test cell (as characterized by exhaust gas composition) and waste settlement in the first year was four times greater than a corresponding anaerobic control cell. Waste temperatures as high as 190 °F were measured, and at times the exhaust gas exhibited smoke and signs of fire, although the issue was reportedly remedied by blower shut down for a period of 50 days (Merz and Stone 1966).

At some large landfills where leachate recirculation is practiced, air is first added to the horizontal leachate addition lines as a means of increasing temperature and stimulating biological activity, especially in colder climates. For example, at the Outer Loop landfill (Kentucky, USA), air was added to a horizontal piping network [4-in. pipes spaced 60 ft apart (10 cm diameter pipes spaced 18.3 m apart)] approximately 30 days after one lift of waste was placed over the pipes to accelerate decomposition. Air addition, via compressed air injection, proceeded for periods of 30–90 days (at a flow rate of 57 m^3/min), until one of three set points were reached: (1) waste temperature reaches 71 °C, (2) temperature change of 6.7 °C (12 °F) in a 24-h period, or (3) air addition duration of 90 days.

At the Sullivan County Landfill in Monticello, New York, a technique described as vacuum-induced semi-aerobic (VSA) biostabilization was explored (Hansen et al. 2002). In this process, horizontal trenches containing 30-cm perforated conduits were placed on the landfill surface (Figs. 14.16 and 14.7). After wetting the waste with leachate and placing a synthetic daily cover, a vacuum was placed on the pipes using the site's existing LFG collection system, causing atmospheric air to be drawn through the surface of the landfill. The objective was to provide rapid

Fig. 14.17 VSA trench under construction (Photo courtesy of David Hansen)

waste stabilization to newly-placed waste while simultaneously reducing CH_4 emissions to the atmosphere. CH_4 flux to the atmosphere from VSA areas was found to be reduced on average by greater than 90 % (up to 17 m away) when compared to wetted areas with no vacuum applied. CH_4 fluxes were greater than non-wetted control areas, demonstrating that waste biostabilization was enhanced. Without application of vacuum, CH_4 flux to the atmosphere from the VSA stabilization area was approximately 30 times greater than the control cell.

In the late 1990s, aerobic bioreactor technology was marketed in the US as a method of producing rapid waste stabilization, reducing CH_4 emissions and eliminating the need for LFG collection, and providing leachate volume reduction (thus reduced need for treatment) through evaporation and stripping (Read et al. 2001). Several demonstration projects in the southeast US were initiated using small diameter vertical wells for the addition of air (via mechanical blower systems) and liquids (Hudgins and Harper 1999; Ritzkowski and Stegmann 2012). Some preliminary results were presented suggesting accelerated waste decomposition compared to anaerobic areas, reduced CH_4 emissions, improved leachate quality, and enhanced leachate evaporation. Figure 14.18 shows an air addition well used for a landfill facility in the Southeast US.

In response to the proposed aerobic bioreactor technology, several intensive research projects were conducted to examine the viability of full-scale aerobic treatment of landfilled waste and to gather needed design and operational data. At the New River Regional Landfill in Florida (see Chap. 4 for more details), air was mechanically pumped into small diameter (5-cm) clustered wells (three different depths) installed in a grid pattern at 16-m center-on-center spacing (Ko et al. 2013). While liquids were added to all of the wells, air was added only to a subset of the wells. Maintenance of aerobic regions through injection of ambient air was found to

Fig. 14.18 Distribution manifold and air addition well for an aerobic landfill in the Southeast US

be very challenging, primarily due to the inability of many wells to accept air. At the Yolo County Landfill in California (also discussed in Chap. 4 for more details), a vacuum was placed on horizontal gas collection pipes (1–15 cm) placed in shredded tire-filled trenches to draw air through the permeable surface of the landfill (Yazdani et al. 2010). This study reported challenges with respect to suppressing anaerobic activity and maintaining an aerobic state. Even in areas with substantial air injection, anaerobic pockets still persisted, and the presence of anaerobic pockets was more prevalent in areas where moisture content was greatest (Yazdani et al. 2010).

References

ATSDR (2001) Landfill Gas Primer: an overview for environmental health professionals, Nov 2001

Bass DH, Hastings NA, Brown RA (2000) Performance of air sparging systems: a review of case studies. J Hazard Mater 72(2–3):101–119

Berge ND, Reinhart DR, Townsend TG (2005) The fate of nitrogen in bioreactor landfills. Crit Rev Environ Sci Technol 35:365–399

Berge ND, Reinhart DR, Dietz J, Townsend T (2006) In situ ammonia removal in bioreactor landfill leachate. Waste Manag 26:334–343

Berge ND, Reinhart DR, Dietz JD, Townsend T (2007) The impact of temperature and gas-phase oxygen on kinetics of in situ ammonia removal in bioreactor landfill leachate. Water Res 41: 1907–1914

Bilgili MS, Demir A, Özkaya B (2007) Influence of leachate recirculation on aerobic and anaerobic decomposition of solid wastes. J Hazard Mater 143:177–183

Boersma PM, Diontek KR, Newman PAB (1995) Sparging effectiveness for groundwater restoration. In: Hinchee RE, Miller RN, Johnson PC (eds) In situ aeration: air sparging, bioventing, and related processes. Batelle, Columbus, pp 39–46

Bolton N (1995) The handbook of landfill operations. Blue Ridge Services, Atascadero

Chong T, Matsufuji Y, Hassan M (2005) Implementation of the semi-aerobic landfill system (Fukuoka method) in developing countries: a Malaysia cost analysis. Waste Manag 25: 702–711

Code of Federal Regulations (1996) New source performance standards for municipal solid waste landfills. 40 CFR 60 Subpart WWW, 12 Mar 1996

Coward HF, Hartwell JJ (1926) Extinction of methane flames by diluent gases. J Chem Soc 129:1522–1532

Coward HF, Jones GW (1952) Limits of flammability of gases and vapors. Bulletin 503, U.S. Bureau of Mines

FEMA (2002) Landfill fires, their magnitude, characteristics, and mitigation. FA-225, May 2002

Hansen DL, Chandwani A, Shaw P (2002) Sullivan County Landfill (Monticello, New York)—New York State Energy Research and Development Authority landfill biostabilization study, final report 03-03

Haug R (1993) The practical handbook of compost engineering. CRC, Boca Raton

Heyer K-U, Hupe K, Ritzkowski M, Stegmann R (2005) Pollutant release and pollutant reduction—impact of the aeration of landfills. Waste Manag 25:353–359

Hogland W, Marques M (2003) Physical, biological and chemical processes during storage and spontaneous combustion of waste fuel. Resour Conserv Recyc 40:53–69

Hudak PF (2000) Principles of hydrogeology. CRC, Boca Raton

Hudgins M, Harper S (1999) Operational characteristics of two aerobic landfill systems. In: Proceedings of the seventh international waste management and landfill symposium, Sardinia

Jain P, Powell J, Townsend T, Reinhart D (2005) Air permeability of waste in a municipal solid waste landfill. J Environ Eng 131:1565–1573

Johnson W, Baker J (1999) Operation characteristics and enhanced bioreduction of municipal waste landfill mass by a controlled aerobic process. In: Fourth annual SWANA landfill symposium, Denver

Johnson RL, Johnson PC, McWhorter BB, Hinchee RE, Goodman I (1993) An overview of in situ air sparging. Ground Water Monit Rev 13(4):127–135

Jung Y, Imhoff PT, Augenstein D, Yazdani R (2011) Mitigating methane emissions an air intrusion in heterogeneous landfills with a high permeability layer. Waste Manag 31:1049–1058

Kim H, Jang Y-C, Townsend T (2011) The behavior and long-term fate of metals in simulated landfill bioreactors under aerobic and anaerobic conditions. J Hazard Mater 194:369–377

Ko JH, Powell J, Jain P, Kim H, Townsend T, Reinhart D (2013) Case study of controlled air addition into landfilled municipal solid waste: design, operation, and control. J Hazard Toxic Radioact Waste 17:351–359

Leeson A, Johnson PC, Johnson RL, Vogel CM, Hinchee RE, Marley M, Peargin T, Bruce CL, Amerson IL, Coonfare CT, Gillespie RD, McWhorter DB (2002) Air sparging design paradigm. Battelle, Columbus

Leikam K, Keyer K (1997) In-situ stabilization of completed landfills and old sites. In: Proceedings of the sixth Sardinia International Landfill Symposium, Cagliari

Marley MC, Bruell CJ, Hopkins HH (1995) Air sparging technology: a practice update. In: Hinchee RE, Miller RN, Johnson PC (eds) In situ aeration: air sparging, bioventing, and related processes. Battelle, Columbus, pp 31–37

Matsufuji Y, Hanashima M, Nagano S, Tanaka A (1993) Generation of greenhouse effect gases from different landfill types. Eng Geol 34:181–197

Matsufuji Y, Tanaka A, Hanashima M (2004) Biodegradation process of municipal solid waste by semi-aerobic landfill type. In: Proceedings of the first Korea-Japan Society of solid waste management, 87–94

Merz RC, Stone R (1966) Sanitary landfill behavior in an aerobic environment. Public Works 97:67–70

Moqbel SY (2009) Characterizing spontaneous fires in landfills. University of Central Florida, Orlando

Onay T, Pohland FG (1998) In situ nitrogen management in controlled bioreactor landfills. Water Res 32:1383–1392

Palmisano AC, Barlaz MA (1996) Microbiology of solid waste, 1st edn. CRC, Boca Raton

Powell J (2005) Trace gas quality, temperature control and extent of influence from air addition at a bioreactor landfill. University of Florida, Gainesville

Powell J, Jain P, Kim H, Townsend T, Reinhart D (2006) Changes in landfill gas quality as a result of controlled air injection. Environ Sci Technol 40:1029–1034

Read AD, Hudgins M, Phillips P (2001) Perpetual landfilling through aeration of the waste mass; lessons from test cells in Georgia (USA). Waste Manag 21(7):617–629

Rich C, Gronow J, Voulvoulis N (2008) The potential for aeration of MSW landfills to accelerate completion. Waste Manag 28:1039–1048

Ritzkowski M, Stegmann R (2007) Controlling greenhouse gas emissions through landfill in situ aeration. Int J Green Gas Control 1:281–288

Ritzkowski M, Stegmann R (2010) Generating CO_2-credits through landfill in situ aeration. Waste Manag 30:702–706

Ritzkowski M, Stegmann R (2012) Landfill aeration worldwide: concepts, indications and findings. Waste Manag 32:1411–1419

Ritzkowski M, Heyer K-U, Stegmann R (2006) Fundamental processes and implications during in situ aeration of old landfills. Waste Manag 26:356–372

Sartaj M, Ahmadifar M, Jashni K (2010) Assessment of in-situ aerobic treatment of municipal landfill leachate at laboratory scale. Iranian Journal of Science and Technology, Transaction B, Engineering, Vol 34, B1, 107–116

Stessel RI, Murphy RJ (1992) A lysimeter study of the aerobic landfill concept. Waste Manag Res 10:485–503

Stone R, Gupta R (1970) Aerobic and anaerobic landfill stabilization process. J San Eng Div, Proceedings of the American Society of Civil Engineers, 96(SA 6):1399–1414

Wu C, Shimaoka T, Nakayama H, Komiya T, Chai X, Hao Y (2014) Influence of aeration modes on leachate characteristic of landfills that adopt the aerobic-anaerobic landfill method. Waste Manag 34:101–111

Yang X, Beckmann D, Fiorenza S, Niedermeier C (2005) Field study of pulsed air sparging for remediation of petroleum hydrocarbon contaminated soil and groundwater. Environ Sci Technol 39(18):7279–7286

Yazdani R, Mostafid ME, Han B, Imhoff PT, Chiu P, Augenstein D, Kayhanian M, Tchobanoglous G (2010) Quantifying factors limiting aerobic degradation during aerobic bioreactor landfilling. Environ Sci Technol 44:6215–6220