BioCycle
ARTICLE SERIES
AERATED STATIC PILE COMPOSTING

Design Considerations In Aerated Static Pile Composting

Examples of a negative aeration system installed at the City of Burlington, North Carolina's biosolids composting facility (left) and a positive aeration system at Blue Hen Organics in Frankford, Delaware (right) are shown.

This article series examines the considerations in forced aeration static pile composting, including the basics of aeration system design and operation, types of aerated static pile systems, and design issues to be evaluated.

ASP fundamentals, including recipe development to ensure adequate free air space, are discussed.

Part I

Craig Coker and Tom Gibson

AERATED static pile (ASP) composting, using negative aeration and simple timer motor controls, was developed by the U.S. Department of Agriculture's Beltsville Agricultural Research Center in the 1970s in support of exploring the beneficial uses of sewage sludge. The "Beltsville method" was refined in the 1980s by Dr. Melvin Finstein at Rutgers University, who developed ASPs with positive aeration and a temperature feedback loop to maintain pile temperatures at a constant level. ASP composting has long been used for heavy wet feedstocks like sludges and manures, but it is getting a fresh look as composting facilities are starting to accept feedstocks like food scraps.

This series of articles will examine both process and mechanical design considerations in ASP composting and the newer containerized and covered ASP technologies on the market today. Part I covers process design, including recipe development to maintain free air space, and aeration fundamentals.

PROCESS DESIGN

Process design, whether for ASP, windrow or in-vessel composting, starts with the same procedure: Develop a good recipe for all the anticipated feedstocks, then size all the processing steps in the composting process. A good recipe should be based on valid characterization data on total carbon, total nitrogen, moisture content, volatile solids content and bulk density (mass per unit volume of material) for each feedstock. The recipe should not only balance the carbon to nitrogen (C:N) ratio (>25:1) and moisture content (50-55%), but should also verify content of at least 80 percent volatile solids and has a predicted free air space of between 40 and 60 percent.

Volatile solids (VS) can be thought of as the "biologically combustible portion" of a feedstock, representing the amount of easily biodegradable content. A compost pile with a high content of brushy and woody material (which has a VS content of around 70-75%) will not reach as high a composting temperature as a pile with a high content of food and paper scraps (which would have a VS content more in the 90-95% range).

Table 1. Example calculation of predicted FAS

Mix Ratio Calculations - Daily

Ingredients	*Food Scraps*	*Carbon*	*Compost Recycle*	*Overs*	*Total Mix*	*Target*
C (% as is)	38.4	49.2	13.2	50.1		
N (% as is)	2.4	0.9	1.0	1.0		
Moisture%	70	40.1	45	45		
Units in mix by wgt (t)	30.0	30.0	8.0	5.0	73.0	
Units in mix by wgt (lb)	60,000	60,000	16,000	10,000	146,000	
Units in mix by vol (cy)	50	115	18	20	202.7	
Density (lbs/cy)	1197	522.5	900	500		
Density (kg/m^3)	710.2	310.0	533.9	296.6		
% air space	36.09	72.10	51.94	73.30		
Feedstock volume (cy)	50.1	114.8	17.8	20.0	153	
Air volume (cy)	18.1	82.8	9.2	14.7	106.7	
Predicted free air space					69.9%	40-60%

Free air space (FAS) is a measure of the structural porosity of a pile, which is important in ensuring good air movement through the pile, either by the natural chimney effect of a windrow or by the persistent effect of fan blades. FAS can be predicted by a correlation to bulk density using a formula developed by Albuquerque (2008):

$$FAS = 100 - (0.09 \times \text{Bulk Density (in kg/m}^3))$$

Table 1 provides a sample calculation of FAS. While it calculates the FAS slightly above the target levels, this is a less important process design criteria than C:N or moisture, and could be adjusted by adding more "compost recycle" (finished and typically screened compost, although some facilities use unscreened compost to increase pile porosity). Recycling 10 to 15 percent compost into a mix serves three functions: Provides microbial life already adapted to the facility (serving as an inoculant); absorbs moisture from high-moisture feedstocks like fruits and vegetables; and can provide a small measure of *in-situ* odor control.

Recipes can also allow for reuse of screened oversized woody particles. Calculating the amount of "overs" available can be done by creating a process flow diagram (PFD) — using the bulk density data to figure out volumes of each ingredient in the recipe, then combining them for a daily, weekly, monthly or annual recipe. If feedstocks are expected to change each day, make a daily recipe and PFD. If feedstocks are seasonal, like a yard trimmings facility, create a weekly recipe/PFD for each of the seasons. Based on assumptions made about volume changes due to grinding, mixing, composting, curing and screening, and about residence times in each process, volumes in each step of the composting process can be estimated. In turn, the physical footprint of each process step, with the blowers and aeration piping sized for the ASP system being designed, can be calculated (more on that in Part III).

Keep in mind that ASP systems are not as forgiving of process design mistakes as are windrow systems, therefore getting C:N, moisture, VS and FAS correct is more important. Traditional ASP systems do not require turning or moving the materials during the active composting process, so grinding, mixing, and feedstock preparation are very important. There is an emerging school of thought in the industry that ASPs should be broken down, remixed and rebuilt at the midpoint of the active composting phase, which allows for midcourse corrections if something in the process design is off-kilter.

AERATION FUNDAMENTALS

The purpose of aeration in composting is three-fold: Satisfy the oxygen demand from aerobic decomposition (known as stoichiometric demand); remove excess moisture; and remove excess heat. Of these, the aeration rate to keep a constant temperature by removing excess heat normally governs the aeration requirements of a composting system (Keener, 1997).

Stoichiometric demand refers to the quantity, or weight, of oxygen needed to decompose organic molecules, nitrify (oxidize) ammonia released during decomposition, and oxidize the cellulosic matter in carbonaceous amendments. This oxygen demand refers only to the volatile solids in the feedstocks. Consider the decomposition reaction for food scraps:

$$4\ C_{18}H_{26}O_{10}N + 75\ O_2 \rightarrow 72\ CO_2 + 46\ H_2O + 4\ NH_3$$

The organic decay stoichiometric demand calculates out to 1.44 grams of oxygen per gram of biodegradable volatile solids (g O_2 /g BVS), and the nitrification demand is 0.16 g O_2 /g BVS. Similar calculations are done for each feedstock in the compost mix and the results summed.

The stoichiometric demand for oxygen can vary from about 1.0 g O_2 /g BVS for highly oxygenated feedstocks like cellulose or starch to 4.0 g O_2 /g BVS for some hydrocarbons (Haug, 1993). Because air contains 23.2 percent oxygen by weight, the *air* demand is the oxygen demand divided by 0.232. This demand concept is different from the air rate required.

The quantity of air needed to remove moisture varies with the moisture content of the feedstocks, the desired moisture content of the final compost product, and the moisture-carrying capacity of the air stream (known as the specific humidity). Assuming a mix moisture content of 60 percent and a desired compost moisture content of 45 percent, with inlet air temperature of 68°F at 75 percent relative humidity and the outlet air at 130°F at 100 percent relative humidity, the oxygen demand for moisture removal in the food scraps decomposition example above is 9.2 g O_2 /g dry solids, which is significantly greater than the demand for biological oxidation.

Rates of biochemical reactions generally increase exponentially with temperature, but elevated process temperatures in composting quickly inactivate the microorganisms, so temperature becomes rate-limiting. Removing that heat is an important part of aeration. Some heat will be removed from a compost pile in the final solids, and some lost to the environment, but the majority of the heat loss is in the exhaust gases leaving the pile. Oxygen demand for heat removal is several times greater than that needed for biological oxidation or for moisture removal. In the food scraps example above, the oxygen demand to maintain temperature at 131°F is 38.4 g O_2 /g dry solids. If the total aeration needed is 100 percent, then, in the example above, 4.3 percent of that air is needed for biological decomposition, 18.2 percent is needed for moisture removal, and 77.5 percent is needed for heat removal.

The aeration rates needed for composting are determined by converting oxygen demands to aeration demands, then by considering the duration over which aeration is needed. This establishes the average rate of aeration. Aeration rates are usually expressed in cubic feet of air per hour per dry ton (cfh/dt) of mix. Aeration rates will vary depending on where the pile is in the decomposition process, with peak demands exceeding average demands by a factor of 2 or more. In the early and late stages of active composting, aeration rates will be in the range of 200 to 500 cfh/dt, while during times of high microbial activity the peak rate might exceed 2,000 cfh/dt.

Insufficient aeration rates cause pile temperatures to increase due to the inability to provide enough oxygen for heat removal. This creates a tradeoff between the need for larger blowers (which cost more) versus pile temperatures that exceed a desired setpoint (like 131°F). It may be more cost-effective to size the system for less than peak demand and accept process temperatures above the setpoint for a while. Given composting does not completely stop until pile temperatures exceed about 165°F, there is some flexibility in system design.

The type of aeration control system used also affects the ability to meet peak aeration demands, as air is only supplied when the fans are on. While it is possible to simply leave the fans on for the entire duration of active composting, this is not very cost-effective. Some form of control is needed to reduce operating costs and wear-and-tear on the aeration system. The simplest control system is simply a manual on/off switch. Early ASP systems used clock timers to regulate airflow on or off, usually on the basis of 20 minutes on, 40 minutes off per hour. This is still a valid control strategy.

ASP systems can also operate on a feedback control strategy, where some external measurable factor is used to control aeration rates. With a feedback control strategy, the externally measured factor is the controlled variable and the aeration rate is the manipulated variable. The two main controlled variables in ASP feedback control systems are temperature and oxygen content. These systems are often linked to the motors controlling the fans by a variable frequency drive unit, which adjusts the electrical voltage going to the motor, which, in turn, controls fan speed and thus air flow rates. So a temperature feedback control strategy would seek to hold pile temperature at a constant level, adjusting fan speed up as pile temperatures increase (to remove excess heat) and adjusting fan speeds down as piles cool off, whereas an oxygen content control strategy would increase fan speed if O_2 content drops below a setpoint like 10 percent and lower fan speed if O_2 content rises above 18 percent.

Good process design is an important first step in aerated static pile composting. The next article in this series will examine types of forced aeration systems, including supply fans and aeration piping. ■

Craig Coker is a Contributing Editor to Biocycle and a Principal in the firm Coker Composting & Consulting (www.coker-compost.com), near Roanoke VA. He can be reached at ccoker@cokercompost.com. Based in Milton, PA, Tom Gibson, P.E. is a consulting mechanical engineer specializing in green building (www.ProgressiveEngineer.com/consulting.html) and can be reached at tom@progressiveengineer.com.

REFERENCES

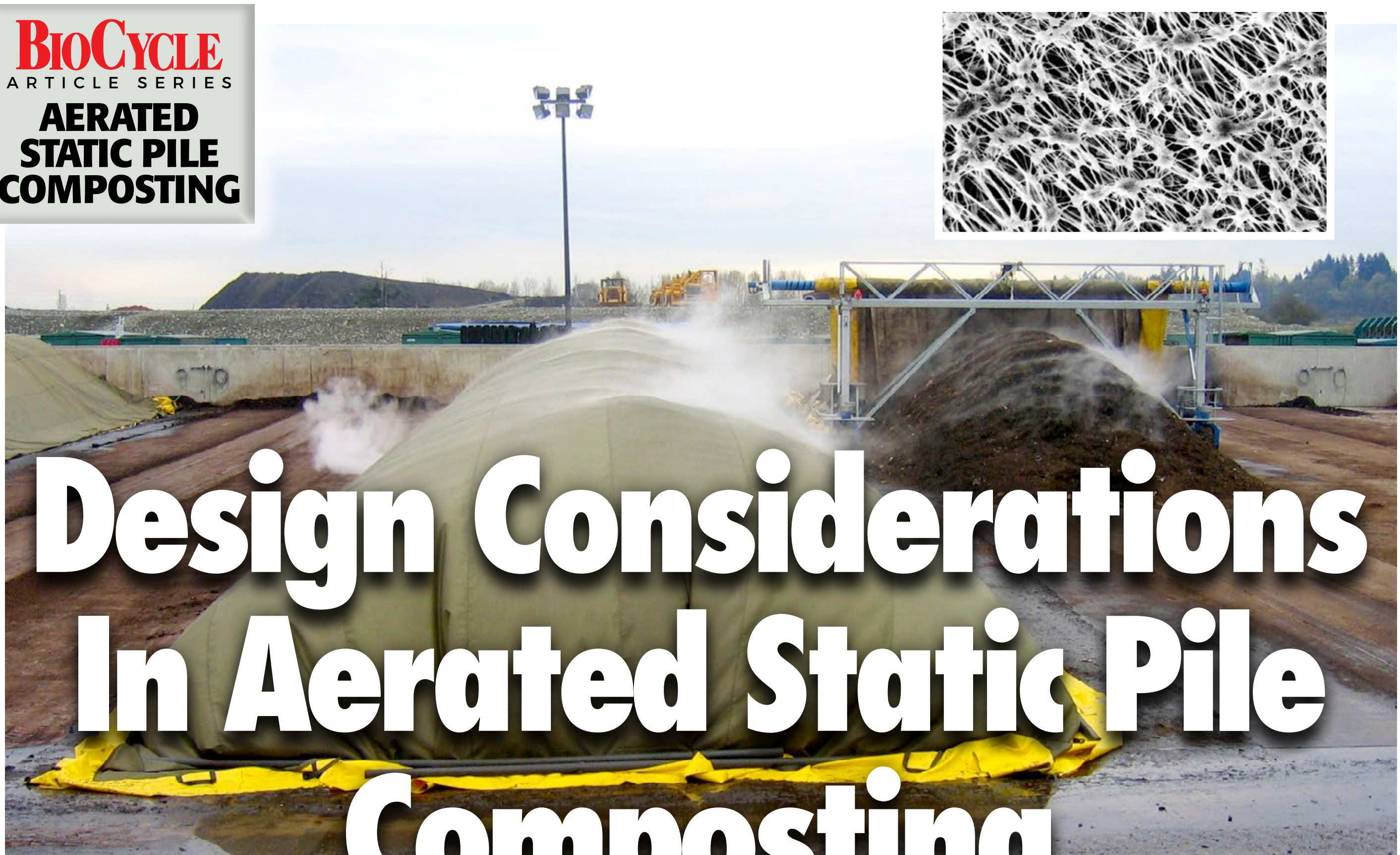
Albuquerque, J.A., *et. al.*, "Air Space in Composting Research: A Literature Review", *Compost Science and Utilization*, Vol. 16, No. 3, 2008, p. 159-170.

Haug, R.T., "Aeration Requirements", *The Practical Handbook of Compost Engineering*, Lewis Publishers, 1993, p. 263.

Keener, H.M., *et.al.*, "Airflow Through Compost: Design and Cost Implications", *Applied Engineering in Agriculture*, Vol. 13, No. 3, March 1997, p. 377-384.

BioCycle ARTICLE SERIES

AERATED STATIC PILE COMPOSTING



Design Considerations In Aerated Static Pile Composting

The Gore cover system uses fabric covers made of a layer of ePTFE (see inset) sandwiched between two layers of polyester for structure.

This article series examines the considerations in forced aeration static pile composting, including the basics of aeration system design and operation, types of aerated static pile systems, and design issues to be evaluated.

Synthetic covers include polyethylene (PE) tarps, flexible vinyl fabrics, PE fleece blankets and expanded polytetrafluoroethylene. Covers are used with both forced and induced aeration.

Part II

Craig Coker and Tom Gibson

THIS series of articles has established that aerated static pile (ASP) composting is increasing in the U.S. composting industry due to the potential for better process and odor control and, when covered, for potential improvements in odor management and storm water runoff quality. The second article in this five-part series focuses on covers.

Equipping a composting pile with a cover, whether made of carbonaceous materials, compost or fabric, serves several purposes: Maintaining moisture levels by reducing evaporative losses; retaining heat in smaller piles and in colder climates; reducing the attraction of the pile to vectors; reducing odors either through in-situ biofiltration (compost cover) or water absorption of odorous molecules on the underside of the cover (fabric covers); preventing rainfall from contacting decomposing waste thus enabling runoff to be managed as storm water; and providing better visual appeal (many facility neighbors smell with their eyes). But the main attraction of covering ASPs is to reduce emissions of volatile organic compounds (VOCs), the primary source of odors and a regulated air pollutant in some places.

Pile covers are either biogenic or synthetic, with biogenic covers including compost (screened and unscreened), wood chips, sawdust, hay/straw and similar materials. The porosity of a biogenic cover greatly influences odor-reducing capability. Synthetic covers include polyethylene tarpaulins, flexible vinyl fabrics (recycled billboards), polyethylene fleece blankets, and expanded polytetrafluoroethylene (ePTFE) covers, although any water-repellent fabric cover will meet some of the goals. Truly impermeable synthetic covers do not allow for heat escape (excepting along boundaries between cover panels). Heat buildup can cause composting issues, such as inhibition of active composting above 160°F.

MICROPORE COVERS FOR POSITIVE AERATION

Many new covered ASP systems in North America are based on the use of microporous ePTFE, an extruded sheet-form version of the carbon-fluorine compound that forms the basis for DuPont's Teflon. This application has been utilized in Europe for over 15 years. W.L. Gore & Associates uses this material in its Gore-Tex fabric found in clothing such as ski jackets, which are known for being breathable yet waterproof. Gore's composting system offers fabric covers made of a layer of ePTFE sandwiched between two layers of polyester for structure. The ePTFE has pore sizes between 0.02 micron (Ìm) and 40 µm.

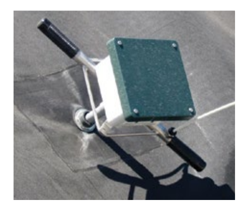
Brian Fuchs, an associate at Gore, explains that moisture control plays a big role in making their cover very suitable for positive aeration systems. "The moisture is retained within our covered system because the air is blowing upward and using the inherent properties of the membrane to keep the moisture in the system, as compared to a negatively aerated system that's drawing the air down and pulling the moisture out with it, which then ends up either in a condenser or the biofilter."

Managed Organic Recycling (MOR) also bases its Compost Cover System on ePTFE fabric. "Our covers are primarily designed for VOC control now because of the California requirements," explains John Bouey, president of MOR. The company is starting to see demand for covers in other states besides California, which are copying the Golden State's regulations.

The ePTFE fabric also is extremely hydrophobic. That feature, coupled with the microporosity, allows small-molecule gas exchange across the fabric but doesn't allow water droplet penetration. Moisture vapor flows through an ePTFE membrane by either bulk gas flow or diffusion. If the pressure differs across the membrane, gas flows from the high pressure side to the low pressure side. Moisture vapor also diffuses through the microporous structure if humidity or temperature varies across the membrane. Evaporated water from the composting pile condenses on the underside of the ePTFE cover, acting as a water scrubber to absorb odorous compounds in solution. Simply put, as moisture and odors rise from the compost pile, the moisture condenses on the inside surface of the cover, and some of the odors get trapped in the condensate (ammonia is not well controlled by microporous covers). The moisture then flows by gravity to pipes running on the ground alongside the pile.

A third company in the mix, Engineered Compost Systems (ECS), builds covers for both negative and positive aeration systems. Its AC Composter is an induced-draft system; there are 10 installed in the U.S. at present. Covers for negative aeration systems are made from a standard tarp material with larger holes up to one-sixteenth-inch in diameter. This keeps most of the rainwater out but allows adequate air flow, which is important because pulling air through a covered pile takes more power than pushing it. According to U.S. Patent No. 7,642,090, "the compost cover is formed of a material that is substantially gas and liquid impermeable, and is provided a plurality of aeration ports, or orifices, that permit the passage of gases through the cover. The size and number of aeration ports may be varied to meet the air flow requirements for given biomass, or feedstocks, zone size and process goals. The compost cover is generally constructed of fabric that is durable, flexible, UV resistant, waterproof, and relatively lightweight."

ECS designs its AC Composter systems around an air flow rate of about 3 to 5 cfm/cy (cu.ft/min./cubic yard) of mix. "Since oxygen levels in active piles can fall to near zero in a few minutes, we prefer continuous aeration rather than 20 and 30 minute off cycles between small puffs of air," explains Tim O'Neill, founder and president of ECS. "We have found over the years that variations in mix porosity are a far greater factor influencing air flow in a pile than cover type or aeration hole patterns. We have come to believe that the design of the aeration floor is very important to realizing consistent air distribution patterns in an ASP system."



Managed Organic Recycling custom builds its Cover Placement Machine (above) to handle its ePTFE fabric covers. Temperature monitoring (right) is on 5-minute intervals.

EFFECT ON BLOWER PRESSURE

Several design and operating factors should be considered with covers on ASP systems. Part III of this series (see "Pipe And Blower Fan Fundamentals In ASP Design") discussed calculating static pressure drop in ASP aeration systems in order to size the blower needed for supplying air to the pile. It stands to reason that a cover over a pile will add one more element in this process because air has to be forced through tiny pores in the tarp, increasing pressure drop and subsequently the blower size required. This can vary from one system to the next and by manufacturer, as they take different approaches.

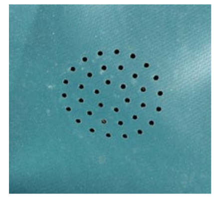
Bouey says for positive aeration systems with 15 to 20 percent porosity in the pile, the cover adds 2 to 3 inches water gauge (W.G.) to the head loss. O'Neill notes that with the ECS covers, the added pressure drop is about 10 percent, or 0.5-inch W.G. over a cover measuring 40-feet wide by 100-feet long — "about the same increase you'd see in a biofilter due to settling over time."

Blowers may actually operate on a reduced schedule, however. For example, Gore's fabric-covered system uses oxygen content as the fan operational control variable, in addition to temperature. "We deliver air using our oxygen-controlled system, which offers greater control over the process by establishing oxygen set points based on the mix recipe," explains Fuchs. "Essentially, we allow the microbes to determine the demand on oxygen, and our experience shows these set points could be as low as 2 percent and as high 18 percent. We use low-energy fans that generally operate only 25 percent of the time, which is a pure energy consumption advantage."

MOR operates aeration blowers based on feedstock characteristics (i.e., average oxygen demand rates for some feedstock materials of about 750 cubic feet/hour (cfh)/dry ton organic matter in the mix and peak demand of 1,250 cfh/dry ton organic matter, assuming 8-inch pressure loss). Temperature monitoring is on 5-minute intervals and compared with control set points. Air flow rates are increased or decreased to maintain the temperature within the set point. MOR systems run at temperatures between 155°F and 165°F in the active composting phase. Typically, this equates to blower run times between 3 to 5 minutes every 30 minutes.

According to Fuchs, the Gore system actually requires less blower pressure because it creates an encapsulated in-vessel system. "The cover is surrounded with a weighting system, which holds down the cover and allows the whole system to be pressurized," he notes. "The membrane is specifically engineered with the trench and blower as one combined system." The cover provides an even backpressure, resulting in an even distribution of resistance and air flow through the pile, and the blower works more efficiently.

With air pressure working against the underside of the cover, some mechanism is needed to hold the covers down. Options include sand bags, perforated truck tires, or perimeter water- or sand-filled anchoring tubes. Holding down a cover is important for two reasons: to keep fugitive emissions from leaking out around the base of the cover and to resist wind. "It is really important to secure them, especially because of wind," says O'Neill. "The covers develop lift like a wing. You can imagine the force over 100 feet. They're huge sails. We discourage them in windy areas."



Engineered Compost Systems offers a negatively aerated cover system with process air treated in a biofilter (above). Its covers are made from a standard tarp material with larger holes up to one-sixteenth-inch in diameter (right).

Another consideration with covered ASP systems is handling the covers. With smaller installations, the cover can be moved by hand, but larger ones are heavy and are usually moved onto and off the piles with machines like sidewinders, straddlewinders, winches or tractor-pulled winders. "We have different types, including a mobile winding machine, wall-mounted winders, and portable winders that are pulled with a trailer hitch behind a loader or pickup truck," explains Fuchs. "We've worked with facilities that have front-end loader-mounted winders." He adds that in Europe, Gore cover system installations include inflatable versions and mechanical roof-types of apparatus. MOR custom builds its Cover Placement Machines (CPM). It offers both two-wheel and all-wheel drive CPM with hydraulic "joy stick" control as well as a towable machine for smaller covers in the 30-foot by 90-foot range.

In conclusion, the main advantages of fabric-covered ASP composting, whether forced-draft or induced-draft, are control of VOCs for air quality reasons, improved moisture control in the aerated pile, and odor control through water absorption under the cover. Composters can choose biogenic covers that are replaced with every new pile, or consider one of these fabric-covered systems that can have an 8- to 10-year lifespan with careful maintenance. ■

Craig Coker is a Contributing Editor to BioCycle and a Principal in the firm Coker Composting & Consulting (www.cokercompost.com), near Roanoke VA. He can be reached at ccoker@cokercompost.com. A consulting mechanical engineer, Tom Gibson is president of Tom Gibson, P.E. Green Building Engineer (www.progressiveengineer.com/consulting.html) in Milton, PA and can be reached at tom@progressiveenginer.com.

BioCycle
ARTICLE SERIES
AERATED STATIC PILE COMPOSTING

Pipe And Blower Fan Fundamentals In ASP Design

ASP composting designs most often use centrifugal blowers (left), as these are recommended for systems with back pressure caused by having long runs of piping or ducting. Facilities can test various piping system designs, such as entrenching the pipes as shown in this pilot test (right).

Effectiveness of aerated static pile composting depends largely on the aeration system, which can comprise a large portion of the facility's cost and energy use.

Part III

Craig Coker and Tom Gibson

This article series examines the considerations in forced aeration static pile composting, including the basics of aeration system design and operation, types of aerated static pile systems, and design issues to be evaluated.

AERATED static pile (ASP) composting is increasing in usage in the U.S. composting industry due to the potential for better process and odor control and, when covered, also for potential improvements in storm water runoff quality. In addition, ASP systems offer a savings of almost 50 percent in processing footprint on a compost pad. This series of articles is examining both process and mechanical design considerations in ASP composting, as well as some of the newer containerized and covered ASP technologies on the market today.

The effectiveness of aerated static pile (ASP) composting depends largely on the aeration system, which can comprise a large portion of the facility's cost and energy use. With an ASP, the operator relies entirely on the aeration system to get air into the pile and make the composting process work by supplying oxygen and removing heat, moisture and odors. Many design considerations go into developing an aeration system, and while an engineer usually handles the calculations and design work, it helps to know what goes into it.

For starters, there are two types of systems to choose from: forced draft (positive aeration) and induced draft (negative aeration). Both types have piping laid longitudinally under the ASP and connected to a blower. In the forced draft system, air blows into the ASP, after which it permeates up through the pile and into the atmosphere. With an induced draft system, the blower pulls air through the ASP and discharges it to a biofilter to treat and eliminate odors.

Typically, one blower serves each ASP; in an induced draft system, several blower outputs may be piped to a manifold, which then goes to one biofilter. Induced draft systems are much more complex than forced draft, especially if several ASPs are feeding the biofilter, which can have its own set of complications. As an example, the authors designed an aeration system for Chesapeake Compost in Baltimore, Maryland that is located inside a repurposed industrial building. The facility has 7 ASPs on each side of the main operating floor for a total of 14 blowers feeding a biofilter. The ductwork had to be run from one bank of blowers above the operating floor to connect with the blowers on the other side and from there to the biofilter.

PIPING SYSTEM DESIGN

The aeration system design process typically starts with the piping system. While systems with pipes and ducts of all different sizes manifolded and running everywhere may look complex, a few basic starting points and rules of thumb simplify the process. Start with the pipes in the ASP and biofilter; these are usually 3- or 4-inch pipe size, spaced 4 feet apart running parallel through the pile. The 4-foot dimension is an industry standard that allows for adequate air distribution in the pile. These pipes can lie on the ground unsecured for a temporary or alterable arrangement or be placed in troughs in a concrete floor for a permanent system.

The main choices for pipe material include polyvinyl chloride (PVC), polyethylene (PE) and flexible corrugated PE. All three are commonly used in ASP composting, often mixed together at the same facility. PVC and PE are different animals, as they come in different lengths and use different methods of joining, so it pays to shop around to determine prices and availability. Many people like PVC because it's available at big-box hardware stores, and they're comfortable with solvent-welding sections together (the solvent essentially "glues" the pipes together via a chemical reaction). PE pipe comes in 40-foot lengths, which can be more conducive to ASP lengths — which tend to be 2 to 4 times longer than they are wide — while PVC comes in 20-foot sections. It is common to see flexible rubber couplings, secured with hose clamps, joining sections of either PVC or PE pipe, as these can handle some misalignment.

Aeration piping can be disposable or permanent. Flexible corrugated PE pipe, similar to that connected to the drain spout on a house, offers a disposable option that gets replaced with every composting cycle. It costs about $0.55/ft. Surface-mounted permanent PVC or PE pipes are pulled out and set aside at the end of a cycle while the loader tears down the pile. Entrenched piping (PVC or PE) is left in place without fear of mangling during teardown, though it does get cleaned and reused for the next cycle. The 4-inch PVC pipe sells for $3.54/linear foot (lf) while 4-inch PE pipe is $3.28/lf. The choice of whether to use disposable, surface-mounted permanent piping versus entrenched permanent piping depends on the facility's budget and the level of confidence in having achieved the optimum (and more permanent) composting process. Laying pipes in concrete is the most costly option and should only be done after the process has been refined. The other two options are best if the facility is in developmental stages and might be modifying the process.

Whatever the choice of material for pile pipes, holes are drilled along their length for air to exit or enter, typically at one-foot intervals and on the underside of the pipe so they don't get clogged with compost material falling in from above. Most installers have two holes at each location — at 4:00 and 8:00 on the pipes or close to that. The rule of thumb is that the total area of the holes should not exceed the inside area of the pipe, so air will be evenly distributed along the pipe. To help that, another convention says to gradually increase the hole size as the distance gets further from the manifold pipe (the header pipe from which the aeration pipes extend). As an example, the pipe will have 3/16th-inch diameter holes along the first third of the pipe, 1/4-inch holes along the middle third, and 5/16th-inch holes in the last third. Place a removable cap on the end of each pile pipe, as that facilitates cleaning and draining them out as necessary.

An interesting option offered by a few companies for the pile piping is a prefabricated product that has pipe with properly sized orifices already in it. It is made to be laid in concrete as part of a permanent system with the air ports lying flush with the floor, so vehicles can operate over the top of it without problems (material does fall into the upward-pointing holes and into the pipe, but these designs have a system for flushing that out). This type of aeration floor, supplied by BuildWorks, is being installed at an ASP retrofit project for the Wasatch Integrated Waste Management District in Layton, Utah.

With ASPs typically about 25 feet wide, the design may require up to five or six pipes running through the pile and connecting to a manifold pipe just outside the end of the ASP. Another pipe will extend from the center of the manifold to the blower. The constant-area rule of thumb applies here in selecting pipe sizes, i.e., the piping flow area should stay roughly the same throughout the system. Another rule of thumb: the velocity of air flowing in a pipe shouldn't exceed 50 feet per minute to avoid high-pressure losses and unacceptable noise generation.

To determine air velocity in a pipe, use the formula:

$$V = Q / A$$

where V= velocity in feet per minute, Q = air flow rate in cubic feet per minute, and A = area of the pipe in square feet. Another guide in selecting pipe size is the blower inlet and outlet size. If a blower in a forced draft system has an 8-inch outlet, an 8-inch pipe could be run from the outlet to the middle of a 6-inch manifold pipe to 4-inch pile pipes. If there are two pile pipes going into the manifold on either side of the 8-inch pipe, for a total of 4 pile pipes, the flow areas would be roughly equal — four 4-inch pipes equal two 6-inch pipes equals one 8-inch pipe.

In negative aeration systems, there is the added piping from the blower outlet to the biofilter. For short runs, this can be plastic pipe, but for longer and overhead runs, consider using ductwork similar to that used in HVAC systems. Typically a sheet metal or HVAC contractor will custom-fabricate a system. Galvanized steel is most commonly used, but thin-wall chlorinated polyvinyl chloride (CPVC) is also an option. Ducting should be round, and blower pipe is typically spiral wound.

Another complicating factor in induced-draft systems is the condensate that comes when pulling air through moist compost. Allow some means for draining it from the piping or ducting coming from the blower(s). This can consist of a drainpipe with a valve affixed to it in each low spot in the piping. If the pipe is small enough in diameter, it can be run into the side of a 55-gallon drum, near the bottom, and exit on the other side, near the top. Place a sump pump with a float switch inside the drum to remove condensate that collects.

SIZING THE BLOWER

With the piping system tentatively designed, the next step is to calculate the head loss in the piping and ultimately size the blower required. When transporting any fluid through a pipe, including air, resistance from friction with the pipe walls and any objects in the flow path (like dampers, turns or T-connections) has to be overcome. This means more pressure has to be generated at the pipe inlet to overcome these frictional resistance losses and still have the pressure needed at the top of the ASP (positive aeration) or top of the biofilter (negative aeration), which is equal to or greater than atmospheric pressure. The formulas used are difficult to solve for pipe diameter, so first select pipe sizes and then calculate pressure drops and tweak the system in an iterative process.

Table 1. Example of WWTP ASP aeration system — 2-pipe design

Components	
4-in PVC pipe, 60-ft long; 2 elbows	Flow rate=400/2(2)=100 CFM Equivalent length=60-ft+2(13.1')=86.2-ft
6-in PVC pipe, 80-ft long; 1 tee, 4 elbows	Flow rate=400 CFM Equivalent length=80-ft+32.7-ft+4(17-ft)=180.7-ft
Component	Pressure drop, inches W.G.
4-in PVC pipe and fittings	0.55
6-in PVC pipe and fittings	1.66
Total	2.21

Pressure drop (or head loss) calculation is based on the Darcy-Weisbach formula, which factors in friction factor for the pipe material, length of pipe, flow velocity and pipe diameter. Head loss can be calculated with this formula:
Where:

$$h_f = f_D \cdot \frac{L}{D} \cdot \frac{V^2}{2_g}$$

- h_f is the head loss due to friction (SI units: meters (m));
- L is the length of the pipe (m);
- D is the hydraulic diameter of the pipe (for a pipe of circular section, this equals the internal diameter of the pipe) (m);
- V is the average velocity of the air flow, equal to the volumetric flow rate per unit cross-sectional area (m/s);
- g is the local acceleration due to gravity (m/s²);
- f_D is a dimensionless coefficient called the Darcy friction factor.

Velocity is calculated from the flow rate of air through the ASP or biofilter in conjunction with the pipe diameter. Friction factors come from the Moody Friction Factor Chart and depend on the relative roughness and specific roughness, which are available on various charts. Corrugated HDPE disposable piping has a higher friction factor due to the corrugations than smooth-walled PVC pipe. Head loss is typically calculated in feet and converted to pressure by multiplying by fluid density and using a conversion factor for inches water gauge (in WG), the most common unit of pressure in air systems. The Darcy formula shows that head loss varies proportionally with the pipe length and diameter, but it varies exponentially with flow velocity. In other words, if the length or diameter of a given pipe is doubled, the head loss also is doubled. But if the flow velocity is doubled, the head loss is quadrupled. This is key — small increases in pipe size can dramatically reduce the velocity and therefore the pressure loss and ultimately the size of blower required and the power to run it.

Start the design and analysis process by determining the lengths of straight sections of pipe, and then for fittings and transitions, look up equivalent lengths on charts and add these to the straight lengths. For example, say the facility is using an 8-inch PVC pipe going from the blower to the biofilter in an induced draft system with an 8-foot straight section straight up from the blower to a long-sweep-radius elbow followed by a 100-foot horizontal section to another elbow, then an 8-foot drop to the biofilter manifold. A chart will indicate that the equivalent length of straight pipe for this elbow is 22 feet. That length is added twice to the straight lengths to get a total of 160 feet of pipe. Therefore 160 feet is plugged into the Darcy formula to calculate pressure loss for this segment, as shown in Table 1.

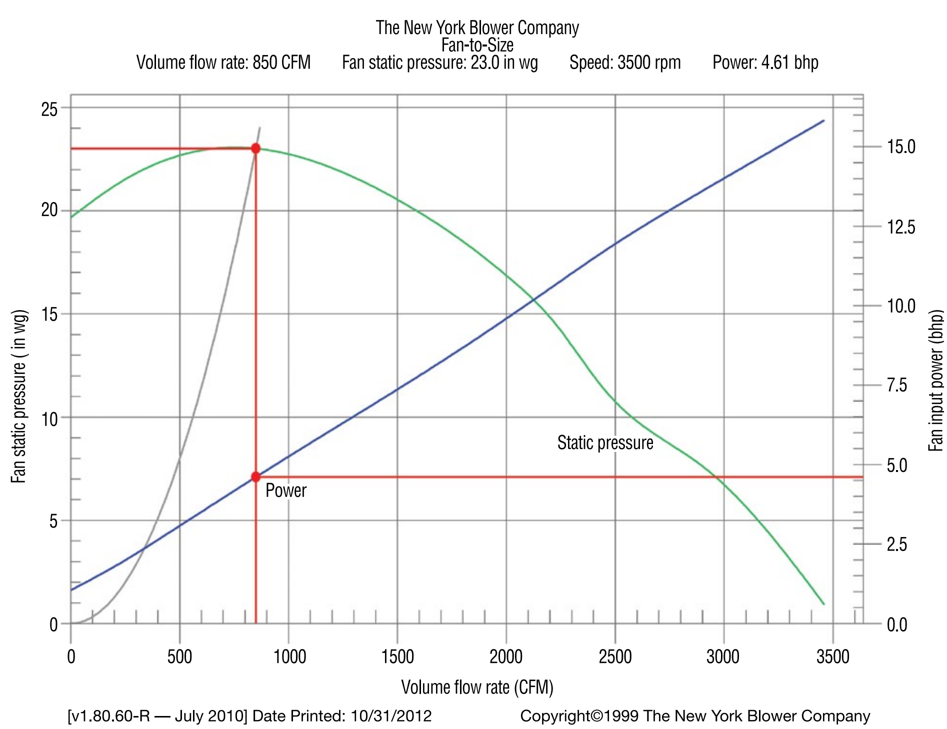
For induced draft systems, head loss on the suction side of the blower adds to that on the discharge side. In addition, the flow resistance of the ASP and biofilter for induced draft systems needs to be added in; as a rule, 6-inch water gauge is used for these. Formulas also exist for calculating the pressure drop across an orifice, in this case the holes in the pile pipes.

Simple programs for calculating head loss in component lengths of pipe are available online; calculations are run for the various sections of the piping system and then can be compiled in a spreadsheet to sum head losses, using different columns for different piping scenarios. Publications such as the "Heating Ventilating Air Conditioning Guide" have charts of friction loss in galvanized steel ducts.

With the piping system designed and head loss calculated, it is now possible to determine a blower to use. Aeration systems most often use centrifugal blowers, as these are recommended over axial fans for systems with back pressure caused by having long runs of piping or ducting. Manufacturers publish performance curves (example shown in Figure 1) to help select an appropriately sized blower. The performance curves plot static pressure versus flow rate. Simply match the flow rate desired with the pressure drop for the ASP system designed and see if the intersection point falls along the curve along the high part of it. If so, that blower is a candidate. In the example in Figure 1, the pressure blower has to overcome 23.0 in WG static pressure and produce 850 cfm of airflow, which requires a motor with 4.61 brake horsepower (bhp).

Piping materials that make up the blower exhaust system are an impor-

Figure 1. Sample manufacturer performance curve to plot static pressure vs. air flow rate.



tant consideration in induced draft systems because compost off-gases get pulled into the blower. Stainless steel for the wheel and housing is most resistant to corrosive chemicals in compost, but an aluminum wheel resists ammonia well enough for most applications (it also saves energy because it's lighter).

Usually located near the manifold, the blower can be bolted to a concrete pedestal or left unattached so it can be moved around as needed. A project the authors worked on at the wastewater treatment plant in Foley, Alabama had six ASPs and blowers located outdoors, and officials requested that the blowers be located together in a shed at the middle of the row of ASPs. While this can offer some advantages, it also adds to piping lengths, increasing costs and pressure losses and subsequent energy use. When piping to a blower, try to have straight piping sections of at least four times the wheel (impeller) diameter in length at the inlet and outlet to allow the airflow to fully develop. (in the example in Figure 1, the pressure blower had a wheel diameter of 24 inches, so at least 96 inches (8 feet) of straight piping is preferred).

It only makes sense that the output of a blower varies with its speed and that the blower output should be set for optimum composting performance. There are several ways to accomplish this — either set the blower at a constant speed or constantly vary its speed. Direct drive is the simplest form of blower, as these have the motor directly coupled to the blower, which will run at 1750 or 3500 RPM. Many blowers, especially larger sizes, have a pulley-and-belt drive that can be sized to achieve the desired speed. With a variable-frequency drive (VFD), the blower speed can be varied constantly according to input from oxygen and temperature sensors in the ASP. If a constant-speed blower is selected, the main method of controlling it is to operate it with a timer that cycles the blower on and off for the desired times. Using VFDs versus timers adds a few hundred dollars of cost to each blower, not to mention the complexities of dealing with sensors and associated wires; however running the fans constantly under a VFD-controlled scenario avoids the high spike electrical costs for fans constantly turning on and off.

In this age of green building and sustainability, many industries that pump fluids through pipes and ducts in their operations are going to larger-diameter pipes that result in lower head loss due to reduced flow velocity. Following this, a smaller blower or lower blower speed can be used for composting, resulting in lower electrical power use. It helps to understand fan laws here; one says that if the speed of a blower is increased, the flow output will increase proportionally, but the horsepower required will increase by the cubed value of the change in revolutions-per-minute (RPM). For example, a blower that puts out 300 CFM at 1750 RPM will draw 0.2 BHP. If the speed is doubled to 3500 RPM, it will put out 600 CFM but draw 1.6 BHP — 8 times as much!

Of course, the added cost of the larger pipes offsets the reduced blower cost and energy use. It is useful to calculate a payback that compares higher piping costs against lower energy use and blower cost for two or more alternatives. This completes the picture and allows the facility to select the best ASP aeration system for its composting operation and feel confident in understanding how it works. ■

A consulting mechanical engineer, Tom Gibson is president of Tom Gibson, P.E. Green Building Engineer (www.progressiveengineer.com/consulting.html) in Milton, PA and can be reached at tom@progressiveenginer.com. Craig Coker is a Contributing Editor to BioCycle and a Principal in the firm Coker Composting & Consulting (www.cokercompost.com), near Roanoke VA. He can be reached at ccoker@cokercompost.com.

BioCycle ARTICLE SERIES
AERATED STATIC PILE COMPOSTING

Aeration Floor Fundamentals

The most common type of aeration floor is a Pipe-On-Grade Sparger (left). In-floor type aeration floors (right) are almost always cast in concrete and provide a flat working surface.

This article series examines the considerations in forced aeration static pile composting, including the basics of aeration system design and operation, types of aerated static pile systems, and design issues to be evaluated.

Adequate air delivery and distribution are keys to an optimized composting process. In forced air systems, the aeration floor is a key element of that optimization.

Part IV

Craig Coker and Tim O'Neill

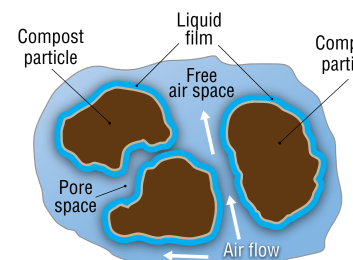
ACTIVE composting is an oxygen consuming, heat generating process primarily carried out by aerobic bacteria. Temperatures in energetic composting piles will rise rapidly and remain at levels that can inhibit these aerobes, slowing stabilization and increasing odor emissions.

There are two fundamental reasons that high temperatures inhibit efficient composting. First is the fact that high temperatures reduce the supply of oxygen to the aerobic bacteria, which require water, nutrients and oxygen to do their work. These conditions exist in the liquid film that surrounds the particles in a compost pile with adequate moisture (Figure 1). Oxygen, supplied to the free air space, must dissolve into this liquid film so the aerobes can respire. The solubility of oxygen in water goes down as temperatures go up — as they tend to early in composting process when the need for oxygen is highest (Sauer, 2013). In field studies, the authors of this article have measured a clear positive correlation between oxygen saturation levels in the liquid film layer and stabilization rates and odor control.

The second reason is that temperature determines the class of microbes that predominate in the composting process. The two classes of interest in active composting are mesophiles (moderate temperature loving) and thermophiles (high temperature loving). It has been well documented in peer-reviewed literature (Sundberg, 2005; Sundberg and Jonsson, 2008; Sauer, 2013) that when mesophilic temperatures are achieved early in the composting process, the pH rises to above 6 (a key performance indicator), nitrogen is more readily converted to nitrates, odor emissions are drastically reduced, and the rate of bio-oxidation of organic matter increases markedly.

On the other hand, when temperatures rise to, and are maintained in, the thermophilic range the opposite is true. Fortunately, composting is a robust process. A composting pile can spend a few days at the beginning of the active phase at elevated temperatures before it is cooled down to more mesophilic friendly temperatures without causing undue inhibition to the process or emitting unmanageable odors. It should not,

Figure 1. Air flow in a compost pile



however, spend weeks at thermophilic temperatures. Fortunately, temperature is the easiest composting parameter to measure.

FORCED AERATION FLOORS

Prolonged elevated temperatures are an indicator of inadequate pile aeration. Forced aeration, using either the aerated static piles or windrow methods, is one approach to supplying oxygen to the composting process. A key element in a forced aeration system is the aeration floor. It serves as the primary working surface, and distributes air through the compost pile. Keeping the aerobes working efficiently requires that the aeration floor must uniformly and reliably supply enough air to match heat production in the pile.

Aeration floors can be designed to drain away excess water. Mixes with significant food waste content tend to release large volume of leachate early in the process. In addition to being acidic and odorous, this liquid tends to occupy the pore spaces, shown in Figure 1, near the bottom of the pile. This inhibits airflow through, the supply of oxygen to, and removal of gasses from, the free air space. A well-designed aeration floor will serve to efficiently drain off and capture leachate to reduce excess moisture.

Aeration systems come in three basic types: positive, negative or reversing (which alternates between positive and negative). Positive aeration refers to a system where air is forced out of the floor into the material. Negative aeration refers to a system where air is drawn into the floor from the material. Each has its strength: positive aeration is the simplest to implement; negative aeration has the highest air emissions and leachate capture efficiencies; and reversing aeration provides the most uniform conditions throughout the depth of the pile.

There are many variations of aeration floors, but they can generally be organized into the following groups: On-Grade versus In-Floor, and Sparger versus Low Friction.

By far the most common type of aeration floor is a Pipe-On-Grade (POG) Sparger. This aeration floor consists of a series of pipes with a designed series of perforations placed on top of the working surface and connected to an aeration system. These pipes are generally pulled from under the pile before it is broken down, then replaced and reconnected prior to building a new pile. A pipe is a sparger if it uses high back pressure across the orifices to overcome the pressure loss along the pipe and thus get semi-uniform air distribution along the length of the pipe.

In-floor type aeration floors can be either sparger or low-friction. In either case they are almost always permanently cast in concrete and provide a flat working surface that does not interfere with the wheel loader or require regular operator intervention. An aeration floor is low-friction if it relies on a balanced low pressure design to distribute air uniformly. Low-friction aeration floors require only 25 to 50 percent of the fan horsepower required for the same air flow from a sparger floor, but they are somewhat more expensive to build.

Table 1. Process Indicators and the BMP Scale

0 On BMP Scale (Inhibited/odorous)	Process Indicators	10 On BMP Scale (Efficient/Low odors)
> 75° C (165°F)	Temperature	< 50°C (120°F)
< 5%	Oxygen	> 15%
< 5	pH	6.5 – 8
< 20	C:N Ratio	25 – 35
> 1,200	Density (lbs/cy)	800 – 900

QUALITY CONTROL MANAGEMENT

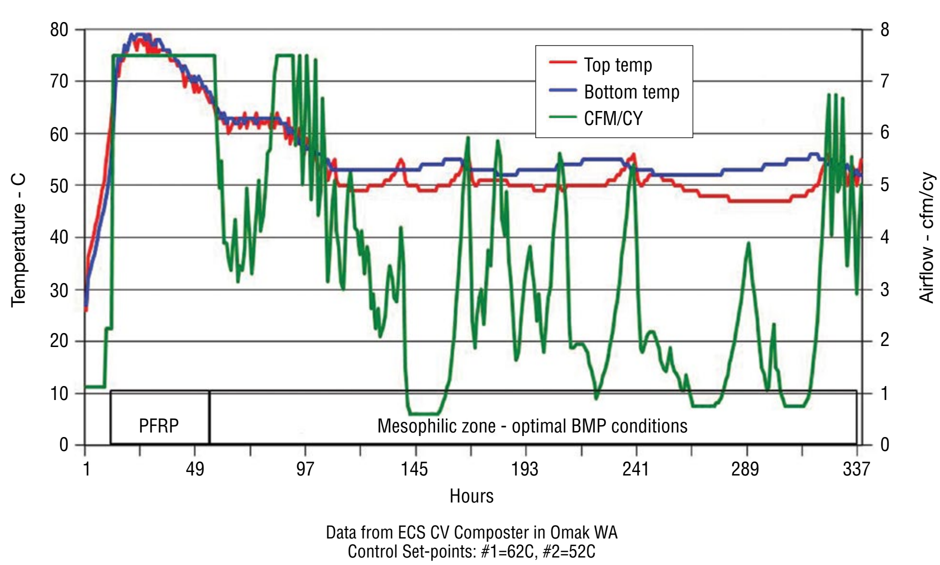
In quality control management, measuring is the first step. Key process indicators to measure for managing composting process quality are well established. These standard indicators are summarized in Table 1, which includes the addition of a "BMP Scale". This scale refers to how closely the conditions in the pile comply with the Best Management Practices value for each of these indicators. As the indicators move toward a score of "10" the biology in the pile becomes optimized and biostabilization becomes more efficient and odor emissions diminish. As it moves more towards "0", the facility will require a very odor tolerant location and lots of area to allow maturation of the final product over an extended period of time.

The first four BMP compliance indicators listed in Table 1 are largely determined by the effectiveness of the forced aeration system in general, and by the aeration floor in particular. The bottom two indicators, C:N ratio and density, are a function of the mix quality (see sidebar). How close to scores of "10" a composting facility needs to be successful depends on a range of factors. Most failed facilities have low scores in most categories. Insufficient aeration is one of the most common underlying factors.

Adequate aeration early in the composting process impacts the whole life cycle of the compost produced. Sunberg's research showed that using high aeration rates to control temperatures early in the active part of the composting cycle provided significant benefits to stabilization, odor control, and nitrogen conversion that endure beyond primary composting. This means that compost curing can be done effectively with little process management if primary composting is highly BMP compliant.

Maintaining BMP parameters is not a static activity. A compost pile is a highly dynamic microbial system with constantly varying rates of oxygen con-

Figure 2. Temperature control requires high peak aeration rates



sumption/heat production. Ideally the aeration system will match these dynamics by varying the amount of cooling air delivered to hold temperatures near a series of operator selected setpoints. Typically the first temperature setpoint needs to be high enough to achieve pathogen control (PFRP, >55°C for 72 hours), followed by a lower temperature setpoint that is more conducive to mesophilic bacteria.

Figure 2 is a graph of temperature and airflow rate versus time (airflow rate is measured in cubic feet per minute per cubic yard of pile volume, or cfm/cy). This is an example of an aeration system with a wide range of aeration rates and an adaptive temperature-feedback control system that responds to variations in heat generation rates. The control system is based on two temperature setpoints: an initial setpoint of 62°C and a second setpoint at 52°C. This data is from a 40-cy insulated vessel that composts a blend of biosolids and fresh deciduous wood chips. As temperatures exceed the initial setpoint of 62°C in less than 12 hours, the control system turns up the airflow (green line) to the peak rate of 7.5 cfm/cy. It takes another 40-plus hours to bring the temperatures down to the initial setpoint. Once PFRP is achieved, airflow is again automatically increased to bring the temperatures down to the second setpoint of 52°C. Thereafter the aeration control system responds to sudden and unpredictable changes in heat generation, sensed as small temperature changes, by rapidly varying the aeration from a low of 0.5 cfm/cy to peak rate of 7.5 cfm/cy. This dynamic control both limits high temperatures and avoids over-cooling.

If adequate air is supplied for cooling, then there is a surplus of oxygen. Typically, ten times as much air is required for cooling as is required to provide oxygen. In a well-aerated system the oxygen is always greater than 15 percent (normal oxygen content of air is 21%). For example, the measured oxygen concentration in the exhaust stream from the vessel in Figure 2 was consistently in excess of 18 percent.

Part V of this series will examine aeration floor design options and how they impact BMP process performance indicators, operations, and economics. ■

ASP Mix Quality

AERATED static piles (ASP) are normally not turned or agitated for one to four weeks at a time during active composting (pile homogeneity improves with more frequent turning). Because of this, it is critical that the mix ratio be correct to minimize odor emissions. Ensuring a C:N ratio above 20:1 will minimize the potential for releases of ammonia, which happens because there is a surplus of nitrogen relative to carbon in low C:N piles. Mix bulk density is often used as a surrogate measure of free air space (FAS) as heavy, dense piles (above 1,200 lbs/cy) are associated with low FAS values which inhibit oxygen transfer in the piles.

Craig Coker is a Senior Editor at BioCycle and CEO of Coker Organics Recycling (www.cokercompost.com) near Roanoke VA. He can be reached at ccoker@cokercompost.com. Tim O'Neill is the President of Engineered Compost Systems (ECS), an compost technology provider based in Seattle, WA. He can be reached at Tim@compostsystems.com.

REFERENCES

Nick Sauer and Eric Crouch, "Measuring Oxygen in Compost", *BioCycle*, December 2013, Vol. 54, No. 12, p. 23.

Celia Sundberg, "Improving Compost Process Efficiency by Controlling Aeration, Temperature and pH", Doctoral Thesis, Swedish University of Agricultural Sciences, Uppsala Sweden, 2005.

Celia Sundberg and H. Jonsson, "Higher pH and faster decomposition in biowaste composting by increased aeration", *Waste Management* 28(3): 518-526, 2008.

BioCycle
ARTICLE SERIES
AERATED STATIC PILE COMPOSTING

Composting Aeration Floor Functions And Designs

This article series examines the considerations in forced aeration static pile composting, including the basics of aeration system design and operation, types of aerated static pile systems, and design issues to be evaluated.

Adequate air delivery and distribution are key to an optimized composting process. Design considerations are provided.

Part V

Craig Coker and Tim O'Neill

PART IV of this series ("Aeration Floor Fundamentals") discussed how performance of the aeration floor is key to maintaining Best Management Practices (BMP) conditions during active composting. The aeration floor is also one of the more expensive elements of an aerated composting process. The initial capital cost is often the main driver when selecting an aeration floor technology. But if the facility is planned to operate more than 5 years, the full life-cycle cost should be considered along with the performance requirements. Another important element is matching the aeration floor to the type of aeration system (positive, negative, reversing).

These two considerations will be discussed toward the end of this article. First, it is important to review a standard set of performance metrics to use when evaluating any aeration floor design.

AERATION FLOOR PERFORMANCE METRICS

Five main performance metrics to consider when designing and evaluating an aeration floor include: airflow uniformity, peak aeration capability, ability to manage leachate, ease of operations and maintenance, and longevity. Each is discussed below.

Air Flow Uniformity

Airflow uniformity refers to how evenly the forced air is distributed through the pile. The metric is "maldistribution," which assigns a percent variation of airflow across the aeration floor (example in Figure 1). While no design is perfect, one of the authors (O'Neill) has measured maldistribution in aeration floors ranging from a high of over +500 percent to a low of about +10 percent. Low maldistribution values (<+20%) more readily achieve consistent temperatures and oxygen levels throughout the pile (see Part IV of this article series). When air distribution is not uniform, significant areas of a pile's biology will be inhibited by high temperatures, low oxygen, and uneven moisture levels represented by the low end of the BMP scale.

Relatively uniform air distribution

Figure 1. Maldistribution of air flow

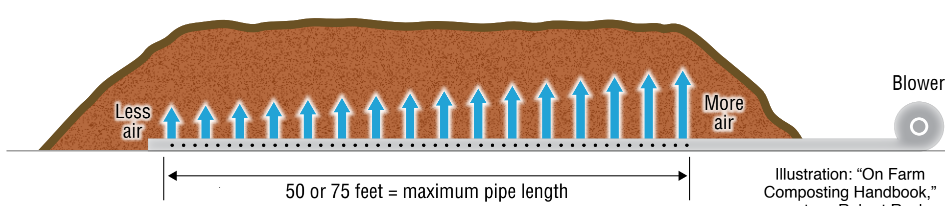


Illustration: "On Farm Composting Handbook," courtesy Robert Rynk

Table 1. Airflow rate variation during composting process

Process Day	Aeration Rate (cu. ft./minute (cfm)/ cu. yd. of pile size)
1 – 10	3 – 6
10 – 20	1.5 – 3.0
20 – 40	0.5 – 1.5

can be achieved using a pipe-on-grade (POG) aeration floor in modest sized piles (i.e. less than 70 feet long) by observing a few simple design rules:

- Maximum spacing between pipes should be less than two-thirds the height of the pile
- Ratio of pipe length to internal diameter should be under 150 (e.g., for a 50-foot length of aeration pipe, the internal diameter of the pipe is at least 4 inches)
- Air velocities in the sparger pipes are below 2,800 feet/minute
- Total combined area of all orifices are under half of the cross-sectional area of the POG pipe

A simplified design template for designing POG pipes is presented on p. 32-36 in the *On Farm Composting Handbook* (Rynk, 1992).

Once either larger aeration floors with high aeration rates and/or in-floor aeration designs are considered, a numerical model should be developed to test and optimize the design. By varying the parameters in the model, the designer can balance air distribution uniformity and power use.

Figure 2. In-floor sparger pipes

Peak Aeration Capacity

Peak aeration capacity determines how quickly the temperature in a newly constructed aerated static pile (ASP) can be brought down to near mesophilic levels. Generally, food waste/green waste composting mixes start off with low pH due to the buildup of organic acids. Mesophilic range bacteria are best able to process organic waste at low pH. Thermophilic range bacteria are rate limited at low pH. ASPs with low peak aeration capability tend to remain above BMP compliant temperatures for the first two to four weeks with lasting negative effects. When early stage ASP temperatures are controlled by sufficiently high peak aeration rates, regrowth of mesophilic bacteria are able to oxidize inhibitory organic acids and raise the pH to within the efficient BMP range of 6.5 to 8, where more rapid stabilization can occur (see Figure 2 in Part I or in the online version of Part II).

The peak aeration rate required to affect cooling depends largely on the amount of bioavailable carbon in the feedstocks; this tends to be highly variable. Generally feedstocks are most energetic early, but the heat output is not linear and varies somewhat randomly over time and certainly between batches (see Figure 2 in Part I). Table 1 provides design guidelines for peak aeration rates at different process stages. An aeration system capable of providing adequate peak aeration rates, if controlled with temperature feedback, can keep the process indicators of temperature, oxygen and pH near optimum conditions without overcooling the pile.

Peak aeration rate is thus a key element of aeration floor design. The design goal should be to provide the peak aeration rates shown in Table 1 with uniform distribution of airflow, and without unduly high operating pressures that waste fan power. Lower pressure aeration systems conserve energy; as operating pressures increase, more fan power is required to move more air into the pile. A highly efficient aeration floor and aeration system can operate with fan pressures below 8.0 inches and still deliver aeration rates as high as 5 cfm/cy (cubic ft/minute/cubic yard).

Figure 3. Trench covers removed for maintenance

Leachate Management

Leachate management is an important aeration floor design consideration since these liquids are highly odorous, carry solids that can clog pipes and sumps, and, if not drained, can saturate the bottom of the piles, inhibiting the biology as described above. The degree to which leachate must be managed depends primarily on precipitation amounts, types of feedstocks and regulations. Collecting these liquids is challenging, since water doesn't flow under piles very predictably (compost itself forms dams and channels) and the entrained solids require regular cleaning/flushing from wherever they are captured.

All negatively aerated floors (where air is pulled through the pile into the floor) will collect leachate and condensate and require special attention to drainage design. Positively aerated floors leave most of the liquid to pool and run off of the working surface and require more auxiliary drains. However, even positively aerated in-floor systems will collect enough water and solids to be a nuisance and will eventually plug if the design doesn't allow for cleaning or they are neglected. The bottom line is that leachate will accumulate in all aeration floors and in most applications there must to be a method to capture and control those liquids, and to have access to all below grade components to remove solids.

Operations and Maintenance

Ease of operations and maintenance is the key determinant of the aeration floor operating expenses (OPEX) and reliability. A well-designed in-floor aeration system will have much lower OPEX than a typical POG system, which requires disconnection/removal/replacement with every batch. Some hybrid POG systems are left on the pad connected and buried in a woody layer while wheel loaders work over the top. In the authors' experience, these systems have been prone to serious airflow distribution problems, plenum and pipe clogging, and pipe damage (often undetected for long periods of time).

In-floor aeration system maintenance includes flushing and removing solids, and occasional repair of damaged surface floor elements caused by wheel loaders. These floors need to be easily accessible for pressure washing, scooping or suctioning to remove solids. For in-floor sparger pipes (example in Figure 2), this requires access at both ends of every straight run. For in-floor aeration trenches, the trench covers themselves must be removable. Fasteners for trench covers should be stainless steel with nongalling threads so that they can be serviced over the lifetime of the facility. An example of a trench with the covers removed for annual cleaning is shown in Figure 3.

Additional maintenance issues associated with a POG system include repairing pipe damaged during pile building and tear down activities, "ovalling" (misshaping) of pipes due to pile temperatures and pressures, and damage to the mechanism that con-

Table 2. Aeration floor suitability to three types of aeration (A = very suitable, F = not suitable)

	Pipe-On-Grade	In-Floor Spargers	In-Floor Trench
Positive/Forced only	A	A	A
Negative/Induced only	D	F	B
Reversing	C	C	A

nects the pipes to the aeration system. Large facilities that use POG aeration floors report needing almost one full-time operator dedicated to the repair and replacement of damaged pipe.

Longevity

Longevity is a key differentiator between an in-floor and an on-grade aeration floor. A well-designed in-floor system will last decades while POG systems have far shorter life spans.

The best choice for POG pipe material is heavy walled (DR 11 or 17) high-density polyethylene (HDPE). This material can handle high temperatures, friction, and even the occasional crushing by a wheel loader. The pipe ends should be heavily reinforced to withstand the stress of pulling pipe out from beneath a pile. The typical lifetime of an HDPE sparger pipe is 12 to 24 months. At very small facilities other pipe materials can be considered such as PVC (polyvinyl chloride), ABS (Acrylonitrile-Butadiene-Styrene) or thin walled HDPE, but these pipes should generally be considered disposable as they are not rated for the temperatures encountered and are easily fractured.

If an in-floor aeration system is going to deliver a long service life, suitable materials must be used in its construction. Buried pipe that will be exposed to elevated temperature and/or stress from above should be fused HDPE, which is tough, and not PVC, which is brittle. In addition, aeration components near the working surface need to be offset below that surface to not be damaged by wheel loaders, but not too deeply offset or they will collect material and plug more often. All metal components exposed to compost, leachate or exhaust airflows should be at least 304 stainless steel to hold up to the corrosive environment.

AERATION FLOOR SELECTION

A number of questions need to be answered in order to select the best value aeration floor for a given facility. The first is: how compliant with BMPs does the facility need to be? Each facility has unique performance requirements regarding odor control, regulatory compliance, and product quality. Part I discussed how the aeration floor design impacts the composting process variables that drive this performance. The other questions to be answered revolve around available land and throughput requirements, operational considerations, type of aeration system to be implemented, and, of course, the economics.

When space is limited with regards to throughput requirements, in-floor systems are generally the best choice since they require less floor space per ton than a POG system. POG systems require a significant area in front of the pile for the wheel loader to pull out a pipe. Unless small diameter pipe is used (and this reduces the workable pile length as described in Part I), the pipe-pulling area required is roughly the length of the POG pipe plus the length of the wheel loader.

Operational cost considerations drive the choice of aeration floor. These include aerated static pile size, labor availability, and requirements for leachate management. POG aeration floors are most successful at facilities with relatively short pile lengths, low cost labor, and modest requirements for leachate management.

Compost aeration systems can be positive (air forced from the floor up), negative (air sucked into the floor), or reversing (alternating between the two). This choice is driven by need to control emissions (negative) and/or the desire to provide more uniformly BMP compliant conditions in the pile (reversing). Table 2 offers a qualitative assessment by the authors of how suitable the different floor types are for these three different aeration methods.

As indicated in Table 2, positive aeration is suitable for the three floor types listed; the positive pressure tends to minimize clogging in the sparger orifices and in-floor trench systems resist plugging by the pressure of the air and the more open nature of the trench air channels. Negative-only aeration systems are more problematic. The high air velocities at the orifices of both the POG and in-floor spargers tend to pull in solids and cause plugging. The in-floor trench, on the other hand, shows minimal plugging when used for all negative application. This is due to the much lower air velocities through the orifices and the great number of orifices compared to a sparger floor. However, even an in-floor trench system using only negative aeration requires a well-structured BMP mix.

Reversing aeration works somewhat better for both sparger variants since the floors can be set in positive while piles are being built and during initial settling to slow down plugging once the aeration system begins cycling from positive to negative. But even with positive aeration cycles, these floors will typically show measurable decrease in flow over a period of 4 to 8 days and require more frequent clearing of the orifices.

Understanding the full economic impact of aeration floor options requires a life cycle cost analysis. This relatively simple calculation uses estimated lifespan, and the costs of construction, operation (labor, repair, maintenance, electrical power) and financing in order to compare the Net Present Value of different options. A free calculator that can be adapted for this purpose is the Harvard Life Cycle Calculator, available at https://green.harvard.edu/topics/green-buildings/life-cycle-costing

Table 3 summarizes the major economic and operational factors that should be considered when selecting an aeration floor. The cost analysis was part of a detailed design study commissioned to help a client determine which

Table 3. Impact of aeration floor utilized on capital and operating costs, and various operational parameters (A = very suitable, F = not suitable)

	Pipe-on-Grade (POG)	In-Floor Spargers	In-Floor Trench
Capital cost ($/tpy capacity)[1]	5.76	9.49	11.69
Additional operating cost ($/ton)	3.00 – 5.00	0	0
Aeration BMP[2]	C	B	A
Leachate management[2]	F	F	A
Fan power use (cfm/hp)[3]	325	275	500
Longevity (years)	1 – 2	20+	20+

[1]Sized for 55,000 tons/year, all concrete floors; [2]Rating/value assessment for meeting this parameter; [3]Positive aeration, includes whole aeration system. For negative aeration, reduce efficiency by 30% – 50%

type of floor would best fit the business model and risk tolerance at a facility intended to compost 55,000 tons/year of source separated organics. This facility was in a dry rural area with yard trimmings as the primary feedstock; the client chose the in-floor sparger with positive aeration.

As increasingly challenging feedstocks are being diverted for composting in more populous areas, the need for more BMP-compliant composting processes is growing. The degree of BMP compliance is strongly determined by how well the design of the aeration system conforms to composting science. Making a well-informed selection of the aeration system and aeration floor better insures facility performance and long-term economic success. ■

Craig Coker is a Senior Editor at BioCycle and CEO of Coker Organics Recycling (www.cokercompost.com) near Roanoke VA. He can be reached at ccoker@cokercompost.com. Tim O'Neill is the President of Engineered Compost Systems (ECS), an compost technology provider based in Seattle, WA. He can be reached at Tim@compostsystems.com.

REFERENCES

R.T. Haug, *The practical handbook of compost engineering*, Lewis Publishers, Second Edition, 1993.

Rynk, R., "On-Farm Composting Handbook", NRAES-54, 1992.