United States
Environmental Protection
Agency

Biosolids Technology Fact Sheet

Multi-Stage Anaerobic Digestion

DESCRIPTION

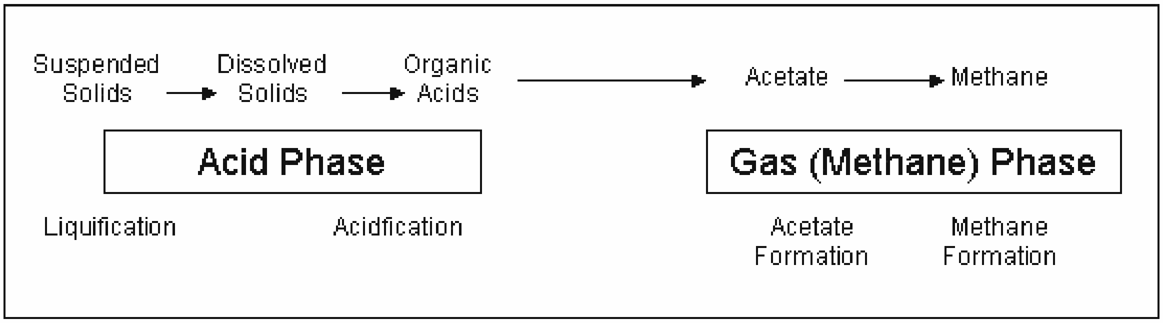
Anaerobic digestion is a naturally occurring biological process in which large numbers of anaerobic bacteria convert organic matter into methane and carbon dioxide (a mixture called biogas) in the absence of air. It is a widely used biological process for treating wastewater solids. This process stabilizes the organic matter in wastewater solids, reduces pathogens and odors, and reduces the total solids/sludge quantity by converting part of the volatile solids (VS) fraction to biogas. Anaerobic digestion results in a product that contains stabilized solids, as well as some available forms of nutrients such as ammonia-nitrogen.

The process of anaerobic digestion can be divided into three separate steps, each of which is performed by a different group of microorganisms:

- *Hydrolysis*, during which the proteins, cellulose, lipids, and other complex organics are broken down into smaller molecules and become soluble by utilizing water to split the chemical bonds of the substances
- *Volatile acid fermentation*, during which the products of hydrolysis are converted into organic acids through the biochemical processes of acidogenesis (where monomers are converted to fatty acids) and acetogenesis (the fatty acids are converted to acetic acid, carbon dioxide, and hydrogen)
- *Methane formation*, during which the organic acids produced during the fermentation step are converted to methane and carbon dioxide.

The efficiency of each step is influenced by the temperature and the amount of time the process is allowed to react. For example, the organisms that perform hydrolysis and volatile acid fermentation (often called the acidogenic bacteria) are fast-growing microorganisms that prefer a slightly acidic environment and higher temperatures than the organisms that perform the methane formation step (the methanogenic bacteria). The acidogenic bacteria are also less sensitive than the methanogenic bacteria to changes in organic strength and composition in the incoming feed stream. Therefore, although many wastewater treatment plants have traditionally performed anaerobic digestion processes in a single tank (in a process called single-stage anaerobic digestion) at a constant temperature, some facilities have separated the process into multiple stages, by physically separating the stages or by controlling the process to separate the stages in time, or both. This approach allows the facilities to optimize the various stages of the anaerobic digestion process to meet their needs.

The standard multi-stage anaerobic digestion system is a two-stage acid/gas (AG)-phased system, in which the acid-forming steps (hydrolysis and volatile acid fermentation) are physically separated from the gas-forming step (methane formation) by being conducted in separate digestion tanks. The first stage, known as the primary or acid phase digester, consists of the hydrolysis and the first acid-production step, in which acidogenic bacteria convert organic matter into soluble compounds and volatile fatty acids. The second stage, known as the secondary or methane stage digester consists of further conversion of organic matter to acetic acid through acetogenesis, as well as the methane formation step, in which methanogenic bacteria convert soluble matter into biogas (primarily methane; see Figure 1). The methanogenic step also produces other by-product gases, including hydrogen sulfide, nitrogen gas, and several other gases. In a typical two-stage system, the primary digester is heated to optimize performance of the hydrolytic and acidogenic bacteria. The secondary digester is not normally equipped with mixing or heating facilities because of the exothermic (heat-producing) nature of the methane formation reaction.



Source: Wilson, et. al, 2005

Figure 1. Standard Multi-Stage Anaerobic Digestion System

An alternative method for designing the system is to separate the stages over time by adding different levels of heating at different times in the process by a process called temperature-phased anaerobic digestion, or TPAD. As described earlier, hydrolysis and acidogenesis can be enhanced by increasing the operating temperature; however, acetogenesis is adversely affected by high operating temperatures (Chang, et al. 2004). If the system is heated to enhance hydrolysis and acidogenesis, the resulting volatile acid production can overwhelm the ability of the slower-reacting acetogenic and methanogenic bacteria to convert the volatile acids, resulting in increased pH and inhibited acetogenesis and methanogenesis (Chang, et al. 2004). Therefore, controlling the temperature can be critical in optimizing system performance.

Numerous facilities use some form of TPAD. For example, in 2002 the wastewater treatment facility in Waterloo, Iowa, rehabilitated its existing anaerobic digestion system to operate as a TPAD system, in which the first digesters were operated in the thermophilic range (50–60 °C [122–150 °F]) to promote pathogen destruction with the intent of producing Class A biosolids, while subsequent digesters were operated in the mesophilic range (30–38 °C [85–100 °F]) to reduce VS (Iranpour and Windau 2004). This type of system can be abbreviated as a TPAD-TM, where the *T* represents the thermophilic first stage, and the *M* represents the mesophilic second stage.

Facilities can separate these stages in both space and time by operating multiple digesters in series, to increase control over the process and enhance the results even further. Facilities in Tacoma, Washington, Inland Empire, California, and Calgary, Alberta, Canada, have gone to three-phased processes. Table 1 provides several examples of wastewater treatment facilities that use different types of multi-stage processes (Wilson 2003 and personal communications).

APPLICABILITY

Multi-stage anaerobic digestion systems are potentially applicable for all wastewater treatment systems, provided that the solids can be delivered to the system at an acceptable concentration. These can include both new installations and retrofits. In fact, much of the current research into anaerobic digestion is directed toward retrofitting multi-stage systems into facilities where single-stage processes are already present (Cumiskey 2005; W. Parker, personal communication, 2006).

The primary factor in determining whether a multi-stage anaerobic digestion process is feasible for a system is the feed solids concentration. Because a multi-stage process can be sensitive to changes in the feed solids, it might not be feasible if the characteristics of the feed solids concentrations vary significantly. The VS content in the feed should preferably be at least 50 percent, and the feed should not contain substances at levels that may inhibit the biological processes associated with anaerobic digestion (see Table 2). Wastewater residuals containing lime, alum, iron, and other substances can be successfully digested as long as the VS content remains high enough to support the growth of microorganisms.

Table 1. Example Wastewater Treatment Facilities with Multi-Stage Anaerobic Digestors

Plant	System Type
Woodridge WWTP, DuPage County, IL	Two-stage AG-MT
Elmhurst, IL	Two-stage AG-MM
Back River, Baltimore, MD (pilot)	Two-stage AG-MM
Inland Empire (RP-1), Ontario, CA (farm manure)	Three-stage AG-MTM
Waterloo, IA	Two-stage TPAD-TM
Waupun, WI	Two-stage TPAD-TM
Rockaway, NY	Two-stage TPAD-MT
Pine Creek WWTP, Calgary, Alberta, Canada (pilot)	Three-stage TPAD (multiple options being researched)
Tacoma, WA	Heated aerobic stage (71° C [160° F]) + Three-stage TPAD-TMM

Table 2. Substances with Potential to Cause Biological Inhibition in Anaerobic Digestion

Substance	Moderately Inhibitive (mg/L)	Strongly Inhibitive (mg/L)
Calcium	1,500–4,500	8,000
Magnesium	1,000–1,500	3,000
Sodium	3,500–5,500	8,000
Potassium	2,500–4,500	12,000
Ammonia Nitrogen	1,500–3,000	3,000
Copper	—	50–70 (total)
Chromium VI	—	200–250 (total)
Chromium	—	180–420 (total)
Nickel	—	30 (total)
Zinc	—	1.0 (soluble)

ADVANTAGES AND DISADVANTAGES

The major advantages of multi-stage anaerobic digestion systems versus single-stage anaerobic digestion systems is that multi-stage systems can optimize the various steps in the process by separating them in space or time and optimizing the specific conditions under which the various steps take place. As described above, they can also allow a facility to adopt a specific system configuration to meet its goals. For example, if the facility wants to produce Class A biosolids, it might require a thermophilic stage; however, if volume reduction is its primary goal, only mesophilic stages may be required (W. Parker, personal communication, 2006).

The major disadvantage of multi-stage anaerobic digestion systems is that they have higher operation and maintenance (O&M) requirements than single-stage systems. In addition, they can be more expensive than single-stage systems, although this is more of a factor when retrofitting into multi-stage systems.

An expanded discussion of the advantages and disadvantages of multi-stage versus single-stage anaerobic digestion systems follows:

Advantages

Gas Recovery and Storage. Multi-stage systems can be optimized to maximize the amount of gas they produce in the digestion phase. The gas produced from the anaerobic digestion of biosolids is typically composed of 55 to 70 percent methane and approximately 25 to 30 percent carbon dioxide, with the remaining fraction composed primarily of nitrogen, hydrogen, and hydrogen sulfide (USEPA 1979). Typical digester gas exhibits a heat content between 18,630 and 26,080 thousand Joules per cubic meter (kJ/m^3) or between 500 and 700 BTU/ft^3, which is approximately two-thirds the heat content of the natural gas delivered by gas utilities. Therefore, digester gas can be an economical energy source for plant operations. It can be temporarily stored and/or mixed with natural gas through the pipeline system for in-plant use as a source for heat, electricity, or steam. It is ideal as fuel to fire hot water boilers, internal combustion engines, heat drying equipment, and incinerators. Some plants scrub their digester gas to reduce the levels of carbon dioxide, hydrogen sulfide, siloxane, and other gases and in several cases have marketed the gas as a high-value natural gas source to their local gas utility systems.

Biosolids Quality. Multi-stage anaerobic digestion systems that use a thermophilic stage can produce biosolids that meet Class A pathogen reduction requirements. Much of the current research into anaerobic digestion is devoted to pathogen control through temperature phasing and pretreatment of waste through processes like enzyme hydrolysis prior to its anaerobic digestion. For example, recent research by the City of Los Angeles indicates that their product resulting from systems operated at thermophilic temperatures achieved Class A status and had lower odor than the product produced by mesophilic processes. In addition, their results indicated that the odor concentrations in solids digested using mesophilic temperatures continued to increase as the biosolids went through the digestion process and even after they were applied on farmland. (Material produced by digestion at mesophilic temperatures and received at their land application site had odor concentrations 10 times higher than the material being introduced into the centrifuges for dewatering.) In contrast, the odor content of material subjected to thermophilic digestion temperatures decreased by about 70 percent by the time it reached the land application site (Haug et al. 2002). Enzyme hydrolysis is being heavily researched in Europe. Additional discussion of pretreatment through enzyme hydrolysis is presented later in the "Design" section.

Other advantages of multi-stage anaerobic digestion versus single-stage anaerobic digestion processes include:

- Multi-stage systems require less digester volume to handle the same amount of input volume because they have lower retention times and allow higher loading rates than single-stage systems.
- Multi-stage systems have achieved VS reduction, which provides better odor control.
- A multi-stage system can be configured to reduce foaming problems. (See discussion of foaming in the "Operation and Maintenance" section below.)
- Multi-stage systems reduce the short circuiting of solids by separating the stages and optimizing the retention time in each stage.

Disadvantages

- The piping requirements for a multi-stage system, operation, and maintenance are more complex than those for a single-stage system.

DESIGN CRITERIA

Location in the Solids Processing Train

Multi-stage anaerobic digestion is typically located in the solids processing train after thickening but before dewatering. Thickening of the solids prior to digestion is beneficial because it reduces the biomass volume, digester size requirement, supernatant volume, and heating requirements (WEF 1998).

Solids Feed Rate

The solids feed rate is typically 5 to 6 percent of the mixed solids retention range.

Organic Loading

Typical VS loading rates for both mesophilic and thermophilic multi-stage systems are in the 482–642 kg/m^3/day (30–40 lb/ft^3/day) range, which is significantly higher than the average of 2.57 kg/m^3/day (0.16 lb/ft^3/day) for single-stage anaerobic digester systems (Sieger 2001).

Solids Retention Time

As discussed earlier in the “Description” section, solids retention time (SRT) is a critical factor in the design of a multi-stage anaerobic digestion system. High SRTs increase the digestion but reduce the rate of throughput for the system. Therefore, each facility must determine the optimum SRT to achieve the required amount of digestion while also maximizing the facility throughput.

Because the stages are optimized to maximize digestion, the SRTs of multi-stage systems are typically shorter than those of single-stage systems. For example, Sieger (2001) reported an average SRT of approximately 20 days for mesophilic single-stage systems, while the SRTs for multi-staged systems typically ranged between 14 and 18 days.

In general, the SRT for a multi-stage system is determined by the required end-product and the sequence of the phasing. For example, if the facility is producing Class B biosolids, it might use a lower SRT than a facility producing Class A biosolids using a similar configuration.

A summary of typical SRTs and VS loading rates is provided in Table 3.

Heat Exchangers

Temperature is important in determining the rate of digestion. The design operating temperature establishes the minimum SRT required to achieve a given amount of VS reduction. As described above, most anaerobic digesters currently in operation are designed to operate in the mesophilic temperature range, although many current designs for multi-stage systems include phases operated at thermophilic temperatures—through TPAD systems with thermophilic processes.

Typical auxiliary heating methods include steam injection, internal heat exchangers, and external heat exchangers. External heat exchangers are the most common because of their flexibility and the ease of maintaining their heating surfaces. Internal coils and heat-jacketed draft tube mixers can become caked and effectively blocked, necessitating removing them or taking the digester out of service to empty and clean the system. Steam injection results in dilution of the digester contents and can be energy-inefficient.

Table 3. Comparison of Anaerobic Digestion Processes

Digestion Process	SRT per Tank at Max Month (days)	Total SRT at Max Month (days)	Operating Temperature Regime	VS Loading Rate at Max Month ($lb/ft^3/day$)	Pathogen Level Produced
Single-Stage Mesophilic	20	20	M	0.16	Class B
Staged or Extended Thermophilic	15/1.5/1.5	18	T	0.30	Class A[a]
TPAD	5/10	15	T/M	0.30	Class A[a, b]
ATP[c]	1.5/15	16.5	T/M	0.30	Class A
Two-Phase	2/12	14	M/T; T/M; T/T; or M/M	0.40	Class A[d]
Pre-Pasteurization	30 min./15	15.02	~70 C/M	0.40	Class A

Source: Adapted from Sieger 2001.
Notes:
[a] Believed to meet Class A requirements, but formal pathogen equivalency has not been approved by EPA.
[b] One process has been approved as a site-specific process by EPA, but the technology has not been approved for national equivalency for Class A.
[c] Aerobic Thermophilic Pretreatment.
[d] Testing may proceed on variations of feed and temperature of each phase.

Mixing

Auxiliary mixing of the digester contents is beneficial for reducing thermal stratification, dispersing the biosolids for better contact with the microorganisms, reducing scum buildup, diluting levels of any inhibitory substances or adverse feed characteristics, and retaining inorganic material (grit) in suspension (WEF 1995). Without adequate mixing, the digestion process can be short-circuited and solids that have not been sufficiently digested might be prematurely discharged. Such solids will not be properly stabilized and might not be suitable for the intended end use.

The three mixing methods that have typically been used are mechanical mixing, hydraulic mixing, and gas recirculation.

Mechanical mixing includes the use of impellers, propellers, and turbine wheels to mix the digester contents.

Hydraulic mixing is accomplished by recirculating digester content through use of an external pump network. The hydraulic mixing can pump the digester contents from the lower half of the digester to the top of the digester to potentially stop the formation of a significant scum layer, which can be a nuisance or detrimental to digester operation.

Gas recirculation systems use the digester gas produced by the anaerobic digestion process to mix the digester contents. The gas is compressed and recirculated through the tank to promote mixing. The gas can be introduced into the tank through one of several methods, including:

- Lances mounted on the inside of the tank cover so they project down into the tank
- Diffusers mounted on the floor of the tank
- Draft tubes in the tank
- Bubble guns mounted inside the tank

The type of mixing device suitable for any digester depends on the design (vessel and cover) and size of the digesters.

Types of Covers

It is necessary to cover the digesters to maintain anaerobic conditions. In addition to keeping ambient air out, the covers prevent digester gas from being released and also reduce the amount of heat loss to the atmosphere. Anaerobic digester covers can be fixed or floating. Fixed covers are flat, conical, or dome-shaped and are constructed of reinforced concrete or steel. Floating covers can rest directly on the liquid surface or float on the gas and be supported by side skirts at the side of the tank.

The appropriate type of cover for any given application depends on the design and size of the digester. Both fixed and floating covers have advantages and disadvantages. For example, floating covers rise and fall with the liquid level in the digester and therefore prevent formation of a vacuum, which could damage the vessel or the cover. Floating covers also prevent air from being drawn into the digester during solids removal. In contrast, a fixed cover is often easier to design, requires less maintenance, and is less prone to develop gas leaks.

Enzyme Hydrolysis Pretreatment

In January 2002 legislation was enacted in the United Kingdom (UK) that required pathogen reduction in municipal wastewater sludge for the first time. This new requirement led many utilities to search for methods to optimize their existing anaerobic digestion systems (Cumiskey 2005), particularly mesophilic digesters, which included the majority of operating systems in the UK at that time. Investigations by United Utilities (UU) in the UK indicated that the major pathway for killing pathogens in mesophilic anaerobic digesters was solubilization or hydrolysis (Mayhew et al. 2004). In anaerobic digestion, hydrolysis occurs before the conversion of organic particulate matter to organic acids. UU found that pathogen reduction could be improved, and could be achieved at much lower temperatures (mesophilic temperatures instead of thermophilic temperatures) by separating the hydrolysis stage from the mesophilic anaerobic digestion stage (Mayhew et al. 2004). Therefore, UU developed a specialized plug flow enzymic hydrolysis process to pretreat the sludge before anaerobic digestion. The enzyme hydrolysis step breaks down cell wall lipoprotein structures (Kelly 2003), enhancing the digestion process. This process results in a better energy balance and the enhanced digestion increased biogas production relative to other processes. UU uses a plug-flow configuration that operates at 42 °C (108 °F) with a 2-day hydraulic retention time. UU began installing the enzyme hydrolysis method in its facilities, including facilities in Macclesfield, Bromborough, Crewe, and Blackburn. Initial tests at the Macclesfield facility show that the enzymic hydrolysis step results in a 10^4 reduction in *E. coli.* The enzyme hydrolysis process in Bromborough enables the plant to operate at 4.0 kg VS/m^3/day (250 lb VS/ft^3/day) while also producing a high-quality product that meets the new standards. The plant has also increased its gas production from 4,500 m^3/day to 5,500 m^3/day (158,916 ft^3/day to 194,231 ft^3/day) (Monsal 2004).

PERFORMANCE

Multi-stage anaerobic digestion can achieve superior performance relative to single-stage conventional digestion for most wastewater solids and for all loading rates. In addition, this increased performance can be achieved with smaller digester volumes because of the higher loading rates that can be achieved with multi-stage digesters. Compared to single-stage systems, the multi-stage process achieves higher VS reduction with shorter residence times. Typical VS reduction for a first-stage digester ranges from 40 to 60 percent, and up to 5 percent additional reduction can occur in subsequent stages. Multi-stage systems also produce more biogas of a higher quality (as measured by its methane content) than that produced by single-stage processes. Finally, these systems reduce, and potentially eliminate, the foaming problem that often occurs in single-stage systems.

Case studies highlighting the performance of several multi-stage anaerobic digestion facilities follow.

Woodridge WWTP, DuPage County, Illinois

The Woodridge wastewater treatment plant (WWTP) was converted from its original single-stage process to a two-stage AG-MT anaerobic digestion system in the late 1980s in an attempt to control foaming problems in the old system. To convert the facility to a two-stage process, a mesophilic acid-stage digester was added to the existing digestion facility, which was converted to a thermophilic gas-phase digester. The new mesophilic acid-stage digester receives a feed of 46,000 GPD at a 4–5 percent solids content, with approximately 11,325 kg/day (25,000 lb/day) of suspended solids and 9,060 kg/day (20,000 lb/day) of volatile suspended solids. This stage has a retention time of approximately 1 day. After passing through this stage, the biosolids flow to the methane-phase digester, which operates at a thermophilic temperature of approximately 52 °C (126 °F) and produces approximately 190,000 standard cubic feet (SCF) of gas per day with an average methane content of 64 percent.

The overall VS reduction averages approximately 65 percent. During the first 4 months of 2000, fecal coliforms were reduced by an average of 99.996 percent. The facility experiences no foaming, and the digested sludge is highly desirable as a soil enhancer for agricultural purposes. The digester gas is recirculated to power the digesters, and excess gas is used to produce electricity.

Inland Empire Regional Water Recycling Plant 1 (RP-1), Ontario, California

The anaerobic digestion system at the Inland Empire Utility Agency's (IEUA) RP-1 was upgraded in 2000 and went online as a three-stage AG-MTM process in 2001. Before 2001 the facility had operated as a thermophilic single-stage system. The system had experienced odor problems, however, and thus it had already gone to separate acid and gas phases using both a semi-batch and a continuous approach. After spending 2.5–3.5 days in a 32–40 °C (90–104 °F) mesophilic acid digester, the biosolids can be diverted to a semi-batch 56–58 °C (133–136 °F) thermophilic gas-phase digester, where they are retained for 18–20 days, or can go to a 50–52 °C (122–126 °F) thermophilic gas-phase digester, where they are retained for 14–16 days. After the thermophilic gas-phase digester, the biosolids are sent to a mesophilic gas-phase digester. Flow from the semi-batch process goes to a 42–48 °C (108–118 °F) system for 13–17 days, while flow from the continuous system goes to a 46–49 °C (115–120 °F) system for 5–6 days.

Overall, VS reduction improved for the facility, from approximately 55 percent to 60–65 percent with the AG-MTM process. Both processes showed non-detects for helminth ova, enteric viruses, and *Salmonella*. The semi-batch process qualified through time and temperature as Class A biosolids under alternative 1 of 40 CFR Part 503, while the continuous process received site-specific EPA approval as Class A was granted under alternative 3 of 40 CFR Part 503 (Wilson et al. 2005).

Waterloo, Iowa

The City of Waterloo wanted to increase its biosolids treatment capacity and improve its VS destruction and gas production. In 2002 the city upgraded its anaerobic digestion process from a single-stage mesophilic process to a TPAD-TM system by converting two of its six digesters into thermophilic digesters. The city began the project by taking each of its six digesters out of service one at a time and retrofitting them with the necessary piping, heating equipment, and mixers for the new system. This approach allowed the plant to continue to operate while the facility was upgraded. Once all the new equipment was in place, two of the digesters were sequentially transitioned to thermophilic temperatures. First, the feed rate into the digester was slowed, and then the temperature was raised from 35 °C (95 °F) to 53 °C (131 °F) over a period of 3 days, allowing the organisms to stabilize until they were achieving good VS destruction. Once the first thermophilic digester was stabilized, the second was transitioned the same way. This quick transition from mesophilic to thermophilic was important because it limited the number of mesophilic organisms that might survive in the thermophilic digester. During this transition, it was also important to limit the loading rate so that the digester would not be overloaded as the thermophilic organisms grew.

The city's new system achieved its goals. VS reduction improved from approximately 47 percent in the old system to approximately 60–64 percent in the new system; gas production increased to 0.18–0.21 m^3 per kg of VS destroyed (14–16 ft^3/lb) (Wilson et al. undated).

Tacoma, Washington

The City of Tacoma, Washington, has operated an anaerobic digestion system for many years, but it has had a history of odor problems. In 1993 Tacoma transitioned from a single-stage thermophilic system to a two-stage AG-MM system, thereby improving the odor of its TAGRO end-product so that it was more acceptable to customers. Although the odor of the end-product was acceptable, the hydrogen sulfide odors in the plant's belt-filter press room were extremely unpleasant to the workers and close to dangerous levels. Therefore, the plant began experimenting with various temperature-phasing approaches to try to reduce odors. Eventually, the plant determined that a thermophilic- mesophilic-low mesophilic approach of 55-38-32 °C (131-100-90 °F) with a total retention time of 21 days was ideal. By lowering the middle digester from 46 °C to 38 °C (115 °F to 100 °F), the plant significantly reduced its odor problems. In addition, lowering the temperature from 38 °C to 32 °C (100 °F to 90 °F) in the final digester seems to have improved dewatering. (Recent data show that dewatering has improved from 22 percent to 24 percent). The facility uses the biogas generated by the digestion process to run its boilers. The plant has been operating with this system since 2004 (D. Thompson, City of Tacoma, personal communication, 2006).

Three-Stage TPAD (bench-scale)

Salasali et al. (2005) performed bench-scale tests of several three-stage TPAD configurations to evaluate the level of VS reduction and biogas production in these configurations. These researchers undertook these experiments to determine whether modifying the operating practices for standard mesophilic digesters could achieve high performance VS reduction and Class A pathogen reduction so that facilities operating mesophilic digesters could achieve high-quality biosolids without going through the substantial costs of adding new digesters or reconfiguring existing digesters. The authors evaluated two three-stage configurations (35-35-35 °C [95-95-95 °F] and 42-35-35 °C [108-95-95 °F]), as well as a two-stage system (35-35 °C [95-95 °F]). The authors used 20l samples of a mixture of primary and thickened waste-activated sludge with a concentration of between

4.0 and 5.2 percent solids from the City of Ottawa, Canada, WWTP. The trials used a hydraulic retention time of 15 days (5 days in each stage for the three-stage systems, and 5 days in the first digester and 10 days in the second digester for the two-stage system) and measured conventional parameters (total solids, VS, pH) as well as pathogen indicators (fecal coliform bacteria, *Escherichia coli*, fecal *Streptococci*, *Salmonella* spp., *Cryptosporidium perfringens*). Each of the configurations was able to achieve the 38 percent VS reduction required for vector attraction reduction, although both of the three-stage configurations achieved better VS reduction and biogas production than did the two-stage configuration. Bacterial results showed that, with the exception of *Salmonella* spp., pathogens were reduced to the greatest extent in the 42-35-35 °C (108-95-95 °F) configuration.

OPERATION AND MAINTENANCE

Because multi-stage anaerobic digestion systems involve multiple stages, each having its own specific O&M requirements, these systems have higher overall O&M requirements than do single-stage anaerobic digestion systems.

Maintaining a stable operating temperature and pH within the digesters is critical, particularly for the methane formers, which are sensitive to changes in temperature and pH (Dague 1968). Changes in digester operating temperature greater than ~1.0 °C (~2 °F) per day can result in process upset due to heat shock of microorganisms. The optimum pH range for anaerobic digestion is 6.8–7.2. A reduction in pH, which can be caused by overloading the digester, inhibits its methane formation. Methane formation is further inhibited as the acid fermentation stage of digestion continues, possibly leading to digester upset and failure. Temperature control is also important to ensure satisfactory operation of the digestion system. Fluctuations in temperature can result in the die-off of microorganisms and process inefficiency. As discussed earlier, heat exchangers are commonly employed to control temperatures in the digester.

Chemical addition to anaerobic digesters might occasionally become necessary for pH/alkalinity control and to control the potential for metals and other chemicals to inhibit the process (see Table 2) (WEF 1995). Sodium bicarbonate, sodium carbonate, and lime can be used to provide alkalinity. Ferrous chloride, ferrous sulfate, and alum can be added to precipitate or coagulate inhibitive chemicals or to control digester gas hydrogen sulfide content.

A common operational problem with any anaerobic digestion system is foaming, which is the trapping of fine bubbles of gas in the semi-liquid digestion contents. Foam forms primarily when the carbon dioxide-to-methane ratio is higher than normal. This usually occurs during start-up operations, but it can occur whenever a fresh food supply suddenly contacts active microorganisms. This is one reason continuous slow feed of solids is preferred to batch feeding of digesters. In addition, a common bacterium, *Nocardia,* has a filamentous structure that traps gas, leading to foaming. These bacteria should be eliminated in aeration basins before the solids are fed to the digesters. Two-stage AG anaerobic digestion naturally overcomes this problem because the first stage (acid phase) digester has low gas production and low pH, along with higher volatile acid concentrations, which together are detrimental to foam-causing microorganisms.

Another important operational concern is odor control at the plant during the anaerobic digestion process. As discussed previously, hydrogen sulfide and ammonia are produced during anaerobic digestion. The most common way to control odors from a digestion system is to use covers, as discussed earlier.

Periodic clean-out of the digesters is necessary for all digestion systems. The frequency of cleaning is based on several factors, including the accumulation of grit and scum (which can reduce the effective volume of the tank); the condition of internal mixing or heating equipment; the availability of backup solids handling equipment; and tank structure (WEF 1998). Typically systems require cleaning approximately every 5 years. Because digesters are confined spaces, safety is a primary consideration. Before personnel enter a digester, the air composition inside the tank must be monitored for oxygen levels and the presence of hazardous gases.

COSTS

The construction and operation and maintenance costs of multi-stage anaerobic digestion depend largely on the quantity and quality of the solids to be stabilized, the size of the digesters, and the type of mixing and heating equipment. Capital items include digester tanks, piping and pumps, digester heating and mixing systems, digester gas-handling equipment, and chemical feed equipment. Design and construction costs from several example facilities follow.

The City of Grand Island, Nebraska, is in the design stages for the construction of a $10.7 million two-stage AG anaerobic digestion system. The city's 12-MGD WWTP receives approximately 40 percent of its flow from large industrial agricultural operations (including a meat packing plant) and has had odor problems. The city determined that replacing its open aerobic digesters with an anaerobic system will reduce these problems and generate a usable end-product for land application as fertilizer (Overstreet 2006).

Western Lake Superior Sanitary District (WLSSD) in Duluth, Minnesota, began operating a new two-stage TPAD-TM anaerobic digestion system at its 43-MGD regional WWTP in 2001. The new system was the result of a multiyear planning process that evaluated options for more environmentally and fiscally responsible alternatives to the existing sludge incineration process. The committee recommended anaerobic digestion, which would produce a usable end-product as well as biogas.

The new anaerobic digestion facility had a construction cost of $32.6 million and consists of four 1-MG digesters. The solids are digested in the first digester for 5 days at a temperature of 55 °C (131 °F). The thermophilically digested solids are then transferred to one of the three mesophilic digesters for an additional 15 days. The facility markets the end-product as "Field Green" and expects to produce approximately 8,000 dry tons of fertilizer per year, providing local farmers with an estimated $47,000 in no-cost fertilizer annually. In addition, the facility directs the biogas to a dedicated boiler, which provides the heat for the digesters, as well as for the solids processing building. By using the biogas from the anaerobic digestion process to power the boiler, the facility has reduced its peak electrical demand by 706 kilowatts per month, a 14 percent decrease (Western Lake Superior Sanitary District 2001).

In addition to constructing new anaerobic digestion systems, many facilities are upgrading existing anaerobic digesters to multi-stage systems to produce high-quality biosolids, reduce odor problems, or produce biogas to power plant operations or sell. Depending on the configuration of the current system (number of digesters, piping configuration, capacity and location of heating and mixing equipment, feed capabilities), the costs of retrofitting existing anaerobic digestion systems to multi-stage systems are typically minimal and usually include only the cost of installing new piping or reconfiguring existing piping. For example, the IUEA RP-1 in Ontario, California, was able to reconfigure its existing system and add new variable speed pumps and controls for $2.5 million (P. Cambiaso, IEUA, personal communication 2006). Similarly, although the exact cost figures were not readily available, the city of Tacoma, Washington, was able to transition from a single-stage thermophilic system to a two-stage AG-MM system at "a very low cost" by re-plumbing its existing system (D. Thompson, City of Tacoma, personal communication, 2006).

Operation and maintenance costs include costs associated with operating and maintaining mixing, heating, and pumping equipment; operating and maintaining gas-handling equipment; cleaning of digesters; and the purchase of chemicals. Table 4 summarizes typical O&M costs in dollars per dry ton of solids through the anaerobic digesters.

Table 4. Typical Operation and Maintenance Costs for Digesters

	Range per Dry Ton of Biosolids	Average per Dry Ton of Biosolids
Operation	\$5.30 – \$41.03	\$17.47
Maintenance	\$4.09 – \$10.48	\$7.44
Total	\$9.39 – \$51.51	\$24.91

Source: Multi-Agency Benchmarking Study 1999.

It should be noted that anaerobic digestion systems often pay for themselves through the combination of reduced costs for biosolids disposal (owing to a reduction in biosolids volume through the digestion process), the potential marketing of a Class A biosolids product, and the recovery of usable biogas. For example, the City of Tacoma markets the end-product from its anaerobic digestion process, TAGRO, for \$6.00–\$23/m^3 (\$8–\$30/yd^3), depending on its final form (City of Tacoma Web site, June 2006).

Other Related Fact Sheets

Odor Control in Biosolids Management
EPA 832-F-00-067
September 2002

Centrifugal Thickening and Dewatering
EPA 832-F-00-053
September 2002

Belt Filter Press
EPA 832-F-00-057
September 2002

Recessed Plate Filter Press
EPA 832-F-00-058
September 2000

Alkaline Stabilization of Biosolids
EPA 832-F-00-052
September 2000

Other EPA fact sheets can be found at
http://www.epa.gov/owm/mtb/mtbfact.htm

REFERENCES

Cambioso, Pietro, Inland Empire Utility Agency. July 2006. Personal communication.

Chang, F., L. Otten, E. LePaige, and B. van Opstal. 2004. *Is 100% Diversion from a Landfill an Achievable Goal?* A Report to the Toronto, Canada, New and Emerging Technologies, Policies and Practices Advisory Group.

City of Tacoma. 2006. Web site. <http://www.cityoftacoma.org/Page.aspx?hid=687>. Accessed June 2006.

Cumiskey, A. 2005. UK Leads the Way in Advanced Digestion Technology. *Water and Wastewater International*, June 2005.

Dague, R.R. 1968. Application of Digestion Theory to Digester Control. *Journal of the Water Pollution Control Federation* 40: 2021.

Ghosh, S., and D. Klass. 1977. Two-Phase Anaerobic Digestion, U.S. Patent No. 4,022,665.

Haug, R.T., W.J. Hartnett, E.B. Ohanian, G. L. Hernandez, et al. 2002. *BioCycle* 43(6): 22–25.

Iranpour, R., and T. Windau. 2004. Thermophilic Digestion: Selected Case Studies. Presented at Virginia Water Environment Association, November 2004.

Kelly, H.G. 2003. Emerging Processes in Biosolids Treatment 2003. Presented at the 2nd Canadian Organic Residuals Conference, Penticton, British Columbia, April 2003.

Kroker, E.J., et al. 1979. Anaerobic Treatment Process Stability. *Journal Water Pollution Control Federation* 51: 718.

Mayhew, M. M.S. Le, D. Harrison, and C.E. Brade. 2004. Plug Flow Digestion—a Case Study. Presented at the 9th European Biosolids and Biowastes Conference, Wakefield, UK.

Monsal. 2004. News release from Monsal. http://www.processingtalk.com/news/meq/meq100.html. Accessed June 2006.

Multi-Agency Benchmarking Study. December 1999. <http://dnr.metrokc.gov/wtd/benchmark/index.htm>.

Overstreet, T. 2006. City on the Right Track to Reducing Odor. *Grand Island Independent* Web site. <http://www.theindependent.com/stories/060706/new_odor07.shtml>.

Parker, W., University of Waterloo. June 2006. Personal communication.

Salsali, H., W. Parker, and S. Sattar. 2005. Influence of Staged Operation of Mesophilic Anaerobic Digestion on Microbial Reduction. Presented at WEFTEC 2005, Washington, DC.

Schafer, P.L. and J.B. Farrell. 2000. Turn Up the Heat. *Water Environment and Technology*. 12(11).

Shang, Y. and S. Sung. 2001. Thermophilic-Mesophilic Two-Stage Anaerobic Digestion System Application. In *Proceedings of WEF/AWWA/CWEA Joint Residuals and Biosolids Management Conference*. Alexandria, VA: Water Environment Federation.

Sieger, R., and L. Stone (eds.). 2001. The Straight Scoop on Biosolids. 4(1, Winter/Spring).

Srivastava, V.J. 1996. Two-Phase Anaerobic Digestion of Carbonaceous Materials. U.S. Patent No. 5,500,123.

Stalling, R.B., et al. 2000. Two Stage Anaerobic Digestion and Liquid Storage Achieve Enhanced Pathogen and Vector Attraction Reduction. In *Proceedings of WEF Residuals and Biosolids Management Conference, 14th Annual Conference*. Alexandria, VA: Water Environment Federation.

Tchobanoglous, G., and F.L. Burton. 1991. *Wastewater Engineering: Treatment, Disposal, Reuse*. 3rd ed. Metcalf and Eddy, Inc.

Thompson, D., City of Tacoma, Washington. 2006. Personal communication.

USEPA (U.S. Environmental Protection Agency). 1979. *Process Design Manual Sludge Treatment and Disposal*. EPA 625/625/1-79-011. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development.

Water Environment Federation, 1995. *Wastewater Residuals Stabilization*, MOP No. FD-9. Alexandria, VA: Water Environment Federation.

Water Environment Federation, 1996. *Operation of Municipal Wastewater Treatment Plants*, MOP No. 11, 5th ed. Alexandria, VA: Water Environment Federation.

Water Environment Federation. 1998. *Design of Municipal Wastewater Treatment Plants*, MOP No 8. Alexandria, VA: Water Environment Federation.

Western Lake Superior Sanitary District. 2001. *Annual Report*.

Wilson, T., and L. Potts. 2003. An Update on Full Scale 2-Phase AG Systems- 2003. Presented at WEFTEC 2003.

Wilson, T., L. Potts, and R. Stallings. 2005. Review of Full Scale 2-phase AG Anaerobic Digester Systems. Presented at the New England Water Environment Association Annual Conference, Boston.

Wilson, T., R. Iranpour, and T. Windau. Undated. Thermophilic Anaerobic digestion in the U.S.: Selected Case Histories. <http://www.earthtech.com/news/whitepapers.htm>. June 2006.

Winfield, G., A.S. Sokhey, J. Dhupar, J.J. Marx, R.B. Schroedel, Jr. 2001. Design of an Acid/Gas Digestion Process for Baltimore's back River Plant. In *Proceeding of WEF Residuals and Biosolids Management Conference, 14th Annual Conference*. Alexandria, VA: Water Environment Federation.

Woods, C.E., and V.E. Melina. 1965. Stage Digestion of Wastewater Sludge. *Journal Water Pollution Control Federation* 37: 1495.

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