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AgSTAR

Anaerobic Digester/Biogas System Operator Guidebook

A Guidebook for Operating Anaerobic Digestion/Biogas Systems on Farms in the United States

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PREFACE

U.S. EPA AgSTAR Program

AgSTAR is a voluntary outreach program that encourages the implementation of anaerobic digestion (AD) projects in the agricultural and livestock sector to reduce methane (CH_4) emissions from agricultural residuals including livestock waste. AD projects can be cost-effective mitigation techniques and provide numerous co-benefits to the local communities where they are installed, including environmental, energy, financial, and social sector benefits.

AgSTAR is a collaborative program sponsored by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Agriculture (USDA) that promotes the use of biogas recovery systems to reduce CH_4 emissions from livestock waste. As an education and outreach program, AgSTAR disseminates information relevant to livestock AD projects and synthesizes it for stakeholders who implement, enable, or purchase AD projects. The program's goals are to provide information that helps stakeholders evaluate the appropriateness of an AD project in a specific location, to provide objective information on the benefits and risks of AD projects, and to communicate the status of AD projects in the livestock sector. Through the AgSTAR website (www.epa.gov/agstar) and at public events and other forums, AgSTAR communicates unbiased technical information and helps create a supportive environment for the implementation of livestock AD projects.

AgSTAR provides technical input to the USDA Rural Energy for America Program, which provides grant funding for AD systems at farms.

AgSTAR works collaboratively with livestock producers, the digester and biogas industry, policymakers, universities, and others to provide unbiased information to assess the use of anaerobic digesters. By identifying project benefits, risks, and options, AgSTAR provides critical information to determine whether an AD system is the right choice for an operation.

Anaerobic Digester Operator Guidebook Purpose

The purpose of this Anaerobic Digester/Biogas System Operator Guidebook is to help on-farm AD and biogas (AD/biogas) system operators improve performance and efficiency. It is also intended to assist in the prevention of common difficulties and challenges that can lead to community opposition and system shutdown. This Operator Guidebook covers technical topics for a wide range of stakeholders. It is intended to be a resource that helps operators maximize profitability by optimizing biogas yield, improving biogas quality, and improving operating uptime, while minimizing operations and maintenance (O&M) expenses. The Operator Guidebook spans all aspects of on-farm AD/biogas production as well as certain utilization processes, providing industry expert experience and suggestions for dealing with performance, safety, and other issues commonly encountered with AD/biogas systems.

Disclaimer

This Operator Guidebook complements other AgSTAR resources for developing biogas projects on U.S. farms. It is designed to be used in combination with the third edition of the AgSTAR Project Development Handbook. The Project Development Handbook and the Operator Guidebook were collectively prepared to improve the successful development, implementation, and operation of on-farm AD/biogas systems.

While this Operator Guidebook addresses numerous aspects of AD/biogas systems, it is not possible to cover every component, as there are many different types of systems, and each AD/biogas project is unique. Therefore, this document should not be considered fully comprehensive, nor should it be used in place of a site-specific O&M manual. Rather, it should be considered a supplement to the operations manual provided by the project developer or the engineering firm that prepared the project design and supervised the construction and start-up of an AD/biogas system. Project stakeholders may utilize this document to ensure that developing or existing site-specific O&M plans cover a baseline of topics needed for successful project operation. The Operator Guidebook will be updated as AD/biogas systems evolve.

Pursuant to 5 CFR § 2635.702(c)(2), names are displayed here as the result of recognition for achievement given under an agency program of recognition for accomplishment in support of the agency’s mission. Any reference to a specific company or commercial product or service by trade name, trademark, manufacturer, company, or otherwise does not constitute or imply the endorsement or recommendation of EPA.

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Table of Contents

List of Tables

List of Figures

Acronyms

AD	anaerobic digestion
ATA	anaerobic toxicity assays
BMP	biochemical methane potential
BOD	biochemical oxygen demand
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
COD	chemical oxygen demand
EPA	U.S. Environmental Protection Agency
H_2S	hydrogen sulfide
HRT	hydraulic retention time
HVAC	heating, ventilation, and air conditioning
IC	internal combustion
IDLH	Immediately Dangerous to Life and Health
kg	kilogram
L	liter
lb	pound
LEL	lower explosive limit
mg	milligram
NH_3	ammonia
O_2	atmospheric oxygen
O&M	operations and maintenance
OLR	organic loading rate
OSHA	Occupational Safety and Health Administration
ppm	parts per million
PRV	pressure relief valve
PSA	pressure swing adsorption
RNG	renewable natural gas
SRT	solids retention time
TKN	total Kjeldahl nitrogen
TS	total solids
UEL	upper explosive limit
VFA	volatile fatty acid
VS	volatile solids

1.0 Introduction

Anaerobic digestion (AD) and biogas systems are designed to convert biodegradable organic materials into recoverable methane (CH_4)-rich gas and a stabilized digestate using a well-documented, complex biological process.

A successful AD/biogas system operator has one primary objective: provide the microorganisms in the digester with a favorable environment to maintain a stable population. If this stability is achieved, the microorganisms will efficiently convert readily biodegradable organic materials into biogas and other products, which can then be captured and utilized, prohibiting their release into the environment. Achieving this primary objective is challenging because AD/biogas systems comprise complex biological and mechanical engineering systems that must work together efficiently. An underperforming mechanical system will limit the AD/biogas system's ability to perform the necessary biological processes. Similarly, a biological system failure means that even the best mechanical system will only be useful for moving ineffective biomass out of the reactor vessel, requiring a restart of the operating system.

The goal of this Operator Guidebook is to increase understanding of effective operations and maintenance (O&M) for the performance of these complex systems. This document is intended to be a resource for AD/biogas system owners, managers, operators, and other project stakeholders to educate, maintain, or improve effective operation. Operators can also maximize profitability by increasing biogas yield, quality, utilization, and operating uptime while minimizing O&M expenses and avoiding common difficulties that can lead to lower performance, shutdown, and community challenges such as odors. The Operator Guidebook addresses fundamental questions about "what it takes" to successfully operate and maintain an AD/biogas system on an agricultural operation.

Effective operator training can increase AD/biogas system productivity and operating efficiency. Training can help avoid some of the common challenges that, if not actively managed, could lead to unintended AD/biogas plant shutdowns, neighbor complaints, or elevated operator costs.

This Operator Guidebook is <u>not</u> intended to serve as a fully comprehensive standalone reference guide, provide regulatory guidance, or take the place of a site-specific O&M manual, but rather to serve as a complement to these essential resources. Each facility should have its own comprehensive, site-specific O&M manual that addresses the following:

- Specific O&M requirements for each portion of the system.
- An operation plan discussing the system's operating sequence.
- As-built drawings, schematics, and diagrams for the system.
- Clear instructions on any automated system, including descriptions of the automated functions and related operating procedures.
- General daily functions.

- Potential site-specific safety issues, mitigation measures, and procedures.
- Specifications and O&M requirements for the major equipment pieces.

All agricultural AD/biogas systems employ two distinct processes that must work together:

- **The biological process** involves the microbial population that breaks down biodegradable organic material and converts a portion of it into CH_4-rich biogas and digestate. Just as livestock farmers work to maintain proper animal nutrition, consistent feeding, and comfortable living conditions to maximize livestock growth or food production (milk or egg), AD/biogas system operators must also work to maintain proper AD nutrition, including consistent and high-quality feed and sustainable living conditions for their microorganisms. If these conditions are consistently achieved, the AD will efficiently produce high-quality biogas, digestate, and resultant saleable products on a consistent basis.
- **The mechanical process** involves the facility's conveyors, pumps, blowers, piping, tanks, and other equipment that move and process the incoming organic material and the recovered biogas and digestate. The mechanical process also includes equipment for biogas utilization (as biogas can be used as a source of energy either for on-farm use or for sale). Just as farm operators must maintain their tractors, implements, and manure-handling equipment to properly maintain farm production, AD/biogas system operators must also maintain the mechanical systems to ensure consistent production of high-quality biogas, digestate, and resultant saleable products.

This Operator Guidebook focuses on biological and mechanical O&M considerations.

2.0 Digester Basics

2.1 What Does an Anaerobic Digester Do?

In simplified terms, anaerobic microbes within the AD degrade or break down organic matter to obtain energy and nutrients for growth and reproduction. Biogas, a byproduct of this process, is composed primarily of CH_4. Biogas also includes carbon dioxide (CO_2), as well as trace amounts of hydrogen sulfide (H_2S) and ammonia (NH_3), which must be removed for certain biogas end uses. An engineered AD system creates a controlled environment that efficiently converts biodegradable organic materials (i.e., manure) into biogas and produces a stabilized residual effluent (digestate) that can be put to beneficial use. The primary responsibility of the AD/biogas system operator is to maintain process stability. If this is done successfully, a well-designed, constructed, and operated AD/biogas system will have a microbial community that is very effective at generating biogas.

AD functions include:

- Converting biodegradable organic matter into biogas, which can be sold as a fuel or combusted for on-farm energy use.
- Reducing biochemical oxygen demand (BOD) and chemical oxygen demand (COD).
- Reducing odors.
- Converting organic nitrogen into more plant-available forms that can be used as fertilizer.
- Reducing pathogens.
- Capturing CH_4 that otherwise would be released.

2.2 How Does an Anaerobic Digester Work?

This section describes the underlying biochemical principles of AD. The biochemical conversions in an anaerobic digester are quite complex; in simple terms, a variety of microorganisms break down the readily biodegradable organic matter to form biogas. Organic matter anaerobically decomposes naturally under wet conditions where dissolved oxygen (O_2) is absent. This most commonly occurs in the bottom sediments of lakes and ponds, swamps, peat bogs, animal intestines, and the interiors of solid waste landfills.

The AD process involves the following four steps:

- **Hydrolysis—**Complex organics are broken down into simple organics. Specifically, hydrolytic microorganisms break down complex organic compounds such as proteins, carbohydrates, and fats.
- **Acidogenesis—**Acidogenic microorganisms ferment the simple organics into short-chain fatty acids (also called volatile fatty acids [VFAs]), CO_2, and hydrogen gases.
- **Acetogenesis—**Acetogenic microorganisms convert the mixture of short-chain fatty acids to acetic acid, with the release of more CO_2 and hydrogen gases.

- **Methanogenesis**—CH_4-producing microorganisms called methanogens convert acetic acid and hydrogen to biogas. The biogas is a mixture of CH_4, CO_2, other compounds of lesser proportion such as H_2S, and numerous trace elements. There are two classes of methanogens: one class primarily converts the acetic acid to CH_4, while the other class combines the hydrogen and CO_2 into CH_4; some unique methanogens can do both.

Text Box 1
Volatile Fatty Acids (VFAs)

VFAs can cause strong odors due to their small molecule size and ability to volatize quickly. VFAs in high concentrations lower digester pH, which can contribute to system upset. VFAs are discussed in further detail in Sections 4.0 and 5.0.

The four steps of anaerobic biodegradation are shown in Figure 2-1.[1] One key to successful AD operation is maintaining a balance between the populations of the methanogenic microorganisms and the hydrolytic, acidogenic, and acetogenic microorganisms—which are heterotrophs, meaning that they consume complex organic substances. It is important to ensure an adequate population of methanogens because methanogens reproduce at a slower rate than heterotrophs. With insufficient methanogens, VFAs will accumulate, and these acids are toxic to methanogens at higher concentrations.

To maintain methanogens, the rate of methanogen loss in the digester effluent should not be greater than the rate of methanogen growth. This can be managed by controlling the amount of time that waste is in the digester, called the residence or retention time. To achieve the desired

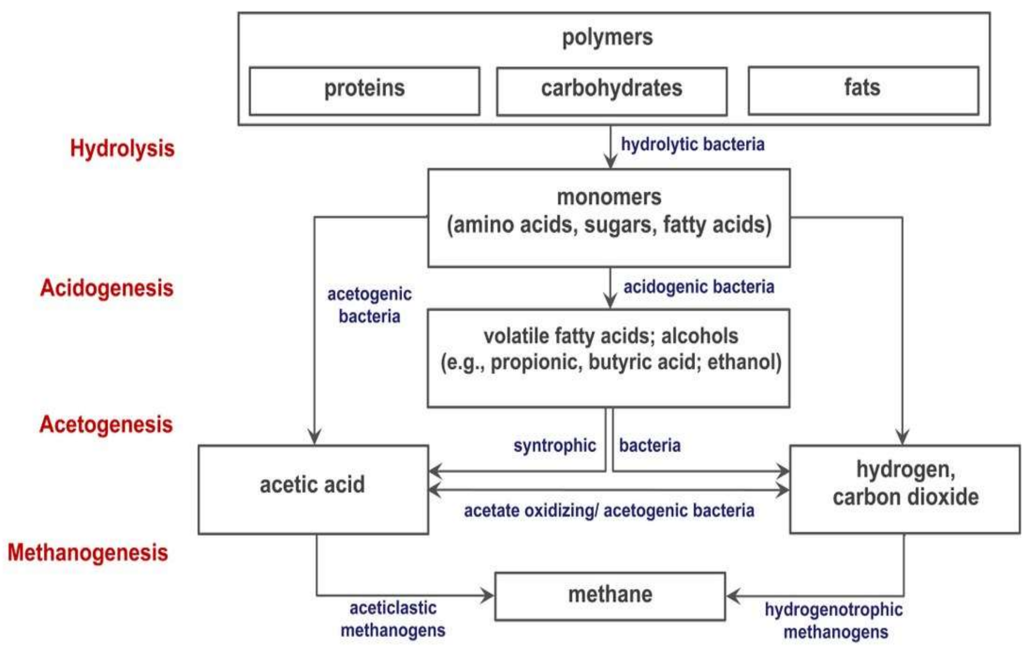

Figure 2-1. The four steps of anaerobic biodegradation.

[1] Image source: "Biomass degradation." Institute of Microbiology, Technische Universität Dresden, https://tu-dresden.de/mn/biologie/mikro/mikdiv/forschung/Projects/methanogenesis.

conversion of any specific organic waste, including livestock manure, operators must maintain the digester-specific design values for residence times (discussed in Section 3.1).

Most AD/biogas systems employ a single reactor, where the production of acetic acid, hydrogen, CO_2, and CH_4 occur concurrently. Theoretically, separating the various populations of microorganisms should provide for more precise process control. Two-stage digesters target microorganisms for the first three phases of digestion (hydrolysis, acidogenesis, and acetogenesis) in the first vessel and the CH_4-forming microorganisms in a second, downstream vessel. However, separating phases of AD has not been shown to offer any significant advantage over single-stage digestion.

In all cases, given the range of process options, the art of deploying a successful digester lies in selecting the best engineering solution for the specific feedstock (i.e., material being converted in the anaerobic digester) being treated. There are numerous design, operational, and cost reasons for choosing a specific type of digester. Each type should be considered carefully for its suitability to treat the specific feedstock. There is not any one AD/biogas system design or technology that works the best for all feedstocks. This Operator Guidebook does not endorse any specific brand or process.

Text Box 2
Basics of Microbial Biogas Production

- Degradable organic matter is converted to biogas via a consortium of microorganisms, which occurs in four steps:
    1. Hydrolysis
    2. Acidogenesis
    3. Acetogenesis
    4. Methanogenesis
- Heterotrophic microorganisms (which perform hydrolysis/acidogenesis/ acetogenesis) grow faster than the CH_4-forming microorganisms (methanogens).
- Due to these growth rate differences, the methanogen colony needs to be larger to convert the acids to biogas.

2.3 Types of Anaerobic Digesters

There are two basic approaches for anaerobically digesting organic matter—conventional AD and high solids digestion. Conventional AD is used when organic matter is managed as a liquid (i.e., manure with a total solids [TS] concentration of up to 10–12 percent). Commonly used conventional anaerobic digesters are listed below, although other conventional designs may be feasible for on-farm applications. See the AgSTAR Project Development Handbook (Section 3.4) for more information.

- Completely mixed digesters
- Covered lagoons
- Plug flow digesters
- Modified plug flow digesters (vertically mixed plug flow digesters)

Conventional AD can be classified by its rate of biogas generation. High-rate digesters are heated and hydraulically or mechanically mixed. Standard-rate digesters are not typically heated or mixed. High-rate digesters include completely mixed digesters (also called complete mix digesters) as well as modified plug flow digesters. Other plug flow digesters do not fit neatly in either category because they are heated but not mixed. A covered lagoon is considered a standard-rate digester due to the absence of heating or mixing. There are numerous variations of these basic types of digesters.

Other types of high-rate digesters that are generally not feasible for on-farm application are:

- Upflow anaerobic sludge beds
- Attached growth (fixed film) systems
- Induced bed reactors

These types of digesters are suitable only for wastes with a very low percent solids.

Figure 2-2. Photograph of an anaerobic digester facility (a patented sequential-batch system).[2]

For manure that is managed as a solid, conventional AD is not an option because of the inability to pump and mix the material. Manures are managed as a solid when the manure is combined with liberal amounts of bedding or another biodegradable organic waste such as a solid food processing waste. Digestion of a solid waste involves stacking the waste in a container that can be sealed to collect the biogas being produced. This process is called high solids AD or "dry

[2] Image source: BioCycle, https://www.biocycle.net/2012/03/14/anaerobic-digestion-in-the-northwest/.

fermentation." High solids AD is normally a batch process (i.e., feedstocks are loaded at once, digestion occurs, then the container is emptied and reloaded).

2.4 Key Factors for AD Efficiency and Performance

The amount of organic material converted into CH_4 by an AD/biogas system and the efficiency of conversion depends on many factors, as shown in the Text Box 3.

This complex set of parameters is highly dependent on site-specific conditions, including chemical and physical characteristics of the feedstock, the AD/biogas system design, technology, etc. These parameters are defined and discussed in greater detail in Section 3.0.

Text Box 3
Key AD/Biogas Parameters Required to Maintain Efficient Biogas Production

Several parameters determine the efficiency of converting organic materials to biogas:

- Retention time
- Organic loading rate (OLR)
- Temperature
- Characteristics of volatile solids (VS)[3]
- Inhibitors[4]

2.5 AD/Biogas System Components

On-farm AD/biogas systems include the following components:

- A structure for waste reception and short-term storage. This may be an aboveground or in-ground tank and include a pump for transferring the waste to the digester.
- A digester, which may be an aboveground tank or a covered lagoon. For high-rate AD, the digester contains a mixing system to maintain completely mixed conditions and internal or external heat exchangers for digester heating.
- An effluent (digestate) storage structure, which most commonly is a fill-and-draw storage lagoon. For effluent stored in the structure, land application is the method of ultimate disposal.
- A biogas processing system to remove impurities, with the degree of processing dependent on the intended use of the gas. When the intended use is onsite fuel, processing usually is limited to the reduction of moisture and H_2S concentrations. When the objective is to produce renewable natural gas (RNG) for sale, more extensive processing is required. This includes removal of CO_2, NH_3, and other impurities in addition to moisture and H_2S.
- Equipment for biogas use or destruction. This often includes one or more engine-generator sets that combust the biogas to produce electricity for onsite use and/or sale to the local electric utility. Typically, waste heat from engine-generator sets is recovered for on-farm use,

[3] VS is the organic fraction of TS, a portion of which is converted into biogas.

[4] Inhibitors refer to toxic chemicals or contaminants or other conditions that prohibit the controlled biological process

such as digester heating or other heating needs. Biogas can also be used onsite as boiler or furnace fuel in place of natural gas, liquefied petroleum gas, or heating oil. Interconnection equipment is required when biogas or generated electricity is used off site. All systems include a flare to safely burn surplus biogas.

Some AD/biogas systems may also include one or more of the following components:

- Waste pretreatment, which most commonly is the screening of dairy cattle manure to remove coarse, slowly digestible fiber before digestion in a covered lagoon. Pretreatment could also include grinding or maceration when there will be co-digestion with other wastes such as food wastes.
- Solids separation, to remove and concentrate solids from the digester effluent. With the digestion of dairy cattle manure, this would most commonly use a screw press with the separated solids used for bedding. These separated solids can be dried, composted, or both for sale as a soil amendment.
- Equipment for nutrient and water recovery. Nutrient capture processes such as dissolved air flotation may be used to recover phosphorus, nitrogen, and potassium from separated solids. Technologies for nutrient recovery using ultra-filtration and reverse osmosis are available but have not been widely used for livestock waste. These systems concentrate primary plant nutrients and produce a dischargeable effluent.

Text Box 4
Safety First—Monitoring Gas Concentrations to Protect Worker Health and Safety

- AD/biogas systems typically produce CH_4 concentrations between 45 percent and 70 percent. CH_4 is combustible with air at concentrations between 5 percent and 15 percent. The combination of CH_4, air, and a spark in a closed condition can cause an explosion.
- CH_4 and H_2S are toxic gases that can cause severe health effects or death.
- Sufficient monitoring and design are required to minimize potential health or safety issues.

2.6 Fundamentals of Biogas Safety

Biogas is primarily composed of CH_4 and CO_2, and it contains small amounts of H_2S, NH_3, volatile organic compounds, water vapor, and other substances. In certain concentrations, some of these gases may be flammable, explosive, toxic, or asphyxiating. Handling biogas requires respect and caution. CH_4 is combustible with air at concentrations between 5 percent and 15 percent, known as the lower explosive limit (LEL) and the upper explosive limit (UEL), respectively. Biogas systems typically produce CH_4 concentrations in the range of 45 percent to 70 percent, and introducing air into the biogas handling system could bring the CH_4 concentrations into the explosive range, presenting risk of an explosion in the presence of an ignition source. H_2S is a toxic gas that can cause severe health effects or death. Adequate safety procedures are necessary to protect workers and equipment. Safety should be the focus of plant designs and operating procedures and is further discussed in Section 10.0.

3.0 Operational Fundamentals

As noted in Section 2.4, site-specific operating parameters influence an AD/biogas system's ability to convert organic matter to CH_4. Key parameters are discussed below. Further information may also be found in the Project Development Handbook.

3.1 Retention Time

Retention (or residence) times are important for maintaining healthy microbial populations in an AD/biogas system:

- **Solids retention time (SRT)** is the average length of time the feedstock VS or COD remain in the digester's reactor and remain in contact with the microbes.
- **Hydraulic retention time (HRT) or hydraulic residence time** is the average length of time the dissolved portion of the waste spends in the digester.

SRT is the most important design and operating parameter for AD. It is critical for maintaining a population of the slower-growing methanogenic microorganisms that is adequate to convert the acetic acid, hydrogen, and CO_2 produced by the heterotrophic microorganisms to biogas. If a digester SRT falls significantly below the design values, the rate of loss of methanogens in the digester effluent will exceed their rate of growth. The result will be the accumulation of VFAs, which are toxic to methanogens in high concentrations. The result is an upset or "stuck" digester.

The required HRT for an AD/biogas system is determined by many factors, including:

- Laboratory data available for similar feedstocks
- BMP test results
- OLRs published for the digester type
- HRT minimum published for the digester type

For plug flow and completely mixed digesters, the HRT and SRT are equal. Therefore, a significant increase in influent volume will significantly reduce SRT, and a "wash out" of the methanogen population will occur. This could happen if a new waste source not incorporated into the original digester design is added to the digester. For unmixed covered lagoons, SRT greatly exceeds HRT due to the accumulation of settled solids. However, a reduction of HRT below design value will reduce biogas production and the degree of waste stabilization.

3.2 Organic Loading Rate (OLR)

The organic loading rate (OLR) indicates the amount of VS that can be fed into the digester per day. Maintaining a consistent OLR is critical to maintaining a healthy microbial population for all digesters and thus effective AD/biogas system performance. OLR usually is expressed as pounds of VS added per cubic foot of digester volume per day. The OLR of an anaerobic digester determines the sizes of the various microorganism populations under steady-state conditions. Therefore, any significant increase in the OLR must be gradual to allow for an increase in microbial populations.

OLR is an important design parameter for covered anaerobic lagoons. For plug flow and completely mixed digesters, maintaining a consistent OLR translates to maintaining a constant SRT and HRT.

Text Box 5
Temperature Ranges of Biogas Production

Biogas is generated in three temperature ranges:

- Psychrophilic (less than 68 °F)
- Mesophilic (86 °F to 104 °F)
- Thermophilic (122 °F to 140 °F)

Conventional AD/biogas systems are commonly designed to operate in either the mesophilic or thermophilic temperature range.

3.3 Operating Temperature

In nature, biodegradable organic matter anaerobically decomposes over a wide range of temperatures; the rate of decomposition increases as temperature increases, since microbial growth increases as temperature increases. However, the species of methanogens present at ambient temperatures differ from those in a heated digester. The microorganisms generally are characterized as psychrophilic (present at less than 68 °F), mesophilic (present at 86 °F to 104 °F), and thermophilic (present at 122 °F to 140 °F).

Ambient conditions are generally used for in-ground, low solids covered lagoons, which are most effective in warm climates. The areas of the United States that have temperatures high enough to support energy recovery from ambient temperature digesters are generally below the 40th parallel north.

3.4 Degradable Organic Material Conversion and Limitations

VS refers to the fraction of TS that are combustible and are used as an estimate of organic matter content. Managing VS is important for maintaining a stable OLR. Manure solids are composed of VS and minerals (commonly referred to as fixed solids or ash). While all organic matter is ultimately biodegradable, its various components degrade at different rates. Organic matter is a combination of proteins, carbohydrates, and fats. Although most proteins and fats are readily biodegradable and decompose rapidly, the biodegradation rates of different carbohydrates vary significantly. For example, simple sugars are readily biodegradable, whereas more complex carbohydrates such as cellulose, hemicellulose, and especially lignin biodegrade more slowly. Of the three, cellulose is the most readily biodegradable, whereas lignin is the most resistant.

3.5 Biomethane Potential

The potential to produce biogas from an organic waste can be determined both experimentally and theoretically. A diagram demonstrating different methods of determining biomethane potential is shown in Figure 3-1.

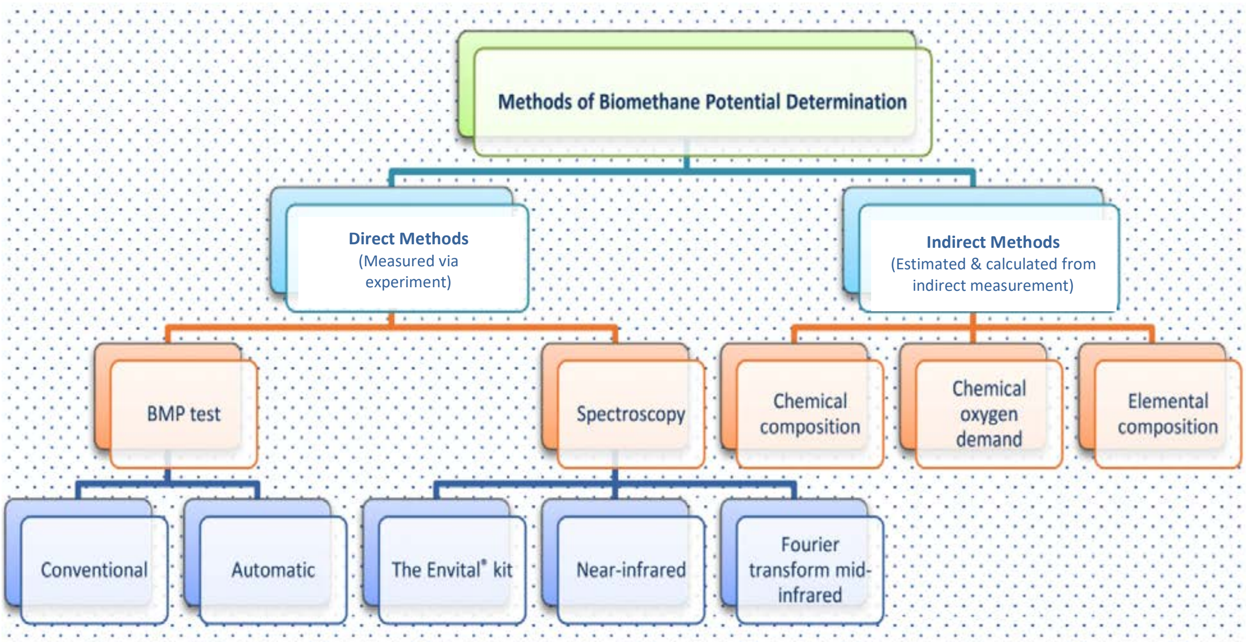

Figure 3-1. Methods of biomethane potential determination.[5]

The direct experimental method is known as the biochemical methane potential (BMP) assay. It is a laboratory-scale batch digestibility study where the waste material is added to an active population of anaerobic heterotrophs and methanogens, and the produced biogas is collected, measured over time, and compared to a control reactor. The control reactor contains an active population of anaerobic heterotrophs and methanogens. The control reactor's biogas production is then subtracted from the biogas production of the reactor containing the waste to determine net biogas production. Usually, VS reduction over time is also calculated to determine the fraction of organic matter that is readily biodegradable.

BMP assays are conducted under controlled conditions and tend to overestimate biogas production when compared to actual full-scale field conditions. A more accurate but more expensive approach is to determine biogas production potential in a pilot plant-scale reactor, simulating expected full-scale digester operating conditions. Pilot plant-scale testing is typically done for municipal systems but is uncommon for on-farm systems.

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[5] Image source: Jingura, R. M., & Kamusoko, R. (2017). Methods for determination of biomethane potential of feedstocks: a review. *Biofuel Research Journal, 4*(2), 573–586. https://dx.doi.org/10.18331/BRJ2017.4.2.3.

A BMP assay can be especially valuable for testing the successful use of AD for mixtures of manure and other wastes. While the BMP of each waste can be determined individually, a BMP assay of the wastes combined in the expected proportions is more accurate since it captures any possible synergetic effects; it also reduces the number of tests and therefore the costs.

Indirect methods are estimated and calculated from indirect measurement. They include analysis of various parameters, including TS, COD, and VS, in combination with subsequent calculations to estimate biogas production. Indirect methods are relatively quick and can be conducted at a lower laboratory cost, but they also require assumptions about biodegradability. For example, based on stoichiometry, the complete conversion of organic compounds under anaerobic conditions would yield 5.6 standard cubic feet of CH_4 per pound of COD destroyed. However, this relationship is only useful for analysis if the expected COD reduction is known. Because indirect methods are estimates based on assumptions, the results are less precise than direct measurements.

3.6 Anaerobic Toxicity Assays (ATAs)

There are a variety of chemical compounds that can inhibit AD and especially CH_4 formation. These include chlorinated compounds, such as detergents and bleach, and quaternary ammonium compounds. These materials are used extensively for cleaning and sanitizing equipment and facilities in the food processing industry and in milking centers on dairy farms. Other substances of concern include antibiotics, other pharmaceuticals, and pesticides.

Toxic compounds are most commonly introduced when another waste, such as food processing waste, is co-digested. When considering co-digestion, the best approach is to initially conduct anaerobic toxicity assays (ATAs) on random samples of the waste. Because it is impractical to perform ATAs on samples of every waste delivery, the digester owner or operator should evaluate the potential risk versus reward based on the assay results and discuss with the waste generator the nature of their operation and the specific processes involved.

4.0 Process Control

Adequate monitoring and controls help the operator maintain proper operating conditions and digester health and ensure AD/biogas system performance. This section describes the necessary process controls and monitoring.

4.1 Consistent Loading

Maintaining a stable microbial ecosystem is critical to successfully operating all types of anaerobic digesters, which includes maximizing the biogas production potential. This requires a regular schedule for waste addition at the design volume to maintain the design SRT. It also requires minimizing variation in influent physical and chemical characteristics, including TS and VS concentrations, to maintain a constant OLR.

When a mixture of different wastes is being co-digested, the wastes should be added concurrently in constant proportions and ideally blended before being added to the digester. Although biogas production can increase drastically with the addition of substrates, inconsistent loading (due to factors such as a lack of storage space, delivery times, types of substrates and their speed of biodegradability), can result in high fluctuations in biogas production. Figure 4-1 illustrates this increase in biogas production and biogas variability when substrates are added to manure but loading is inconsistent. As seen in the figure, biogas production was considerably lower, with far less fluctuation, during the period where no substrates were added.

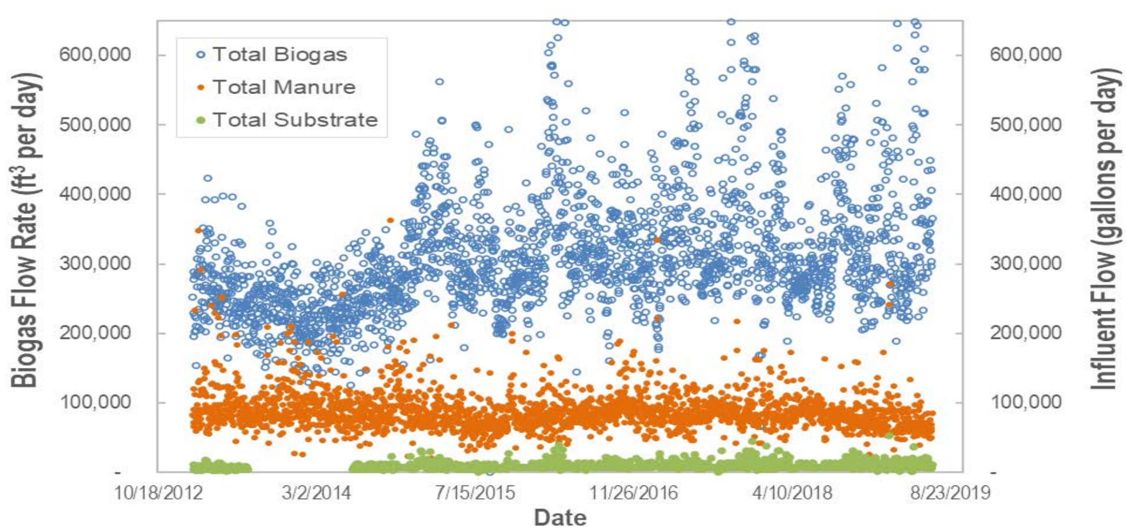

Figure 4-1. Biogas fluctuation with feedstock variability.[6]

[6] Source: Data provided to AgSTAR by Regenis for farm-based anaerobic digester data 2012–2019. Data recorded with online liquid and gas flow meters as well as substrate delivery volumes. Dairy manure and various pre-consumer food processing organic wastes.

A digester can be operated as a continuous or semi-continuous flow reactor. Operating a digester as a continuous flow reactor involves adding a constant flow of waste uniformly over a 24-hour period. Semi-continuous flow operation, where waste is added one or more times per day at equal time intervals, is more common.

The various mechanical systems involved in the routine addition of digester influent, such as piping and pumps, must operate reliably to ensure maintenance of steady-state conditions. Therefore, routine performance monitoring and preventative maintenance as specified in the manufacturer's O&M manual are necessities. Operators should check for blockages, as blockages can lead to over-pressurization and structural damage. Operators should also verify actual pumping rates. Measuring digester influent holding tank drawdown during a feeding cycle can be an easy way to check influent pump performance.

4.2 Performance Monitoring

AD/biogas system operators should monitor the system's performance to look for inconsistencies and notable changes, as these are indicators of digester upset or impending upset.

4.2.1 Biogas Monitoring

The key indicator of anaerobic digester performance is biogas production. Therefore, biogas production should be continuously measured and recorded. A reduction in biogas production is a clear indicator that either design operating parameters are not being maintained or a toxic substance has been fed into the digester. Biogas composition, the relative percentages of CH_4 and CO_2 by volume, is also an important indicator of process stability or instability. While the ratio of CH_4 to CO_2 in biogas will vary to some degree depending on the influent waste's chemical composition, an abrupt or even gradual increase in the percentage of CO_2 also indicates a loss of process stability due to a reduction in the conversion of CO_2 to CH_4.

4.2.2 Digester Monitoring

To keep the AD/biogas system operating, it must be monitored to detect problems and prevent upsets that can interrupt operation. Daily checks or monitoring should be made, at a minimum, of digester flow rates and loading rates. For heated digesters, the temperature of the digester contents should be continuously measured. In addition, the heat source being used for digester heating should be routinely inspected and maintained in accordance with the manufacturer's O&M manual.

Toxicity testing should be routinely done when co-digesting feedstocks come from outside sources. For example, typical sources of inhibitory materials in food processing wastes are compounds used for cleaning and sanitation such as chlorine and ammonia (NH_3). Many operators also check VFA levels on a regular basis but typically not daily. Measuring VFA concentrations requires more sophisticated analytical methods, either distillation or gas chromatography, and a specialized laboratory must perform these. The cost of these methods is significant and probably not justified for routine performance monitoring.

4.2.3 Effluent Monitoring

Digestate pH and alkalinity should be monitored. A properly operating digester will have neutral or slightly alkaline effluent pH between 7.0 and 8.0. However, pH tends to be a lagging indicator of anaerobic digester process instability.

The most reliable indicator of process stability is alkalinity. Alkalinity is the measure of a buffering capacity, or the ability to resist a change in pH due to the addition of an acid or base. Therefore, the accumulation of VFAs and CO_2 will be reflected in a reduction in alkalinity even before a decrease in pH. Measuring alkalinity is a relatively simple procedure and can be determined on site at a modest cost (the cost of chemicals and laboratory glassware).

4.3 Co-Digestion Recordkeeping

When wastes obtained from offsite sources are being co-digested with livestock manures, detailed records should be kept. Each source should be recorded, along with the date and time of delivery and the volume delivered. At a minimum, pH should be measured and recorded. Ideally, a representative sample of each delivery should be collected and preserved for possible future toxicity, physical, and chemical analysis.

4.4 Critical Issues Analysis and AD Performance

4.4.1 Digester Loading Risks

As noted previously (see Sections 3.2 and 4.1), maintaining a constant OLR is critical to successful AD health and performance. Rapid changes in OLR can adversely affect the biological balance, can cause undesirable conditions such as foaming, and can even cause the death of the methanogenic bacteria. When a digester fails because of unbalanced microbiological conditions, it must be emptied and restarted.

The main causes for upset conditions are an increase in feeding (OLR) or a drastic change in feedstock composition. Such changes cause an OLR spike that allows the acidogenic bacteria to exceed the growth rate of the methanogenic bacteria, lowering the digester's pH. A second cause would be the introduction of toxic elements. This would likely result in a more rapid system death than an overfeeding situation.

A digester will give several "warning signs" or indications as performance decreases and before catastrophic failure. The first indicator is a reduction in the CH_4 concentration of the biogas. Continuous biogas analyzers are preferred for monitoring the CH4 concentration of the biogas, as they provide the most frequent and accurate indicators of system upsets. However, due to cost, many systems do not use a continuous biogas analyzer and rely on handheld meters that provide manual measurements. Regardless of approach, the monitoring system must be routinely calibrated according to manufacturer recommendations and the data recorded and analyzed on a frequent and routine basis.

A second early indicator of digester health is the digestate's total alkalinity content. A digester may be experiencing an upset condition when the alkalinity decreases. pH is often used as a health indicator. However, because changes in pH happen over a longer time period than changes in alkalinity, pH testing does not give an early warning of an upset condition. Other digester heath indicators are a rise in the concentration of VFAs and the ratio between VFAs and alkalinity.

Regardless of approach, the monitoring system must be routinely calibrated according to manufacturer recommendations and the data recorded and analyzed on a frequent and routine basis.

4.4.2 Foaming

A sudden, rapid increase in organic loading may cause solids to float on the digester surface and trap air, leading to the collection of foam on the digester surface; this is called foaming.[7] Foaming is a serious problem, typically found in the main biogas reactor or in the pre-storage tank within a biogas plant. Entrapped solids in the foam can cause severe operational problems, such as gas meter blockage and pump collapse, as well as over-pressurization and thus overflowing of tanks. Experiments and observations of full-scale digesters have shown that foaming results from an increase in the OLR. Foaming leads to reduced biogas production for shorter or longer periods of time, which results in poor economic consequences for the biogas plant.

4.5 Critical Issues Response

The system operator should begin making the required adjustments when the digester monitoring program first detects any trends of increased VFAs, reduced alkalinity, reduced pH, reduced CH_4 concentrations, or increased CO_2 concentrations in the biogas. Digesters take a long time to respond to certain changes, and when indicators associated with these changes show issues, the problem has usually been developing for some time. For example, by the time pH is affected, the problem has likely become serious.

The most probable causes of digester failure are a sudden increase in the organic loading rate, a sudden decrease in the HRT, or the introduction of one or more toxic compounds. These scenarios lead to a decline in the population of the slower growing autotrophic methane forming bacteria relative to the population of the faster growing heterotrophic acid forming bacteria. The result of this population imbalance is an increase in the concentration of VFAs, which toxic in higher concentrations. A significant increase in digester effluent VFA concentration is a leading indicator of impending process failure. Both effluent alkalinity and pH will decrease in response to the increase in the VFA concentration (with alkalinity being the more sensitive parameter). Ultimately, this population imbalance will be reflected in biogas composition with the CO_2 fraction increasing due to the reduced reduction of CO_2 carbon to

[7] Kougias, P. G., Boe, K., & Angelidaki, I. (2013). Effects of organic loading rate and feedstock composition on foaming in manure-based biogas reactors. *Bioresource Technology, 144*, 1–7. https://doi.org/10.1016/j.biortech.2013.06.028.

CH_4. Table 4-1 summarizes the relationship among these parameters when process failure is imminent or occurring.

Table 4-1. Digester failure relationships.[8]

VFA (mg/L)	Alkalinity (mg/L)	pH	CO_2 (%)	CH_4 (%)
Up	Down	Down	Up	Down

[8] Spencer, C., & Sheff, B. B. (2017, June 18). *Chemistry for digesters* [Presentation]. American Biogas Council.

5.0 Laboratory Testing and Data Recording

5.1 What Tests Should You Do?

Every AD/biogas system should be equipped to perform routine testing of operating parameters. Refer to manufacturers' instructions to ensure all routine tests are calibrated appropriately and on a required schedule. These data should be recorded and ideally graphed over time to monitor system performance. The following parameters are essential to determining system performance and efficiency:

- TS
- VS
- pH
- Total alkalinity
- Temperature
- CH_4

These critical operating parameters require frequent monitoring and testing. The actual frequency varies by parameter and is discussed in further detail in Section 5.3. These measurement tests do not require significant expenditures for equipment, nor extensive training. Various manufacturers sell test kits for TS/VS and alkalinity that are relatively simple and accurate. Meters for determining pH are commonly available with calibration liquids to assure their accuracy.

Monitoring additional parameters generally requires onsite sampling and lab analyses, including those listed in Table 5-1

The specific types of tests that should be run vary for each digester. Many are only relevant to digestate, and some only apply to discharge limits for effluent discharge to a municipal sewer system. Some may not apply to livestock manure systems. When the facility is connected to a municipal sewer system, the facility's discharge permit may contain limits for other parameters that will need to be tested. The recommended sampling for parameters in digester influent and effluent, as well as individual feedstocks and post-digestion separated liquids, is shown below in Table 5-1.

Table 5-1. Recommended sampling for operating parameters.

Parameter		Each Feedstock	Digester Influent	Digester Effluent	Separated Liquids
Total Solids	TS	✓	✓	✓	
Volatile Solids	VS	✓	✓	✓	
pH	pH			✓	

Parameter		Each Feedstock	Digester Influent	Digester Effluent	Separated Liquids
Total Alkalinity				✓	
Temperature			✓	✓	
Biochemical Methane Potential	BMP	✓	✓		
Volatile Fatty Acids	VFAs			✓	
Chemical Oxygen Demand	COD	✓	✓	✓	
Biochemical Oxygen Demand	BOD				✓
Ammonia	NH_3	✓	✓		
Total Kjeldahl Nitrogen	TKN	✓	✓		
Total N-P-K		✓	✓		✓
Secondary Nutrients		✓	✓		✓
Metals		✓			✓
Microbial Inhibitors		✓	✓	✓	
Sodium	Na	✓			✓
Pathogens		✓	✓	✓	
Toxicity	ATA	✓	✓		

Effluent testing for TS, VS, pH, total alkalinity, temperature, COD, and pathogens should be part of every operating digester's regular testing program. Individual feedstocks should be tested before being added to an existing digester, including testing for TS, VS, COD, NH_3, and TKN. BMP and toxicity (ATA) testing of individual feedstocks can indicate their impact on the digester system. A BMP test for digester influent should be done using a proportional recipe that reflects the relative volumes of existing and proposed feedstocks. Once BMP testing is completed, the remaining tests for the feedstocks should be done to assess any other potential impacts they may have on the system. BOD testing is usually only done on the effluent if it discharges to a publicly owned wastewater treatment system or if a permit is required for surface water discharge.

5.2 Where Samples Should Be Taken and Proper Sampling Procedures

Proper sampling is required to obtain accurate test results. It is difficult to obtain a representative sample due to the large volumes generally associated with digesters. Digester facilities should have sampling ports for collecting samples at various points in the process. Many pumps have valve drainage ports to allow for their servicing. These ports may also serve as sampling ports.

For conventional low solids digester systems, the digester's influent and effluent should be sampled. Samples should be taken downstream of the feed pump while the pump is operating. If the system includes a storage tank with mixing and equalization, the sample taken from the feed line will be representative of the composite feedstock. If the feedstocks are fed separately, a sample will need to be taken while each feedstock is being added, and a composite sample that reflects the volume of each feedstock will need to be created. As with the influent, samples of the effluent should be taken while it is flowing. The effluent from a wet digester is mixed enough to serve as a representative sample. The effluent should be sampled prior to any solid separation.

When taking the sample, let the sample port run for a small time to flush any accumulated material in the valve and piping. Samples should be placed in clean jars designed for the appropriate sample.

When dealing with high solids waste, it may be difficult to capture a representative sample. It is best to start with a large sample and create a usable sample by visually selecting appropriate representative components based on observed ratios. Ideally, the large sample would be divided into components and each component weighed to get its relative percentage. This sampling procedure is difficult and is not regularly performed for farm-scale digesters.

Biogas should be sampled from at least three points: in the biogas line exiting the digester, after water separation, and after removal of H_2S. Sampling can be done using an automated or handheld sampling and analysis device. If samples are to be sent to an offsite lab, containers recommended by that lab should be used for the samples.

If solids are separated from the effluent, the liquids should be sampled after separation. The samples should be collected as the liquid is being separated. Most separators use a gravity discharge, so the sample could be drawn from the liquid discharge point into a holding vessel or a sample port in the gravity line.

It is important to protect the integrity of any samples. For onsite lab analysis, the samples would ideally be analyzed immediately. If this is not possible, the samples should be refrigerated until analysis. For samples being sent to an outside lab, the samples should be immediately cooled and transported. Most samples should be shipped in ice to ensure they degrade little during transport.

5.3 Frequency of Testing

Influent and effluent should be tested daily for:

- TS
- VS
- Alkalinity
- pH

- Temperature

Influent and effluent should be tested weekly for:

- COD
- Pathogens

The remainder of tests for influent should be based on a monthly sampling program. Effluent should initially be tested for VFAs daily. Once the digester effluent shows stable VFA values, this test should be done weekly. If the VFA/total alkalinity ratio is 0.25 or greater, VFAs and total alkalinity should be tested daily.

Biogas should preferably be sampled and tested using an online continuous meter programmed to collect and analyze samples at regular intervals. The meter should produce a record of continuous biogas characteristics. If using a handheld analyzer, the operator should take samples at least twice a day.

While manure-only AD systems should not have issues with siloxanes, these compounds can be found in a host of consumer products that may be present in co-digestion feedstocks. If feedstocks are suspected of being from sources that could create siloxanes, the biogas should be tested once the substrates have been in the system long enough to be converted to biogas. Siloxanes are volatile organic silicon compounds. When biogas is burned as fuel, the silicon in siloxane oxidizes to silica. High silica concentrations can reduce the lifespan of capital equipment, resulting in greater plant O&M expenses. Filtering systems can be used to reduce siloxane concentrations prior to combustion, but filter efficiency must be evaluated regularly. A variety of methods that use different sampling techniques and detectors have emerged to measure siloxanes.[9] Accurate monitoring of all the siloxanes known to be present in biogas is needed to avoid damage to power generation systems. If biogas testing indicates that siloxanes are being formed, the supplier of the suspect feedstock should be notified, and the feedstock eliminated.

5.4 Data Evaluation

Data from lab testing for TS, VS, total alkalinity, VFAs, COD, BOD, NH_3, TKN, total N-P-K, secondary nutrients, and sodium are generally expressed as either percentages or in mg/L. By definition, a liter of water weighs 1,000,000 mg, so by inference, 10,000 mg/L is a 1 percent solution. Some labs report the test result concentrations as mg/kg; in practice the units are used interchangeably, since under standard conditions a liter of water weighs 1 kg.

The critical factor for feeding a digester is OLR, which is mass per unit of volume per day. For test results to be meaningful, the concentrations noted above must be converted to a mass flow.

[9] Hayes, H. C., Graening, G. J., Saeed, S., & Kao, S. (n.d.). *A summary of available analytical methods for the determination of siloxanes in biogas*. https://www.eurofinsus.com/media/15873/a-summary-of-available-analytical-methods-for-the-determination-of-siloxanes-in-biogas.pdf.

To do this, one must know the volume of flow to which the concentration corresponds. Digester facilities should have flow meters on the influent, effluent, and liquid flow from a post-digestion separator. If the facility feeds separate feedstocks from multiple containers to the digester, there should be a flow meter on each line to the digester. Few digester facilities are equipped in this manner and instead rely on estimated flows for analysis. Proper flow metering is a relatively small investment and makes monitoring the digester's performance easier and more accurate.

In the United States, most flow meters read in gallons. They can provide gallons per minute or can be equipped with a flow totalizer to record accumulated flow over a time period. If the meter reads in gallons per minute, the flow rate (gallons per minute) will need to be multiplied by the number of minutes the flow occurred over a 24-hour period to get the total gallons of flow per day. If the flow meter has a totalizer, the operator will need to record the totalizer reading at a consistent time for each 24-hour period to determine gallons per day. To calculate the mass, gallons will need to be converted to pounds and kilograms. It is also possible to purchase meters that record in cubic meters. A cubic meter contains 1,000 kg of water.

To convert mg/L and gallons/day to lb/day, multiply the test result in mg/L by 0.0000083454, times the gallons per day. This is derived from:

$$\frac{lb}{day} = (\frac{mg}{L}) \times \left(\frac{1\ kg}{1{,}000{,}000\ mg}\right) \times \left(\frac{2.20462\ lb}{kg}\right) \times \left(\frac{3.78541\ L}{gal}\right) \times \left(\frac{gal}{day}\right)$$

For mg/kg, the same multiplier applies, as the numerical values of mg/L and mg/kg are equal.

TS is expressed as the concentration of the solids in the sample. VS may be expressed as the concentration in the total sample, but it is most commonly expressed as a percentage of the TS. If the lab report shows TS equals a percentage and VS equals a percentage of TS, convert the TS percentage to a value in mg/L and multiply that TS value by the VS percentage to get the VS value in mg/L.

For example, if TS is expressed as 10.7%, this is equal to 10,700 mg/L. If VS is expressed as 83% of TS, this means that VS is 10,700 x 0.83 = 8,881 mg/L.

To calculate the VFA/total alkalinity ratio, divide the mg/L of VFAs by the mg/L of total alkalinity. This value should normally be between 0.1 and 0.25. A ratio higher than this indicates an upset condition.

To properly monitor the digester's performance, the operator must record the test results and the calculated mass based on the test results. The trending data will help the operator maintain the proper biological balance required for healthy bacteria.

Biogas quantity and quality should be plotted as well so that any variations can be trended. If the facility contains multiple digesters, it is best to record flow rates and biogas characteristics for each digester separately. While digesters may appear identical, they are each individual living colonies and respond as such. Monitoring each digester independently allows the system operator to maximize biogas production while minimizing potential upsets.

6.0 Fundamentals of Digester Mechanical Systems

An AD/biogas system is primarily a mechanical system. To function properly, digesters rely on an integrated conveyance network moving materials throughout the entire facility. A key part of the conveyance network is the system of pumps and pipes controlling the digester's feeding and the discharge of treated digestate.

6.1 Pumps

A digester's ability to produce biogas depends on regular feeding and digestate removal. A pump is the equipment primarily responsible for moving feedstocks from storage and then later moving the treated digestate through the process. Maintaining the pumps to operate at their design capacity is critical to maintaining system health.

6.1.1 Pump Types

The type of pump used depends on the feedstock or influent TS concentration and piping system pressure requirements for moving the material. Dilute materials with a low TS concentration (i.e., less than 6 percent) are generally pumped using centrifugal pumps.

For influents with higher TS concentrations (up to 12 percent), most digesters using manure feedstocks either use "chopper pumps" or positive displacement pumps. Chopper pumps are essentially centrifugal pumps with a cutter on the pump inlet that grinds the solids a bit finer prior to pumping them. This type of pump allows for a more uniform particle size and can pump higher TS concentrations than a conventional centrifugal pump. These pumps are typically used for feedstocks with TS concentrations between 4 percent and 12 percent.

Text Box 6
Pump Types

Different pumps are designed for specific types of substances:

- Centrifugal pumps are for substances with low TS.
- Chopper pumps grind solids before pumping.
- Positive displacement pumps are for substances with high TS.

Another pump type is the positive displacement pump. This pump works by forcing small slugs of material through the pipes. This allows the pipes to move higher TS-concentration materials using less horsepower than a comparable chopper pump. Positive displacement pumps are generally used for pumping slurries with TS concentrations between 10 percent and 15 percent. The main types of positive displacement pumps are as follows:

- Rotary lobe
- Progressive cavity
- Piston

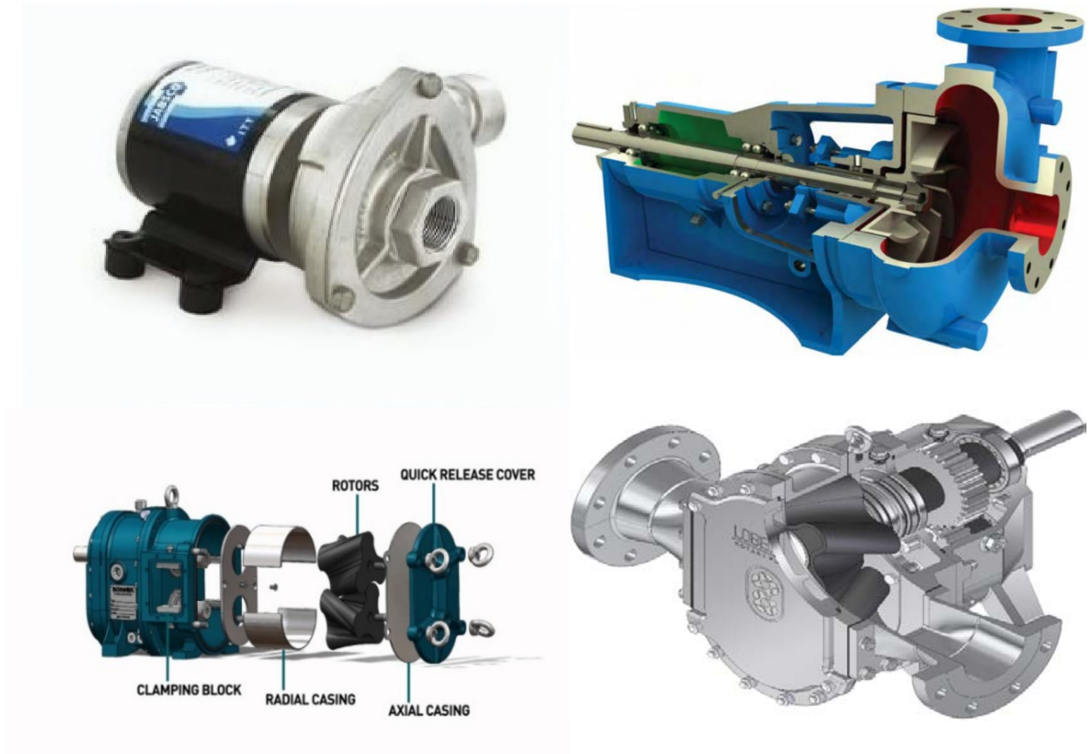

Figure 6-1. Pump type examples.

This figure features the 50840 series Low Pressure Cyclone Centrifugal Pump (top left),[10] a Horizontal Hydro-Solids pump (top right),[11] the BLUEline rotary lobe pump (bottom left),[12] and a LobePro Rotary Pump (bottom right).[13]

For a pump to perform properly, the piping system must be designed for the pump's pressure requirements and the expected TS concentration of the material to be pumped.

6.1.2 Redundancy

Because pumps are critical to the system's operation, system redundancy is important. System redundancy is to have duplicative equipment at critical points in the system to limit interruption of waste flow. A system's specific redundancy needs depend on the design of the entire AD/biogas system, including storage, pump rates, and the potential for environmental issues if the system fails. While digesters will continue to make biogas for an extended period without influent flow, projects are seldom able to store feedstocks for long periods. Redundancy is

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[10] Image source: Xylem, https://www.xylem.com/en-tj/products-services/pumps--packaged-pump-systems/pumps/end-suction-pumps/clean-water-clear-liquid/50840-series-low-pressure-cyclone-centrifugal-pump.

[11] Image source: Phoenix Pumps, Inc., https://www.phoenixpumps.com/goulds-pumps-itt-hs-hsd-horizontal-hydro-solids-pumps_8_1237_1306.html#.XLoGxehKiUl.

[12] Image source: Börger, https://www.boerger.com/en_US/products/rotary-lobe-pumps/pump-series/the-blueline-rotary-lobe-pump.html.

[13] Image source: Phoenix Pumps, Inc., https://www.phoenixpumps.com/lobepro-rotary-lobe-pumps_8_1231_1109.html#.XLn2Y-hKiUk.

important for critical areas where pump repairs cannot be made in a timely fashion. In these process areas, having at least one redundant pump is recommended.

A similar pump from a non-critical location can be substituted for a failed critical-use pump, but this requires that the same manufacturer and type of pumps are used throughout the conveyance. A single redundant pump can also serve multiple locations.

6.2 Piping Systems

The piping system must be monitored and maintained to allow the proper feeding of feedstocks and movement of digestate. The piping should routinely be checked for leaks, and all manual and automated valves should be periodically checked for proper operation. Manual isolation valves should always be kept serviceable. It is beneficial to have pressure sensors on the piping to control over-pressurization.

6.3 Mixing

Mixing is an integral part of the AD/biogas system. This section describes why mixing is important, where mixing should be done, what types of mixers are available, and several other important factors to consider.

6.3.1 Why Mix?

To provide a uniform feed rate, most AD/biogas systems accumulate waste in an influent storage tank before periodically transferring it to the digester. Typically, manure is removed from livestock confinement facilities on a periodic basis. For example, manure may be collected by flushing two to three times per day. In addition, wastes for co-digestion may be delivered daily or even less frequently. Thus, mixing is important to maintain uniformity in the influent's physical and chemical characteristics.

High-rate AD requires continuous mixing. Mixing's primary function is to prevent settling and the accumulation of settled solids. Settled solids reduce the actual HRT and SRT and therefore need to be removed, which creates additional work. Mixing in a high-rate digester also facilitates heat transfer from heat exchangers and keeps the digester temperature uniform. Mixing also improves substrate-to-microorganism contact.

6.3.2 Mix Where?

Mixing should be done wherever feedstock is stored, even for short periods. Mixing inside a digester should be done at differing height levels throughout the tank to ensure complete mixing. A dedicated mixer, or a mixer that can be brought to the surface of the liquid in the digester, is used to prevent crust formation.

6.3.3 What Are the Mixer Types?

Depending on the purpose of the mixer, different types of mixers are used. Mixers can be used for agitating solids to keep them suspended (typically a high rate of mixing) and for creating homogeneous conditions inside the digester (typically a slow rate of mixing), among other purposes. This section provides a general introduction to various options.

Mixers are generally divided into two types: submersible and external mount. Depending on their functions, mixers operate at either high speeds or low speeds. Mixers are powered with either electric motors or hydraulic motors. Submersible mixers are generally mounted to rails or lifts attached to the tank sidewall. This allows for easy removal for maintenance and repair. External mount mixers are located outside the tank on sidewalls or ridged digester covers.

Digesters can also be mixed hydraulically using a submersible or external pump with nozzles that increase discharge velocity to recirculate the digester contents. Another option is gas mixing using compressed biogas released from the base of the digester.

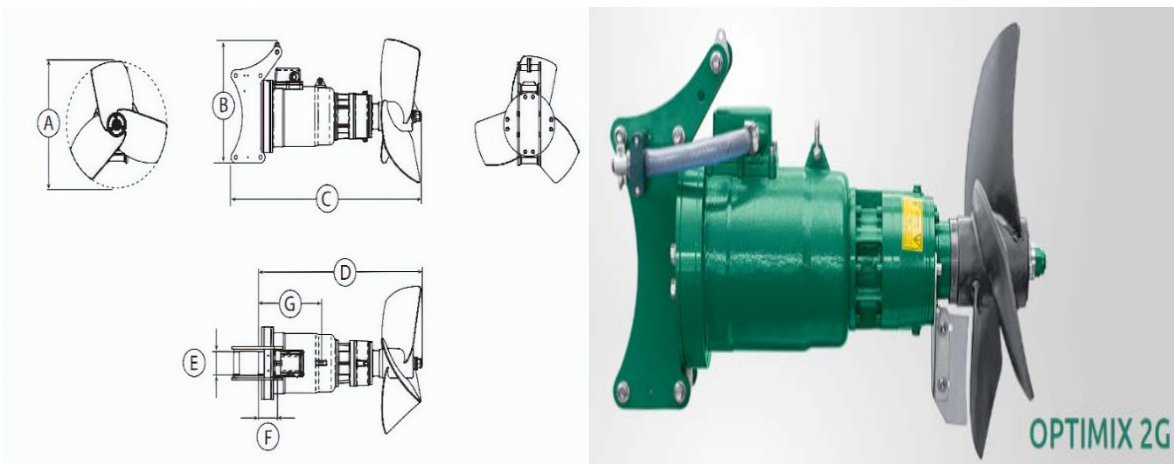

Figure 6-2. Illustration of a submersible mechanical mixer.[14]

6.3.4 What Are Mixer Maintenance Concerns?

O&M concerns for external mixers include the proper lubrication of the gearbox and the integrity of the penetration where the mixer enters the tank. For example, poor maintenance of the seal where the mixer enters the tank can result in biogas or liquid leaking from the tank.

O&M concerns for submersible mixers involve maintaining the seals that prevent the intrusion of water into the motor and other electrical parts, the integrity of the mounting structure, and the integrity of the seal for electrical wiring or hydraulic lines.

6.4 Influent and Effluent Management

The digester influent may require pretreatment and flow equalization. The digester effluent may require processing and storage.

[14] Image source: SUMA America Inc., https://www.gosuma.com/gosuma/agitators-biogas-agriculture-optimix_2g.html.

6.4.1 Pretreatment

The type of feedstock used, the conveyance system, and the type of digester used dictate the amount and type of preprocessing. Preprocessing involves using storage to control the feeding of the digester. Preprocessing systems include:

- Separating fiber of dairy manure, if necessary
- De-packaging food wastes
- Reducing feedstock particle size
- Screening non-volatile materials
- Removing grit
- Separating sand

6.4.2 Flow Equalization

As noted in Section 6.3.1, feedstocks are rarely brought to a digester facility in a continuous manner, whether they are manures being collected or feedstocks transported from off site. For this reason, many digester plants include feedstock storage to provide flow equalization by allowing for a continuous, consistent input of influent.

6.4.3 Digestate Processing/Storage

Typically, digestate it is composed of undigested organic and inorganic materials contained in the digester feedstock, as well as water. One of the many management issues associated with using an AD/biogas system is how to properly treat and manage the digestate.

Digestate is typically discharged to a storage lagoon or pond, and then it is often land-applied on crops. When anaerobically digested dairy cattle manure has not been screened before digestion, a significant quantity of coarse fiber remains in the effluent. This coarse fiber consists primarily of lignin, which biodegrades very slowly. Mechanical solids separation equipment such as screw presses or vibrating screens can remove this fiber. The separated solids have value as a bedding material or soil amendment. Depending on the end use, the separated solids may be dried, composted, or both.

After the fiber is removed, the main digestion product is a liquid organic substance commonly called “filtrate.” Filtrate from manures commonly has combined nitrogen, phosphorus, and potassium percentages ranging from 3 percent to 4.5 percent on a dry matter basis, and it can be spread directly onto farmland to provide nutrients. Filtrate can also be further processed into a liquid material called “centrate” and a solid product called “cake.”

Another aspect of AD/biogas system effluent management to consider is nutrient management. This is critical when wastes from offsite sources are being incorporated into the digester influent. These wastes may contain significant concentrations of the primary plant nutrients nitrogen, phosphorus, and potassium. Thus, the impact on the ultimate disposal site’s comprehensive nutrient management plan must be considered. Some AD/biogas systems include nutrient recovery technologies to help manage the amount of nutrients in the digestate.

7.0 Biogas Handling and Conveyance

Biogas handling and conveyance is an important aspect of AD/biogas system management to ensure safety, ensure proper system operation, and prevent equipment damage. Biogas is generally between 50 percent to 75 percent CH_4. The remaining amount is primarily CO_2, trace quantities (0 to 15,000 parts per million [ppm]) of corrosive H_2S, and water vapor.

7.1 Biogas Handling and Conveyance

Because both CH_4 and CO_2 are only slightly soluble in water, biogas produced by an AD/biogas system is continuously emitted from the digesting substrate and is collected and temporarily stored in the digester's headspace. Because biogas is continuously produced, it must be continuously removed to maintain a safe pressure level in the digester. Otherwise, mechanical failure of the cover or some other structural element will occur.

When produced, biogas is a saturated gas. This means it is at 100 percent relative humidity and contains all the water vapor that it can possibly absorb. Untreated, this water vapor can readily condense and cause damage inside piping and equipment. The water vapor must first be separated from the biogas and then properly disposed of.

CH_4 and H_2S are both flammable gases, and considerations must be taken to prevent a fire or explosion. Additionally, both H_2S and CH_4 can be toxic to humans. H_2S also forms highly corrosive sulfuric acid when it is combined with water. Due to these factors, special considerations must be taken to ensure personnel safety (see Section 10.0) and to prevent damage to the AD/biogas system's components (see Section 8.0).

7.2 Leak Testing

Because of the toxic, flammable, and corrosive nature of biogas, a leaking biogas handling system can pose a major threat to personnel safety and AD/biogas system operation. Avoiding biogas leaks also has financial significance, as lost biogas is lost income.

Prior to the startup of a new or newly modified AD/biogas system, all biogas piping and connections should be pressure-tested to ensure that there are no leaks. This testing is typically performed by isolating and pressurizing the biogas handling system with compressed air or nitrogen. System pressure is then monitored over a time period specified by the system designer. In the event of a leak, the leak's location can be identified by spraying the exterior of the biogas handling system with a mixture of soap and water – bubbles will form where leaks are present. This method can also detect leaks in a biogas handling system after disassembly or modification.

Leaks are common at places like piping joints, fittings, valves, and equipment connections. AD/biogas system operators can monitor for biogas handling system leaks by looking for odors, physical changes in the piping, and unexplained decreases in biogas flow rates. A portable meter designed for detecting natural gas leaks should be used routinely to test for leaks in biogas piping and all other possible sources of leaks, such as flexible digester covers.

When biogas is processed or utilized in an enclosed structure, the risk of fire or explosion increases. Therefore, it is recommended to install a permanent gas detection and alarm system (see Figure 7-1).

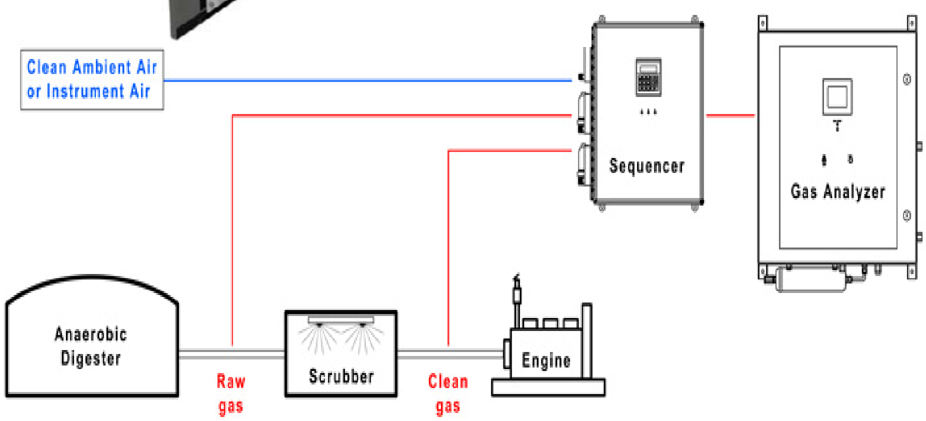

Figure 7-1. Gas analyzer and flow diagram of sequence and gas analyzer.

Biogas handling system leak detection technologies monitor odors, physical changes in the piping, and unexplained decreases in biogas flow rates. Examples include the BIOGAS 3000 (top), a gas analyzer.[15] A flow diagram (bottom) shows how a sequencer and a gas analyzer help evaluate the quality of the gases.[16]

7.3 Pressure Regulation

Because anaerobic digesters are sealed vessels and biogas is generated continuously, any restriction of the flow of biogas from the digester will increase the internal digester pressure

[15] Image source: Landtec, https://www.landtecna.com/product/biogas3000-2/.

[16] Image source: Nova Analytical Systems, https://www.nova-gas.com/analyzers/landfill-biogas.

above the design value. Other causes of excessive digester pressure include a biogas production rate that exceeds biogas use or processing capacity, processing equipment failure or other circumstances that result in failure to use the biogas. A blockage caused by condensate buildup, foam carry-over into the piping, or frozen valves/fittings can also raise the internal digester pressure.

To ensure the integrity of the digester's reactor and the biogas handling system, an automatic pressure relief valve (PRV) should be a component of every AD/biogas system. The PRV should be connected to an automatically igniting flare to burn the released biogas. See Figure 7-2 for examples of PRVs. Depending on the type of downstream equipment, pressure/vacuum relief valves can also be installed to prevent an excess vacuum from occurring inside the digester or biogas handling system.

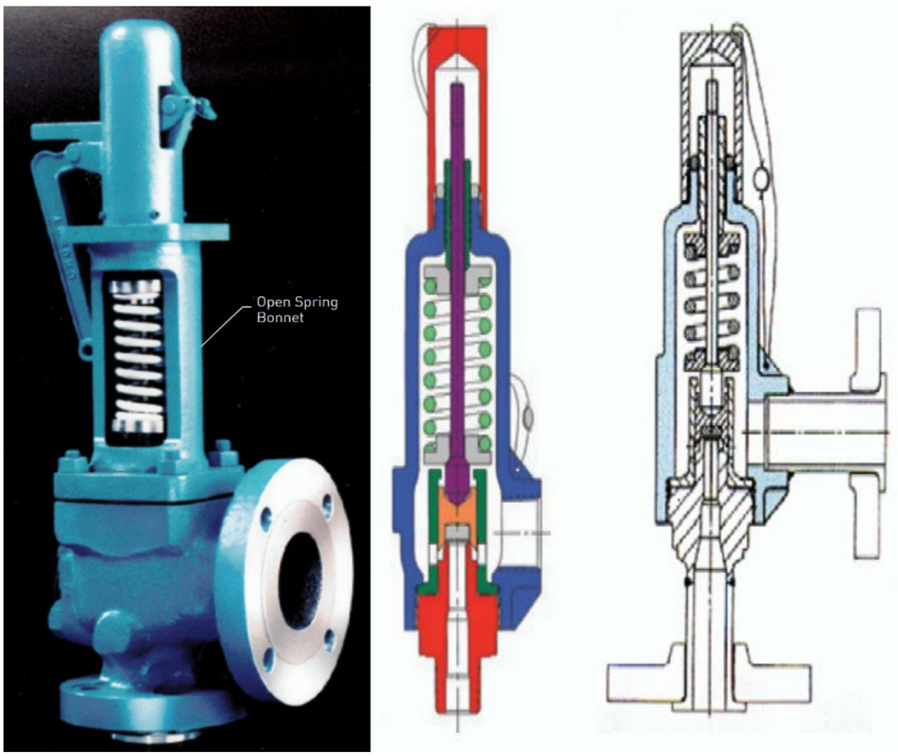

Figure 7-2. Examples of PRVs.

Pressure relief systems are designed to protect the vessels and piping in the event of a blockage or biogas generation pressures that exceed design specifications. PRV examples include an open bonnet direct spring PRV (left), a threaded portable direct spring PRV (center), and a flanged portable direct spring PRV (right).[17]

7.4 Condensate Removal and Freeze Protection

The amount of water vapor in biogas is a function of temperature and pressure. The water vapor will condense as the biogas cools. To avoid condensed water vapor accumulation, biogas piping

[17] Image source: Emerson, https://www.emerson.com/documents/automation/pressure-relief-valve-engineering-handbook-en-us-3923290.pdf.

should be sloped and fitted with one or more self-dumping condensate traps. In regions where freezing temperatures are probable, the biogas piping system should be insulated and possibly heated. It is important to note that insulation slows the transfer of heat from inside the piping to the outside environment, but it does not stop it entirely. In most cases, heat tracing must be installed to provide a heat source inside the insulation to prevent freezing in the case of extreme temperatures, extended shutdowns, or long piping runs. These freeze protection methods must be checked periodically to ensure they are functioning properly.

7.5 Piping

Biogas piping system designs are based on:

- Flow rate
- Pressure
- Moisture content
- Temperature

Piping systems are sized to allow for a certain pressure drop at a given biogas flow rate. Pressure drop through the piping system results from friction along the pipe walls and obstructions such as reducers, elbows, strainers, filters, and valves. If the biogas flow rate is higher than the design value, then the pressure drop through the system will also be higher than the design value.

Biogas piping systems should be constructed from corrosion-resistant materials due to the moisture content and corrosive nature of H_2S. Stainless steel, PVC, and high-density polyethylene are common construction materials used in biogas piping systems. Biogas piping systems should be designed and installed to allow for thermal expansion and contraction caused by temperature changes to the piping system. If piping system thermal expansion problems arise, expansion loops, flexible couplings, and rolling or sliding pipe supports can be installed to mitigate the issue and to help prevent damage to the piping system.

All piping systems should be adequately supported to prevent excessive stress, sagging, vibration, and the resulting damage to the piping system and potential risk to the system operators. Piping should be adequately supported throughout straight runs, at all direction changes, at equipment connections, and at wall penetrations. Piping systems should never be operated with modified or missing supports unless the designer has approved the modification.

7.6 Valves

Valves are used to isolate biogas lines and equipment for maintenance, to regulate line pressure, and to direct biogas flow to varying locations. Valve types commonly used in biogas handling systems include ball valves and butterfly valves, due to their relatively low pressure drop and positive shut-off capabilities.

Biogas handling valves can be manually operated by a lever, gear, or chainwheel, or they can be automatically operated by a pneumatic or electric actuator. The selection of the valve operator or actuator depends on the purpose of the valve, the location of the valve, and how quickly the valve must be opened or closed.

Valves used in biogas handling systems must have internal components that are compatible with the corrosive nature of biogas and condensate, as well as external components that are suitable for the environment in which the valves are installed. Valve internals commonly used in biogas handling systems include 316 stainless steel and Viton™. Valve external components are commonly cast iron, stainless steel, or polymer. Electric valve actuators must meet all electrical and fire prevention requirements for the environment in which they are installed. Valves should be exercised, or fully opened and closed, regularly to maintain their functionality and positive shut-off capabilities. The valve operator or actuator should also be inspected regularly for signs of wear or corrosion.

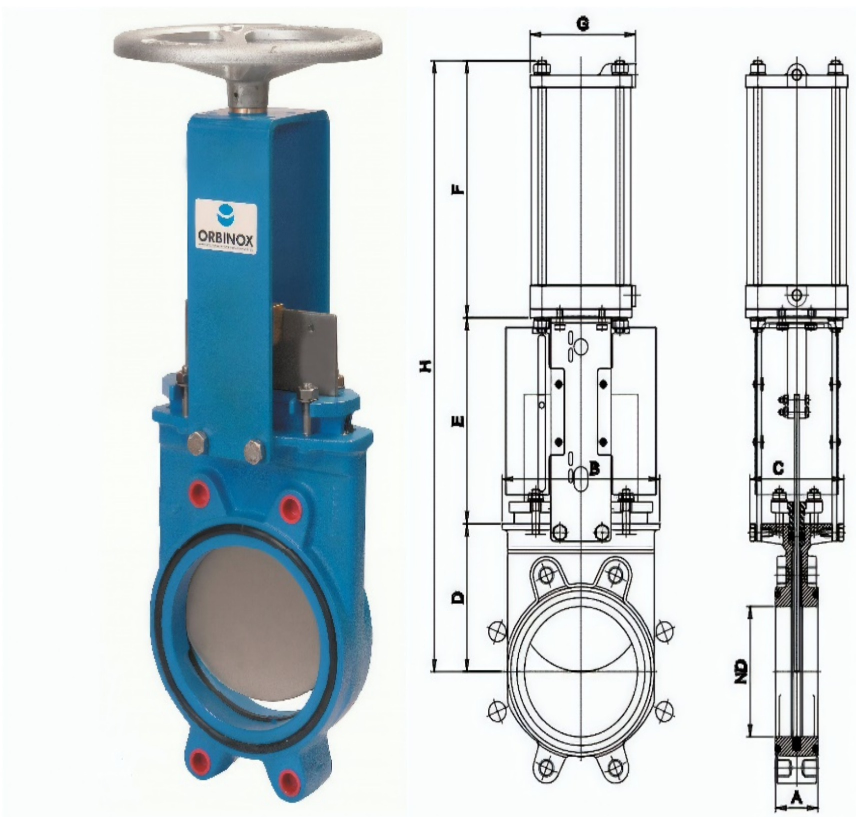

Figure 7-3. Photograph and schematic of an isolation valve.

Shown above is a type of isolation valve, a bidirectional knife gate valve that assures non-clogging shut-off on suspended solids. [18]

[18] Image source: Orbinox, http://www.orbinox.com/eb-ser11-bidirectional.

7.7 Blowers and Compressors

Blowers and compressors are designed to process biogas at specified flow rates, inlet and outlet pressures, and temperatures to increase the biogas pressure. Compressors generally increase the pressure to higher values than blowers. It is important to be aware of the design conditions for a blower or compressor system and to monitor the temperature and pressure at the inlets and outlets of blowers and compressors to gauge equipment performance and detect problems early.

Biogas blowers generally are equipped with bearings to support the drive shaft and seals to prevent biogas from escaping around the drive shaft into the surrounding atmosphere. It is important to monitor the condition of these bearings and seals and to make sure the bearings are lubricated according to the manufacturer's instructions.

Biogas compressors are often packaged with circulating oil systems to lubricate and seal the compressor components. It is important to monitor and maintain the condition of the compressor oil system, including the oil level, temperature, pressure, and replacement interval according to the manufacturer's instructions.

7.8 Biogas Use

7.8.1 Combined Heat and Power (CHP)

Historically, the most common use of biogas has been to produce combined heat and power (CHP) in a reciprocating internal combustion (IC) engine-generator set. Traditionally, spark-ignited diesel engines have been used. CHP systems are relatively efficient in converting biogas into heat and electric power. Common electrical conversion efficiencies approach 40 percent, and thermal recovery efficiencies exceed 50 percent. Thus, a CHP system can potentially recover around 90 percent of the available biogas energy content. In a CHP system, heat exchangers recover the heat generated by biogas combustion and engine friction from the engine cooling and exhaust systems. The recovered heat is typically used to maintain the operating temperature in the digester, with excess heat available for other uses such as space heating.

To prevent engine damage, moisture and most of the H_2S must be removed from the biogas prior to combustion. Proper O&M of the IC engine and generator is essential. Lubrication, cooling, electrical, and emission control systems must follow the manufacturer's instructions to ensure reliable service.

A few CHP systems have microturbines instead of an IC engine to drive the generator and to generate heat. In most microturbine systems, a separate combustion chamber allows for the combustion of biogas with higher H_2S and moisture levels than biogas that can be used in an IC engine. Microturbines generally operate with lower electrical efficiencies but higher thermal efficiencies than engine-based systems, making them more suitable for projects with a higher demand for heat or hot water. They also have lower emissions, making them more acceptable in areas with air pollution concerns.

Because onsite demand for electricity varies hourly and in some instances seasonally, most on-farm AD/biogas systems that generate electricity are interconnected with the local electric utility with a net metering agreement. This arrangement allows for electricity delivery to the local grid when electricity production exceeds onsite demand. The interconnection also allows the local utility to meet onsite demand during periods when the electricity generated from biogas is not adequate to serve all on-farm needs.

7.8.2 Boilers and Furnaces

Biogas also can be used in place of conventional fossil fuels to heat hot water (in a boiler) or air (in a furnace). Because biogas has a lower heat value, burners designed for natural gas or liquefied petroleum gas must be replaced to burn biogas. For boilers and furnaces designed to burn fuel oils, more extensive modification or possibly replacement is necessary.

Biogas composition must be carefully considered in the planning and design of a biogas-fueled boiler system. Biogas moisture content, as well as its H_2S and possible siloxane content, can cause problems in the boiler's internal workings. A biogas-fueled boiler may also be subject to a more stringent air pollutant emission monitoring and control requirement.

It is possible to replace the burners on other direct-fired unit process equipment, such as kilns and dryers, with burners designed for biogas. The burner and fuel delivery systems should be sized to provide the unit's required heat rating according to the equipment manufacturer's instructions. In this case, the biogas composition should also be carefully considered to properly account for H_2S, siloxane, and moisture content.

Variation in onsite demand is also a problem when biogas is used directly as fuel. A solution to this problem can be biogas compression and storage in a repurposed liquefied petroleum gas storage tank.

7.8.3 RNG

For farms with access to a natural gas pipeline, upgrading biogas to produce RNG can be a financially attractive option. However, the economic feasibility of this depends largely on the availability of renewable energy subsidies for which the project qualifies.

7.9 Biogas Processing

7.9.1 Processing for Onsite Combustion

The principal components of biogas are CH_4 and CO_2, with lesser amounts of water vapor, H_2S, and NH_3. During combustion, H_2S reacts with water vapor to form highly corrosive sulfuric acid. This acid atmosphere creates corrosive conditions that can quickly degrade combustion and emission control equipment. Therefore, removing or at least substantially reducing H_2S and water vapor concentrations in biogas is a prerequisite for biogas use in a combustion device. The degree of biogas processing that is necessary depends on its planned use.

Using biogas to fuel an IC engine or microturbine requires removal of most of the H_2S and ideally the water vapor to prevent corrosion of internal parts. Removal of H_2S is also necessary when biogas is used as a boiler or furnace fuel. Using ceramic burners designed for burning biogas also is advisable.

H_2S can be removed via adsorption into solid media, a biological scrubbing system, or a chemical scrubbing system. A small amount of air can be injected into the digester vessel headspace to support the formation of sulfur-reducing bacteria, which can provide a simple biological scrubbing system and contribute to H_2S removal inside the digester vessel.

The most appropriate method of H_2S removal depends on the biogas flow rate, H_2S concentration, and downstream processes being used. Generally, solid media adsorption is used for projects with lower biogas flow rates and H_2S concentrations. Biological or chemical scrubbing systems are used for projects with higher biogas flow rates and H_2S concentrations.

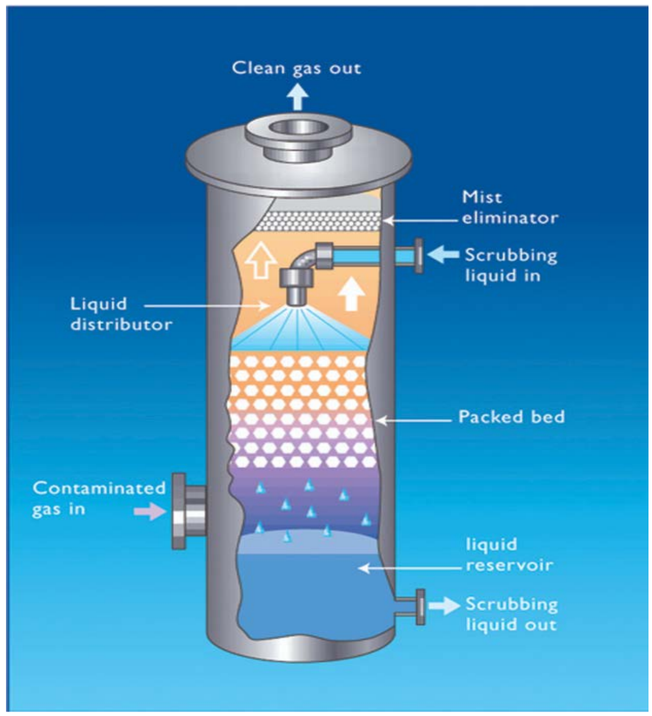

Figure 7-4. Cross-section of a packed tower scrubber for an H_2S removal system.[19]

Adsorption into solid media involves passing biogas through a bed of woodchips impregnated with hydrated iron oxide. The H_2S reacts with the iron oxide to form iron sulfide and water. Bed regeneration is performed by exposure to air, which converts the sulfide to oxide and liberates elemental sulfur (see Figure 7-4).

Because biogas is saturated with water vapor when it leaves a digester, some natural cooling results in at least partial condensation of the water vapor present. This condensed water vapor is easily removed using a series of one or more automatically dumping water vapor separators or traps. The quantity of water vapor removed depends on the difference between the biogas temperature and the ambient air temperature. Biogas produced in heated digesters contains more water vapor than gas produced in an unheated digester such as a covered lagoon.

Additional moisture removal can be achieved by cooling the biogas in a heat exchanger to condense the water vapor or through water adsorption into solid media. The most appropriate method for removing moisture depends on the biogas end use and its flow rate. Performance

[19] Image source: CR Clean Air Group, LLC., https://www.crcleanair.com/products/the-jet-venturi-scrubber/.

monitoring of any moisture removal system must be done to prevent downstream equipment O&M issues.

Silicon-based compounds, generally referred to as siloxanes, can also be present, particularly with the co-digestion of municipal or industrial wastewater treatment residuals. When burned, siloxanes precipitate out as a solid material similar to glass or sand. These precipitants can coat equipment surfaces, causing severe O&M problems. If siloxanes are present, they must be removed prior to burning the biogas.

As noted earlier, it is necessary to limit biogas pressure in a digester to avoid structural damage. However, some biogas compression is necessary during processing to ensure adequate fuel pressure and flow to the engine-generator set.

7.9.2 Upgrading to RNG

Selling biogas as RNG usually requires injection into a natural gas pipeline. Prior to injection, the biogas must be processed to satisfy natural gas industry standards, which include maximum allowable concentrations of CO_2, H_2S, and water vapor. The same standards generally apply when compressed RNG is sold locally as a vehicle fuel or liquefied for transport. Several options are available for moisture, H_2S, siloxane, and CO_2 removal (see "Biogas Cleanup Technologies" text box).

As noted in the Text Box 7, CO_2 can be removed using a pressure swing adsorption (PSA) process, membrane separation, chemical (amine) scrubbing, or a spray tower.

In a PSA process, CO_2 removal occurs in large, medium-pressure vessels containing solid media that have an affinity for CO_2 at moderate to high pressures. As biogas is passed through the vessel, the adsorption media capture the CO_2. When the adsorption media become fully saturated with CO_2, they are regenerated in place, and the CO_2 is liberated by lowering the vessel pressure. The low-pressure waste CO_2 is then vented. Figure 7-5 presents a typical adsorber bed.

Text Box 7
Biogas Cleanup Technologies

The following are technology options for biogas conditioning and upgrading.

Moisture Removal:

- Refrigerated drying
- Media adsorption

H2S Removal:

- Media adsorption
- Biological scrubbing
- Chemical scrubbing

Siloxane Removal:

- Media adsorption
- PSA

CO_2 Removal:

- PSA
- Membrane separation
- Chemical scrubbing
- Spray Tower
- Chopper pumps grind solids before pumping.
- Positive displacement pumps are for substances with high TS.

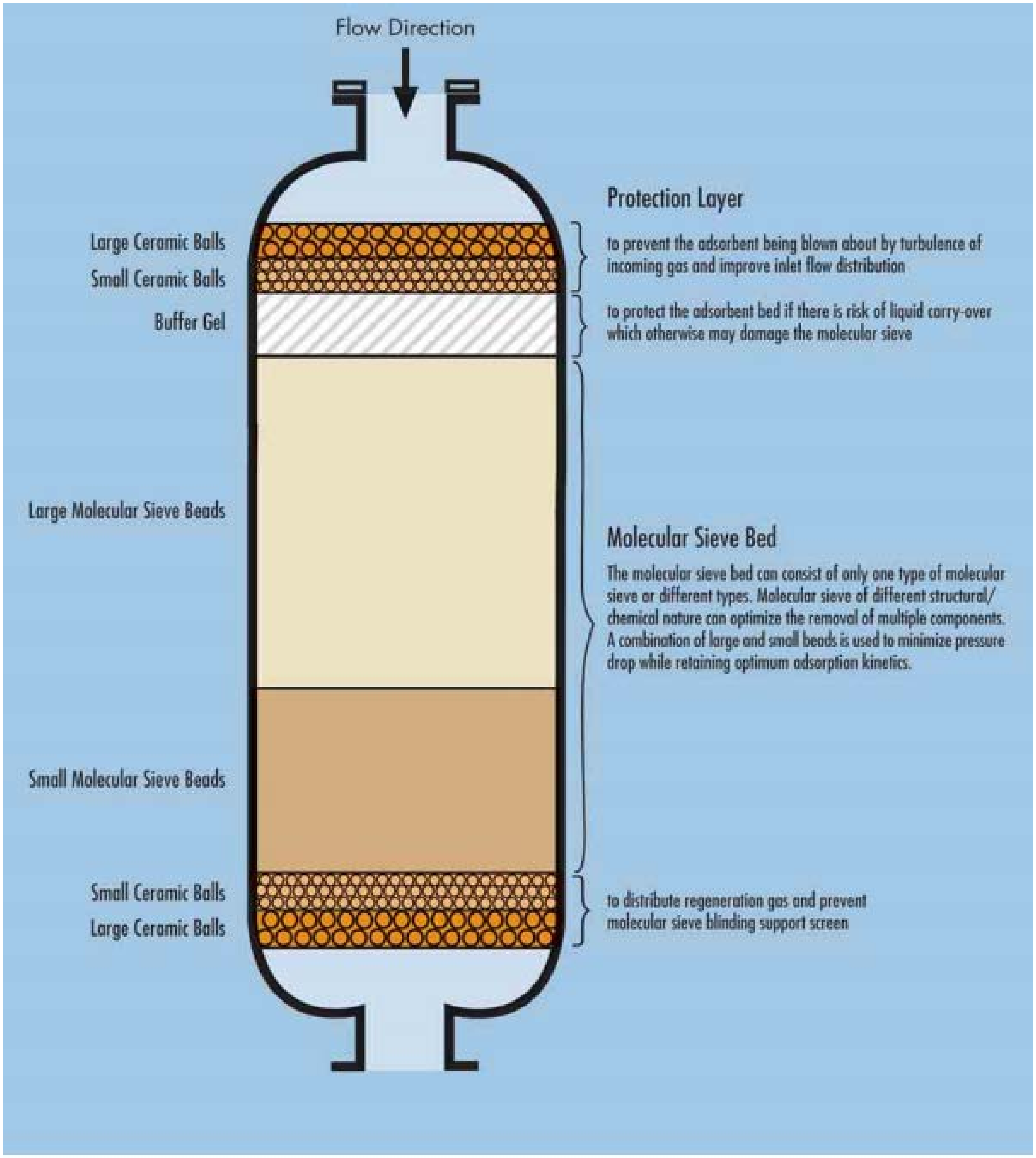

Figure 7-5. Cross-section of a typical adsorber bed.[20]

[20] Image source: GRACE Davison, https://grace.com/general-industrial/en-us/Documents/sylobead_br_E_2010_f100222_web.pdf.

The membrane filtration process, illustrated in Figure 7-6, uses physical separation that selectively separates the biogas based on the specific characteristics of its components.

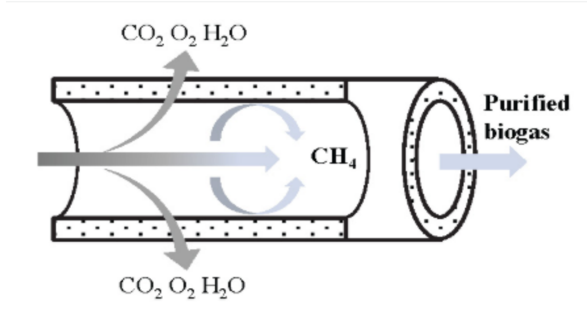

Figure 7-6. Schematic diagram of a membrane permeation. [21]

Amine scrubbers use the process of adsorption where a chemical solution, mono di-ethanol amine, is sent through the scrubber. Amine scrubbers are recommended for H_2S levels less than 300 ppm. The CO_2 is adsorbed by the solution and is removed with the solution. The CO_2 is separated from the solution in a heated tower and can be recovered. The amine solution is recycled to the amine tower.

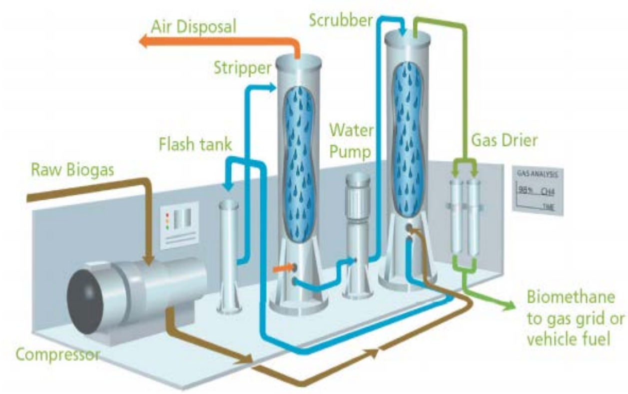

Figure 7-7. Water scrubbing unit flow schematic. [22]

A spray tower or wash system can remove both CO_2 and H_2S (Figure 7-7). The biogas is sent through the tower with a countercurrent stream of water particles. The soluble gas, CO_2, dissolves in the water and exits with the liquid. A send vessel releases the CO_2, and the solution is recycled. The system also removes H_2S, so water must be added to maintain the pH level to avoid creating acidic conditions in the vessels.

Bulk moisture is removed earlier in the process, but even more water vapor must be removed to produce pipeline-quality RNG. Maximum water content for most natural gas pipelines is either 105 ppm or 147 ppm, depending on the location. This dehydration level is usually achieved with a PSA system using a desiccant material. This is a system just like the CO_2 removal system, except that a different adsorption material is used.

If the biogas is being upgraded to RNG, extra compression is required to boost it to a high enough pressure to be introduced into a natural gas pipeline. Reciprocating or screw-type positive displacement compressors are frequently used to boost RNG to pipeline pressures. These compressors generate a lot of heat during the compression process. This usually causes the discharge gas temperature to become very hot, and a discharge cooler may be required. Oil

[21] Image source: Ohio State University Extension, https://ohioline.osu.edu/factsheet/AEX-653.1-14.

[22] Image source: EPA Landfill Methane Outreach Program, https://www.epa.gov/sites/production/files/2016-11/documents/pdh_full.pdf.

is used as a compressor lubricant, but it also functions as both a sealant and a coolant within the compressor.

Activated carbon is often used as a polishing step to remove any volatile organic compounds that were not removed during the previous biogas conditioning. The activated carbon adsorbs these contaminants.

8.0 System Inspection and Maintenance

Successfully producing biogas depends largely on the ability to prevent the failure of any AD/biogas system components. Operators should follow site-specific O&M plans, standard operating procedures, and maintenance schedules provided by vendors. Operators should also document and keep records of maintenance. Documentation of routine maintenance is helpful not only to the operation of the project but also in demonstrating effective management of equipment to regulators or community officials. Regulators may require records of maintenance and logs of operating parameters.

8.1 General Maintenance Requirements

Consistent and active O&M is the key to maximizing an AD/biogas system's uptime and ultimately project profitability. Operational prospects are enhanced when the basic process conditions remain at steady state and equipment operates properly. Equipment running poorly can cause process upsets or even digester shutdowns due to erratic swings in the process conditions. These swings negatively impact an operation's ability to make product-grade specifications and thus reduce profitability.

8.1.1 Routine Versus Major Maintenance

Performing routine maintenance on a regular schedule helps avoid unplanned equipment outages and possible process upsets. It may also help reduce the complexity and duration of scheduled major maintenance tasks. Operators should refer to their site-specific O&M plans for maintenance schedules and ensure that vendors are scheduled for routine maintenance. Comprehensive O&M plans include standard operating procedures.

8.1.2 Impact of Process Conditions on Frequency

Process conditions can affect equipment O&M schedules. The presence of H_2S in biogas that is used as boiler or engine fuel can have profound schedule impacts and can increase the complexity of equipment O&M. Sediments and debris in the piping can foul inlet strainers and filters, and if these issues are not monitored and dealt with in a timely manner, they can cause equipment damage or failure.

8.1.3 Monitoring Changes in Process Conditions

A typical indication of O&M issues is a change in process conditions with no other obvious related cause. An increased pressure drop across a heat exchanger, a different pitch to a pump's whine, or an increased temperature on a compressor's oil outlet are all early indicators of potential problems. Pay extra attention to these small signs of potential trouble, and schedule O&M as soon as possible—a small O&M job done early may prevent a much larger O&M job later. An excellent operator monitors process conditions and uses critical thinking to recognize and evaluate any process changes, such as unusual pump noises or abnormal trends in monitoring output, and identify potential problems these changes may indicate.

8.1.4 Insulation and Freeze Protection

In hard freeze-prone areas, any piping, valves, or instruments that regularly contain even small amounts of water should be heat-traced and insulated. Systems requiring the removal and then reinstallation of heat trace and insulation can make even the easiest O&M task more difficult. When properly installed, an electrical self-limiting-type heat trace and wrap-and-tie-type insulation for valves and instruments can make maintenance easier. Some equipment, such as pumps and the lower portion of vessels that contain water, may require insulation as a minimum and possibly heat tracing as well. Be diligent about reinstalling heat trace and insulation following inspection or repair of piping and equipment systems. Consider installing equipment, piping, valves, or instruments containing water that are difficult or impossible to heat-trace and insulate in a heated enclosure or building.

8.1.5 Housekeeping

It is important to keep the work areas around the AD/biogas system free of clutter and dirt. This will help to prevent trip hazards, keep pests at bay, and keep equipment running properly.

A dusty environment can be hard on equipment, especially equipment requiring combustion air such as boilers and IC engines. In dusty areas, increase the frequency of inlet air filter changes for boilers and IC engines. Aerial coolers used for waste heat dissipation on an IC engine or CHP system also require more frequent inspection and cleaning. Lastly, dust buildup on motor exteriors can decrease a motor’s cooling efficiency and lead to premature failure.

Keeping up with painting is a never-ending job, but it is important to maximizing the longevity of the system. Remember to not paint over the equipment, valve, and instrument tags and labels; these contain vital information that will need to be read sooner or later.

8.1.6 Buildings/Heating, Ventilation, and Air Conditioning (HVAC)

Portions of some systems are simply better off when located in a building. This is not just for freeze protection or better climate control but to make O&M easier. For example, locating a CHP engine-generator set in a building allows for the permanent installation of building cranes required for larger O&M tasks. Also, it is significantly easier to perform some O&M tasks in a climate-controlled building with cover from snow, rain, and wind. Some equipment, such as the generator and electrical gear, must be installed in a climate-controlled building or enclosure regardless. An HVAC system for the building housing the engine and generator helps warm winter restarts and keeps the equipment from overheating in the summer.

8.1.7 Site safety

Sites that include AD/biogas systems may use safety measures such as lighting, cameras, keypad locks, or alarms. These items should be periodically checked to ensure they are operating as expected.

8.1.8 Third-Party Expertise

Several O&M tasks require advanced expertise or specialized equipment to perform safely and properly. For these tasks, an operator may want to hire a third-party contractor with the experience, trained personnel, and specialized tools. In some cases, hiring a contractor may be required to comply with equipment warranty standards. Examples of specialized tasks are IC engine overhaul, compressor overhaul, H_2S scrubber material change-out, CO_2 removal material change-out, water dehydration material (desiccant) change-out, and corrosion monitoring. Hiring a third-party contractor to perform more involved and difficult O&M tasks can free up operating personnel to keep the system's process running smoothly.

8.1.9 Warranty

Documenting that both routine and major O&M has been performed on schedule may be required to maintain equipment warranties. In some cases, the warranty may require having an equipment manufacturer's representative perform, or at least supervise, major O&M tasks.

8.1.10 Digester Tanks and Vessels

Digester tanks are typically made of concrete or steel, and they should be checked periodically for leaks, cracks, or other evidence of structural problems. If hot water coils are used to heat the digester, then the surface of the coils should be checked for any slurry caking. Caking reduces heating coil efficiency, and a drop in the digester's operating temperature is an indication that caking is occurring. The depth of grit, sand, and other non-volatile solids accumulating in the bottom of the digester should be monitored. The buildup rate should be monitored to determine if and when a digester clean-out is needed. Check seams and joints between the digester and cover for biogas leaks.

8.1.11 PRVs

PRVs help prevent over-pressure and damage to digesters from thermal expansion, fires, or equipment failure. These PRVs are critical safety equipment. Because they must operate when needed, PRVs that are seldom or never used should be periodically checked and operated to verify that they are not "stuck" due to corrosion or deposits. They should be inspected at least annually and tested or replaced every three to five years, depending on service conditions.

8.1.12 Drains and Vents

High-point vents on liquid lines and low-point gas line drains should be briefly opened and checked as a routine O&M task, especially around pumps and compressors. Exercise caution when performing this task if CH_4 or H_2S is known or suspected to be present in the line.

8.1.13 Leaks

Checking the piping and equipment for leaks daily is one of the easiest—yet most important—O&M actions an operator can perform. This is especially important following repairs and reassembly of piping and after a hard freeze. See Section 7.2 for more details about leak testing related to biogas handling and conveyance.

8.1.14 Corrosion Monitoring

Mild steel corrosion is inevitable anytime H_2S, CO_2, or water is present. Corrosion rates are generally worse when H_2S and CO_2 are together or at higher digester operating temperatures. Any mild steel portions of the system containing H_2S and water, CO_2 and water, or both should be routinely monitored for internal corrosion. This is best done with a small device that uses an ultrasonic frequency to measure the thickness of pipe or vessel walls. The device is very accurate when used properly. Insulation and paint should be removed prior to taking a reading, and the location should be marked so that subsequent readings can be taken at exactly the same spot. Readings should be taken frequently at first, until a normal corrosion rate can be established for that location. Third parties specializing in corrosion protection and monitoring frequently perform this O&M task.

8.1.15 Fresh/Waste Oil Storage Tanks

Fresh oil make-up storage tanks and waste oil storage tanks require very little O&M. After emptying the waste oil storage tank, the bottom of the tank should be checked for sludge and cleaned out if any is present. If either tank is below-grade and has secondary containment, then the interstitial space should be checked periodically for the presence of liquids.

8.2 AD Mechanical System Maintenance

8.2.1 Pumps

A pump can be easily damaged if something goes wrong that is not corrected quickly. Pumps can handle varying particle sizes and TS concentrations. A minimum fluid flow through the pump is required to remove the buildup of heat in the pump head. Ideally, there should be a pressure gauge on each side of the pump so that pump clogging or piping can be easily identified. A blocked discharge can damage a pump due to lack of fluid movement.

Positive displacement pumps, such as gear pumps, can damage the discharge piping, instrumentation, or the pump itself if a valve in the discharge line is closed while the pump is operating. Monitoring the suction and discharge pressures across a pump on a regular basis is the best way to check pump health. If possible, it is also always good to check the pump's flow rates. A damaged pump can appear to be operating normally while producing less-than-normal flow rates. Reduced pump flow generally indicates wear on the pumping components, such as the stator of a progressive cavity pump, the lobes of a rotary lobe pump, or the impeller of a centrifugal pump.

A pump seal is located at the intersection of two moving parts, and as a result, the seal will eventually fail. Worn or damaged seals usually cause pump vibration or leakage, so pumps should be routinely checked for excessive vibration or leaking. Misalignment between the pump shaft and the motor shaft, as well as excessive impeller wear, can also cause excessive vibration. Unusual or excessive noise is a typical indicator that something is going wrong. Some pumps use drive belts between the motor and the pump, and in that case, the drive belt's tension and condition should also be checked. Seal and drive belt replacements are required more frequently than impeller/piston/plunger replacements or pump overhauls.

Submersible pumps particularly need performance monitoring, as the material being pumped can be abrasive and cause the pump components and seals to wear prematurely.

8.2.2 Mixers

Mechanical mixers should be frequently checked for excessive vibration. Vibration usually indicates that something is amiss at the mixer's working end. This could be from a buildup of scale or cake on the blades or from missing or loose blades. Excess fiber, loose plastic, or similar materials introduced into the digester can foul the blades, and the blades will need to be cleared.

Fouled blades on slow-speed mixers are less likely to experience vibrations and instead usually require more power to rotate the shaft. This could be indicated by the motor running at an excessively high temperature or tripping off from an overload. Some mechanical mixers use a drive belt, and the drive belt's tension and condition must also be checked. Bubble-type mixers should be checked for adequate bubble flow and for uniform distribution. Problems could be caused by a compressor malfunction or partial plugging of the vapor line or distribution piping.

Jet mixers operate by removing liquid from the anaerobic digester and returning it in a piping system with a series of nozzles that are designed to mix the vessel. The system relies on a pump that is subject to the issues discussed in 8.2.1 above. Jet mixing systems are usually used for dilute material, as excess solids can clog the nozzles. For this reason, the pump should be installed with a pressure switch that would stop the pumping when the outlet pressure reaches a preset value. All piping that is external to the digester should be routinely checked for leaks.

8.2.3 Heat Exchangers

Heat exchangers come in a wide variety of shapes, sizes, and configurations, and they are generally designed for specific applications. An exchanger transfers heat from a hot fluid on one side of a metal interface to a cold fluid on the other side of the interface. There is fluid movement on each side of the metal interface, and the greater the temperature difference between the two fluids, the greater the amount of heat transfer. If there is no fluid movement or no temperature difference, there is little to no heat transfer.

Most of the heat exchangers used in AD/biogas systems are simple pipe coils. Plate and frame heat exchangers are preferred for efficiency in applications requiring maximum heat transfer in a small size. They can be easily fabricated from corrosion-resistant materials. A big advantage of plate and frame heat exchangers is that they can be readily disassembled for inspection and cleaning, and spare plates and gaskets can be kept on hand if any replacement is needed. The main disadvantage is that the exchangers' fluid passageways are small and easily fouled or plugged. For this reason, most plate and frame heat exchangers are used to transfer heat from a CHP to hot water loops.

It is important to have a pressure gauge on the inlet and outlet of both sides of the heat exchanger. A higher-than-normal pressure drop across either side of the exchanger indicates either a higher flow rate or potential fouling. If the flow rate has not changed, the inlet strainer has been checked and cleaned, and the pressure drop continues to increase over time, then the exchanger is likely fouled, and a cleaning should be scheduled. Many external heat exchangers use a spiral heat exchanger or a tube-in-shell or tube-in-tube exchanger. These exchanger types are susceptible to fouling and clogging. Therefore, the pressure across them must be monitored for their sustained operation.

8.3 Biogas System Maintenance

Biogas system maintenance varies depending on the biogas use and type of equipment in operation. There are essentially three basic levels of biogas processing, based on the type and quantity of gas contaminants.

The lowest level of processing requires the removal of free water from the biogas and the slight pressurization of the biogas using a blower so that it will flow into a boiler or IC engine. Biogas processed to this level still contains H_2S, water vapor, and CO_2. The biogas will burn, but the H_2S and water vapor can cause safety and equipment reliability issues. System maintenance involves checking the effectiveness of the water separation and maintaining the blower.

The next level requires more equipment and processing to remove the H_2S and the majority of the water vapor. At this level, the biogas still contains a significant amount of CO_2 and a small amount of H_2S and water vapor, but it is much safer to handle and provides a cleaner fuel source that should not harm a boiler or IC engine. Many scrubbers are designed to reduce H_2S to a predetermined level. Either the engine manufacturer or air permitting requirements determine the H_2S removal level.

Upgrading to the last level, requiring still more equipment and processing, involves removing nearly all the CO_2, H_2S, water vapor, and other contaminants followed by compressing the gas to pipeline pressure or higher. At this point, the gas has been converted from biogas to RNG and is suitable for injection into the local natural gas utility pipeline system or for use as a localized compressed natural gas replacement.

This section and the following section describe the general maintenance requirements for AD/biogas systems.

8.3.1 Blowers and Compressors

Blowers and compressors have many of the same O&M issues as pumps and are checked in a similar fashion. Leaks and excessive vibration indicate problems with seals or mechanical interference or misalignment in other areas. Leaks in biogas blowers or compressors can be hazardous, so gas-monitoring devices should be permanently installed near the compressor or operators should wear personal monitoring devices when working around the biogas compressor. Drive belts should be checked for tension and condition.

Compressors, unlike pumps, produce a lot of heat during the compression process. This usually results in the discharge gas temperature being very hot, and a discharge cooler may be required. Oil is used as a compressor lubricant, but it also functions as both a sealant and a coolant within the compressor. A high oil temperature indicates a problem. Inlet and outlet gas temperatures and pressures should be monitored, as well as inlet and outlet oil temperatures. As is the case with all mechanical equipment, excessive or unusual noise typically indicates that something is wrong.

Larger compressors often have several subsystems. Subsystem examples are jacket water heating and cooling with a jacket water pump, lube oil heating and cooling with a lube oil pump, a pre-lube/post-lube pump, and starter. As the complexity and number of subsystems grows, so does the likelihood of something going wrong and requiring maintenance. The importance and frequency of preventive O&M increases dramatically with compressor size and complexity. The compressor's operating manual should be consulted for specific O&M requirements and frequencies.

8.3.2 Heat Exchangers

Heat exchangers have been described in Section 8.2 above. Please see that section for maintenance requirements for biogas heat exchangers.

8.3.3 Particulate Filters

Particulate filter O&M involves checking the differential pressure gauge to ensure it is functioning properly, and then scheduling a filter change when the differential pressure reaches a predetermined set point. It is important to keep the spare filter cartridges and also to have an extra O-ring or two for the lid/cover. Use caution in disposing of old filter cartridges, as some amount of iron sulfide has likely collected on the filter material. This can heat up and catch fire when exposed to air if the filter cartridge is allowed to dry out.

8.3.4 Coalescing Filter/Separator

Much like the particle filters, coalescing filter O&M primarily involves checking the differential pressure and changing the coalescing filter cartridges when the differential pressure reaches the predetermined set point. Coalescing filters remove small liquid aerosol droplets, which are drawn off as a liquid and do not permanently collect in the filter cartridges. Because of this, coalescing filter cartridges are designed for a much longer life cycle than normal filter cartridges. The level indicator and level control valve also require checking and maintenance. Because these filters usually maintain some liquid in them, the drain piping and lower portion should be heat-traced and insulated to prevent freezing in colder climates. Heat tracing should be checked occasionally to verify that it is working as intended.

8.4 Power and Heat Generation O&M

8.4.1 IC Engine

IC engines and gas turbine engines can generate power with biogas. IC engines are more commonly used than gas turbine engines, primarily because an IC engine has a lower capital cost, higher conversion efficiency, and wider operating range than a gas turbine engine. Even though the O&M costs are higher for an IC engine, overall operating costs are generally lower for IC engines used in smaller-scale biogas applications.

IC engines have several subsystems. These include fuel gas compression, conditioning and regulation, jacket water circulation, heating and cooling, lube oil circulation, jacket water supply and drain, lube oil supply and drain, starting power from batteries, inlet combustion air with a filter and regulator, and an exhaust system with a muffler, among others. The fuel gas, lube oil, and jacket water subsystems require the most attention and maintenance.

The manufacturer's recommended O&M requirements and schedule should be followed to maintain engine warranty and extend the equipment's useful life. Keeping up with the recommended routine O&M and major overhaul schedule can be difficult, but doing so maximizes engine runtime and system profitability.

8.4.2 Routine

As is the case with most IC engines, lube oil/filter, inlet air filter, fuel gas filter, and spark plug changes are the most common routine O&M items. In addition, if the biogas contains H_2S, then inlet fuel gas system parts will require flushing, cleaning, lubrication, or change-out on a frequent basis to avoid corrosion or deposit accumulation.

8.4.3 Oil Changes

Oil and oil filter changes are two of the most critical routine O&M items. Establishing a regular routine contributes greatly to the longevity of the IC engine. If there is H_2S in the biogas, then the importance and frequency of oil/filter changes are greater. H_2S will cause the oil to become acidic over time, increasing engine component wear and decreasing engine life expectancy. Using a buffered lube oil with frequent change-outs can help mitigate the problem.

8.4.4 Monitoring

Monitoring flow rates, temperatures, and pressures is an excellent way to identify performance trends, and changes in these trends indicate the need for O&M. Additionally, an oil analysis program that samples the used oil and monitors for contaminants is recommended. This analysis is used to predict potential wear problems and identify the need and timing for upcoming O&M.

8.4.5 Overhauls

An engine overhaul should be performed at intervals recommended by the manufacturer and is generally based on the engine's cumulative operating hours. If the engine-generator set operates on a continuous basis, then overhauls will likely be required every one to two years. The used oil sampling and analysis program may indicate a need for more frequent overhauls.

8.4.6 Heat Exchangers and Pumps

Additional heat exchangers, pumps, expansion tanks, and associated controls make the CHP system somewhat more complicated, but they do not add significantly to the overall O&M requirements. Most CHP systems use radiators to dissipate heat that is produced in excess of the system's heating needs.

8.4.7 Boilers

A boiler uses a direct flame to heat water flowing through adjacent tubes or pipe coils. In the case of a biogas-fueled boiler, a low-British thermal unit gas is burned in a boiler to heat water. In principle, this is no different than using a fossil-fueled hot water heater. The hot water can then be pumped to provide digester heating, building space heat, and hot water for other operations. The only real moving part is the water pump, which requires periodic inspection and O&M similar to any other pump. The boiler's fuel gas controls include several safety-related items to keep the boiler running safely and efficiently. These include automated shutdown valves on the main fuel gas line, pressure regulators on the main and pilot gas lines, blower controls and/or purge timers, and flame and high-temperature detectors. Because these are safety-related items, they should be routinely checked and verified for proper operation.

Boilers sometimes use biogas containing H_2S. When H_2S is burned, it produces exhaust fumes that are acidic and very corrosive when condensed. If the boiler is operated using a low duty cycle, starting and stopping frequently and allowed to cool off, excessive corrosion will occur on the water coils or tubes and also on the heater's cover panels. Corrosion can also happen when the boiler is operated at too low a temperature.

Due to the relatively cooler temperature of the water inside the coils/tubes, corrosion will be most evident on the outside of the coils/tubes, and these coils/tubes should be inspected regularly to determine their condition and rate of corrosion. The boiler stack should be monitored for corrosion as well.

8.4.8 Chillers

A chiller is essentially a mechanical refrigeration system that uses a refrigerant, much like an air conditioning system. Most standard chiller systems use a motor-driven compressor. Chillers sometimes use an intermediate fluid, such as a glycol-water solution, in combination with a pump and heat exchanger to better control biogas temperature and avoid over-cooling the biogas. Routine O&M on an electrical motor-driven chiller system is minimal. Monitoring the inlet and outlet biogas temperature is the best way to check whether the system is functioning properly. Operators should occasionally check the glycol-water solution level and the condition and tension of drive belts where used.

Similar to the standard chiller, a gas-fueled refrigeration system uses an IC engine to drive the compressor. Gas-fueled systems typically use a refrigerant to cool air for refrigerated storage or building climate control, and they generally do not use an intermediate fluid. Because of the IC engine, both routine and major O&M on a gas-fueled refrigeration system are more involved than for a motor-driven chiller system. The maintenance becomes even more complicated if the biogas contains H_2S. The IC engine must be specifically designed to use biogas, and if H_2S is present, then certain engine components will require upgrading to H_2S-resistant metals. Even with material upgrades, H_2S will cause the engine oil to become acidic over time. This acidity can be somewhat mitigated by using buffered oil and performing frequent oil changes, but ultimately it will result in accelerated engine wear and reduced equipment life expectancy. As with an engine-driven CHP, it is best to scrub H_2S out of the biogas before using it in an IC engine.

8.5 Biogas Upgrading System Maintenance

There are many different biogas upgrading technologies and systems, as discussed in Section 7.9. This section provides a general overview of their maintenance considerations. It does not address any one system, nor provide a comparison of systems. It is highly recommended that the system manufacturer be consulted to establish an adequate O&M program.

8.5.1 H_2S Removal

H_2S removal systems are discussed in further detail in Section 7.9.1. Under normal circumstances, the O&M requirements for H_2S removal systems are minimal. Regular tasks involve checking for leaks, verifying proper calibration and operation of the instrumentation and biogas analyzers, and evaluating the reactive media's condition to determine the schedule for the next media change-out.

Media change-out of the H_2S scrubber vessels can be difficult. The process involves significant media handling, safety, and disposal problems. Change-out is best performed by a third party with the trained personnel, skills, experience, and equipment.

For example, if an iron sponge is used as the H_2S removal media, then the spent media must be properly handled or it will catch fire. A third party usually hauls away the spent media for reconditioning or disposal. During media bed change-out, there is also a possibility of exposing operators to high concentrations of H_2S vapors.

Other than periodic change-out of the bed media, the H_2S removal tanks should not require regular O&M. Instrumentation that monitors the process conditions in the vessel (temperature, pressure drop) and biogas H_2S concentrations should be checked to confirm that the removal system is operating within specifications. By monitoring the temperature, pressure drop, and biogas H_2S concentrations, an operator can evaluate how well the H_2S removal beds are performing and predict how soon the media will need to be changed.

Solid media adsorption requires that the media be replaced at regular intervals, and the spent media must be disposed of as solid waste. Biological scrubbing systems require heat, fresh water, and electricity to maintain a microbial population that removes biogas contaminants. Biological scrubbing systems generate a wastewater stream that must be disposed of. Chemical scrubbing systems require replacement of the chemicals that are consumed in removing the biogas contaminants, electricity to circulate the chemical solution, and a system to manage a byproduct sludge stream that must be disposed of as solid waste.

8.5.2 Bulk Moisture Removal

Bulk water vapor removal is usually done after the H_2S is removed. A chiller system is used to lower the temperature of the biogas so that most of the water vapor condenses. The condensed water is then removed by gravity in a separator. The cooled biogas is then warmed prior to further use or processing.

As noted in Section 8.4, routine O&M on an electric motor-driven chiller system is minimal. Inlet and outlet biogas temperature is the best indicator of proper system function. Additional checks of coolant temperature, glycol-water solution level, and drive belts should be made periodically as applicable.

An increase in cooling temperature can indicate a problem with the chiller. The separator will not operate at its designed efficiency with elevated chiller fluid temperatures. In addition, there will likely be heat trace and insulation installed if the unit is in a cold climate, and the operability of the heat trace should be verified periodically.

8.5.3 CO_2 Removal

As noted in Section 7.9, CO_2 can be removed using a membrane filtration process, amine scrubbing, a spray tower, or a PSA process.

O&M on membrane filtration process systems is relatively inexpensive, except for occasionally replacing the membrane filter cartridges. The membrane filtration process usually requires additional compression and therefore incurs high capital cost and expenses.

The PSA process generally requires little O&M. Because the adsorption media can be regenerated in place, they can be used for a long time without requiring a total change-out. Even so, eventually the adsorption media wear, degrade, and lose efficiency and must be replaced. Monitoring outlet biogas CO_2 content is an effective way to predict when a change-out will be needed. Media change-out is the only major O&M required. Unlike the H_2S scrubber material change-out, this media replacement does not present any real safety issues. Even so, there are challenges with media handling and disposal, so this may also be a good task for a third party.

Dust or fines from the adsorption material are produced over time due to normal wear and can cause fouling in downstream equipment, so it is important to change the dust filter cartridges. Routine O&M involves checking the pressure drop across the vessels to make sure the adsorption material has not shifted or plugged.

8.5.4 Dehydration

As discussed in Section 7.9.2, a PSA system using a different adsorption material is used to remove the additional water vapor required to produce pipeline-quality RNG. Media regeneration, material change-outs, and routine O&M are essentially the same as for the CO_2 removal system.

8.5.5 Compression

If the biogas is being upgraded to RNG, extra compression is required to boost it to a high enough pressure to be introduced into a natural gas pipeline. If the compressor uses an IC engine, then the O&M requirements will be similar to those for the IC engine described in

Sections 7.8.1 and 8.4.1. The main difference is that the frequency of oil changes and overhauls will be lower because all of the H_2S has been removed. If the compressor driver is an electric motor, then the O&M will be limited to checking the shaft alignment, vibration detectors, bearing temperatures, and winding temperatures.

Compressor O&M requirements can vary considerably, depending on the compressor's type and size. Routine O&M on either reciprocating or screw-type compressors involves oil and oil filter change-outs. On reciprocating compressors, piston rings and cylinder valves require routine replacement. On screw-type compressors, there typically is an oil coalescing filter on the gas outlet, and the filter cartridges need to be replaced periodically.

Reciprocating or screw-type positive displacement compressors may require a discharge cooler if the heat generated from these compressors causes the discharge gas temperatures to increase too much. Inlet and outlet gas temperatures and pressures, as well as inlet and outlet oil temperatures, should be monitored. Oil is used as a compressor lubricant, but it also functions as both a sealant and a coolant within the compressor. High oil temperatures indicate a problem. As is the case with all mechanical equipment, excessive or unusual noise typically indicates that something is wrong.

8.5.6 Activated Carbon and Other Media

Activated carbon adsorbs volatile organic compounds that were not removed during the previous biogas conditioning. Breakthrough occurs when the media is saturated, so the media must be replaced with new activated carbon periodically to maintain operations.

8.6 Flare Maintenance

The flare is a key piece of safety and environmental protection equipment because it effectively disposes of biogas during periods when production exceeds use, during system O&M, and during emergency situations.

Always remember that biogas is explosive when mixed with air. Biogas can also be fatally toxic when inhaled and can be an asphyxiant when it displaces breathable air. Also, a flare is essentially an open flame, so it is important to keep any combustible materials away from the flare.

Biogas is flammable, so it is important to keep the pilot light burning at the top of the flare. The pilot light gas can be a source other than the biogas, such as natural gas or liquified petroleum gas. Once the pilot light gas controls and safety features are set up, they should require minimal O&M going forward.

The primary O&M for flares is to verify that the pilot is lit, check filters to verify that the pilot gas is clean, and check the pressure gauge to verify the gas is provided in a sufficient quantity. Some flares use spark ignition, and proper operation must be periodically verified. A flame or detonation arrestor may be installed on the inlet line to the flare and requires periodic inspection and cleaning.

The flare can only work if its piping is unobstructed. If the digester or any of the biogas processing equipment is over-pressured, the best way to deal with the excess biogas pressure is to create a clear path to the flare. Check for closed valves upstream or downstream of relief valves or pressure control valves that control the flow of biogas to the flare. Check for the accumulation of liquids in low points of the flare piping system, and, in the winter, make sure the liquids do not accumulate and freeze.

9.0 Odors and Odor Control

9.1 What Are Odors?

Odors are distinct smells, most commonly unpleasant ones, caused by malodorous chemical molecules entrained in the air we breathe. These malodorous molecules become entrained in the air when, for example, a breeze blows across a manure pile or overloaded storage lagoon, or when a lagoon is agitated in preparation for load-out. These malodorous sources may provide effective feedstocks for the digester, but unmanaged odors are frequently a source of problems for the operator.

9.2 How Can Odors Impact the Viability of an AD Operation?

Odors can impact the operational viability of an AD/biogas system if they become a continuing nuisance to neighboring residents and businesses, potentially causing complaints, notices of violation, regulatory fines, or even shutdown orders. Uncontrolled strong odors may also negatively impact the health and welfare of the AD/biogas system employees. This could cause safety concerns, reduced productivity, and higher overhead costs for the operation.

9.2.1 Potential Odor Sources

At any AD operation, malodorous molecules can be released into the air from the following sources:

- Feedstock receiving areas and equipment
- Feedstock preprocessing equipment
- Feedstock tank headspace vents
- Feedstock pits, piles, or bunkers
- Digester reactor vents or PRVs
- Digestate transfer, aeration, separation, or processing equipment
- Digestate storage tanks, pits, lagoons, piles, or bunkers
- Biogas processing and treatment rain
- Biogas utilization equipment

9.2.2 What Do Unusual Odors Mean?

The presence of a new or unusual odor at an AD/biogas system can signify a problem with the biological or mechanical systems. This should immediately prompt the operator to investigate the odor’s source. For example, a biological system upset from an OLR overload event can cause a rapid change in digestate odor. A leak in the biogas handling system can cause the presence of a distinct odor at the facility; if this occurs, the operator should take precautions and attempt to find the source of the leak.

Factors including barometric pressure, ambient air temperature and humidity, and wind speed and direction can affect the nature and severity of odors present at an AD/biogas system. These factors should be considered in the planning, implementation, and evaluation of odor control or masking systems.

9.2.3 Odor Control

Odor control is the process of directing and collecting malodorous air to be treated before being released into the atmosphere. Odor control systems can be separate from or combined with HVAC systems, and they can include ductwork, blowers, biofilters, and scrubbers. There are two distinct methods of odor control applicable to AD/biogas systems: building control and source control, both described below.

9.2.4 Building Control

Building control involves the collection and direction of air within a building to a treatment and discharge system. Building control is achieved by drawing slightly more air into the odor control system than is discharged back into the building. Operating the system under a negative pressure prevents malodorous air from escaping the building through openings such as doors, vents, and windows.

A building control system consists of fresh air inlets, collection points, ductwork, and fans or blowers. The fans or blowers draw odor-contaminated air into the ductwork from the collection points, and fresh air enters the building through the fresh air inlets.

Building control systems should be set up so that the air flows inside the building from the least malodorous areas to the most malodorous areas. This reduces odors being spread throughout the building and reduces the risk of malodorous air escaping the building.

In a high-odor environment, such as the feedstock receiving or solids separation areas, odor control systems are typically designed to provide 10 to 20 air exchanges per hour. This means that 10 to 20 times the volume of air the room contains is drawn in from outside the building every hour.

The odor control system ducting and equipment are sized to provide a certain air flow rate, which can be converted to the number of air exchanges per hour the system provides. For example, if a room is 100 feet long by 100 feet wide with a 30-foot ceiling height, the room volume is:

$$100ft \times 100ft \times 30ft = 300{,}000\ ft^3$$

For an odor control system to provide 10 air exchanges per hour in this room, the system would need to be sized for:

$$300{,}000ft^3 \times 10\ \frac{air\ exchanges}{hour} = 3{,}000{,}000\ \frac{ft^3}{hour}$$

While this high air flow rate would be required when malodorous materials are present, in some cases, it may be beneficial to plan for a variable flow rate system that can be turned down when malodorous materials and operators are not present to reduce operating expenses.

9.2.5 Source Control

Source control can be applied at specific locations inside a building or when malodorous materials are present outdoors. Source control systems collect odor-contaminated air from locations very close to the malodorous materials and direct the air to a treatment process. These systems generally process less air volume than building control systems.

Odor source control systems can include fume hoods directly above an odor source, flexible ductwork positioned near an odor source, partial enclosures around odor sources, or odor control systems directly connected to a tank headspace.

Proper housekeeping is also an odor source control method. Frequently cleaning and removing organic material from corners, ledges, recesses, and equipment areas can significantly reduce odors at an AD/biogas system.

9.2.6 Odor Treatment

Odor treatment includes the processing of odor-contaminated air to remove or neutralize malodorous molecules prior to releasing the air into the atmosphere. Odor treatment methods commonly used at AD/biogas systems are biofiltration, chemical scrubbing, and adsorption. The details of these methods are discussed below.

9.2.7 Biofiltration

Biofiltration is a common odor treatment method for many industrial processes. Biofilters typically use a fixed bed of porous media, such as woodchips or volcanic rock, through which the exhaust air is directed. Naturally occurring microorganisms grow in the porous media and react with the malodorous compounds in the air. Biofiltration typically requires a humid environment, which is achieved by either humidifying the air prior to biofiltering or directly irrigating the biofilter media with water.

9.2.8 Chemical Scrubbing

Chemical scrubbing can also remove malodorous molecules. This treatment method places the odor-contaminated air in contact with a flowing liquid stream that reacts with the malodorous compounds. Typically, chemical scrubbing reactors are tall cylindrical vessels and use water or chemicals for scrubbing. The treatment liquid flows down from the top of the vessel, and the odor-contaminated air flows from the bottom up. Chemical scrubbing processes can be tailored to remove a wide variety of odors and generally take up less space than a biofilter. However, they require the addition of chemicals and disposal of the residual liquid.

9.2.9 Adsorption

Adsorption is an odor treatment method that typically uses a fixed bed containing adsorbent media, such as activated carbon, through which the odor-contaminated air is directed. The adsorbent media captures and retains the malodorous compounds. Once the media are saturated with malodorous molecules, they are either regenerated through a thermodynamic process or replaced. Adsorption odor treatment systems are generally robust, can be tailored to remove a wide variety of odors, and generally take up less space than a biofilter. However, they require replacing the media and disposing of the spent media. There are many types and manufacturers of adsorbent odor treatment media with various properties and life cycle costs.

9.2.10 Odor Masking

Odor masking typically involves in-place treatment of odor-contaminated air by mixing the air with a water or chemical mist. This can be a cost-effective solution for temporary or seasonal odor sources, such as those generated during tank cleaning, lagoon solids removal, or outdoor pickup or delivery of malodorous materials.

Odor masking systems can be point systems (i.e., a single mist generator) or linear systems consisting of mist nozzles surrounding an area or along a fence line. Masking systems can use chemicals that present a more appealing odor (i.e., "perfumes"). However, this method should be approached cautiously, as the perfumes may create a more unpleasant odor than the original material.

Proper implementation of odor masking systems requires a careful evaluation of air movement in the vicinity of the odor source and the corresponding masking system placement and sizing.

9.2.11 Minimizing Odors During Operation

Proper operational practices can play a large part in reducing or eliminating odors at an AD/biogas system. Operators can reduce the number of times doors are opened per day and the duration that each door is open. Operators can schedule pickup and delivery of malodorous materials at times when neighboring facilities are unoccupied. Operators can also set up and maintain strict cleaning and sanitation schedules to minimize the buildup of malodorous materials.

Various digester feedstocks and their end products can produce odors that change depending on the specific feedstock mixture each AD/biogas system uses. It is important for operators to understand the fundamentals of odor control and treatment, which allow them to quickly optimize and adapt their odor control plan to changes in feedstock and end products as necessary.

10.0 Safety

Accident prevention is an important responsibility of owners and operators of AD/biogas facilities. Preventing accidents, injury, or other negative health impacts requires minimizing the risks associated with:

- Fire and explosion
- Confined space entry
- Inadequate ventilation
- Slips, trips, and falls
- Electric shock
- Electrical fire
- Entanglement
- High pressure
- Extreme temperature
- Noise
- Drowning
- Pests

10.1 Biogas Safety Considerations

Biogas is primarily composed of CH_4 and CO_2, as well as small amounts of H_2S and NH_3. Each of these gases can be dangerous or lethal to humans in sufficient concentrations. Some of these gases are flammable/explosive, some are toxic, some are asphyxiants, and some are a combination of all these attributes. Biogas safety requires respect and caution in biogas handling.

Figure 10-1. Safety signage on AD feed system.[23]

10.1.1 Flammability and Explosion

CH_4 must be between 5 percent and 15 percent concentration by volume in the air to be flammable/explosive. This means that any CH_4 concentration in the air of less than 5 percent simply will not ignite. This is called the LEL. Similarly, any CH_4 concentration in the air that is greater than 15 percent will not ignite. This is called the UEL.

Biogas CH_4 concentrations usually range from 50 percent to 75 percent, so the biogas contained inside the digester or system piping is well above CH_4's UEL. Explosion danger occurs when biogas leaks outside of its containment area and mixes with the outside air or when air leaks into the digester or piping. CH_4 is lighter than air but accumulates in confined spaces lacking adequate ventilation. This is where the risk of fire or especially explosion is the greatest. An

[23] Image source: "Cayuga County manure digester virtual tour." eXtension Farm Energy, https://farm-energy.extension.org/cayuga-county-manure-digester-virtual-tour/.

explosive atmosphere is formed when the CH_4 concentration reaches the UEL (15 percent CH_4 in air). At this point, any ignition source in the immediate area will produce an explosion.

H_2S has an LEL of 4.3 percent and a UEL of 46 percent. Because it is heavier than air, it is most likely to be found at flammable/explosive concentrations in poorly ventilated confined spaces.

Because of the potential for fire or explosion, the following prevention practices should be observed:

- Prohibition of smoking and vaping at the project site.
- Prohibition of open flames and sparks.
- A regularly scheduled biogas leak detection inspection program.
- A permanent CH_4 detection monitor and adequate ventilation in any enclosed structure where CH_4 is processed or used as a fuel.
- Restricted site access by appropriate fencing.
- Appropriate signage.

If gas or arc welding is necessary for plant or equipment repair, the area should be checked for the presence of CH_4 before and during the repair. This also applies to any repairs involving the generation of sparks. In summary, eliminating potential ignition sources is the best way to avoid a biogas-fueled fire or explosion.

Note that neither PVC nor copper should be used for biogas piping. Black steel is recommended with the caveat that there is the risk of corrosion leaks due to biogas water vapor and H_2S reacting to form sulfuric acid.

10.1.2 Explosive Gas Hazard Zones

Hazard zones are areas where an explosive CH_4 air concentration could possibly exist. These hazard zones are typically around the seams and joints between the digester tank and the biogas containment (cover) and the area immediately surrounding any PRV that discharges biogas to the atmosphere. Buildings, enclosures, pits, or vaults that house biogas processing equipment without adequate ventilation are also hazard zones.

The National Electrical Code defines three levels of hazard zones for explosive gases. A Class I, Division 1 area is an area that has an explosive mixture during normal operation or may have frequent potential for an explosion due to maintenance, leaks, or equipment or process breakdown. This area has the most stringent ignition source restrictions.

A Class I, Division 2 area is an area that would only have explosive mixtures caused by a containment breach, accidental rupture, or abnormal equipment operation or an area that immediately surrounds a Division 1 area. Division 2 areas have lesser restrictions on ignition sources. With the addition of adequate ventilation, a Division 1 area can sometimes be reclassified as a Division 2 area.

An Unclassified area is an area for which there is no reasonable expectation of having an explosive mixture.

Many items can serve as ignition sources. Obvious examples are cigarettes, lighters, pilot flames, welders, light switches, electrical outlets when devices are being plugged in or unplugged, and any arcing or sparking electrical fixtures. Less obvious ignition source examples are radios, cell phones, cameras, and computers. The National Electrical Code requires that industrial electrical equipment, fixtures, and devices be individually rated for service in Class I, Division 1; Class I, Division 2; or Unclassified areas.

While operators cannot always prevent the presence of explosive mixtures of biogas at an AD/biogas system, they can control the presence of an ignition source. After all, it takes both explosive mixtures and an ignition source for an explosion to occur.

10.1.3 Toxic Gases

Gases can potentially become Immediately Dangerous to Life and Health (IDLH) when concentrated within facility areas. At high enough concentrations, some of these gases can be lethal within seconds. The Occupational Safety and Health= Administration (OSHA) defines an IDLH to be the concentration of toxic, asphyxiant, or corrosive substances posing an immediate threat to life, causing irreversible or delayed adverse health effects, or interfering with a person's ability to escape from a dangerous atmosphere. An asphyxiant is a substance that replaces O_2 or inhibits the body's ability to use O_2.

Figure 10-2. Explosion potential sign. [24]

H_2S is a highly toxic gas. It is colorless, heavier than air, and has an IDLH of 100 ppm. It can quickly cause dizziness, unconsciousness, and death. At low concentrations, H_2S smells like rotten eggs. However, smell alone cannot always be used to detect the presence of H_2S because when the gas is at higher concentrations, a person's sensitivity to its smell decreases rapidly.

NH_3 is an irritant and asphyxiant at low concentrations but can become toxic at higher concentrations. NH_3 has a pungent smell, is colorless, is lighter than air, and has an IDLH of 300 ppm.

[24] Image source: U.S. EPA AgSTAR, https://www.epa.gov/sites/production/files/2014-12/documents/safety_practices.pdf.

CO_2 is an asphyxiant that can cause unconsciousness and death. It is odorless, is colorless, is heavier than air, and has an IDLH of 40,000 ppm (4 percent). CO_2 can become toxic beginning at concentrations of 5 percent.

CH_4 is a simple asphyxiant, and there are no specific exposure limits if O_2 levels remain greater than 19.5 percent. The primary concern for CH_4 is its ability to cause an explosion. CH_4 is odorless, colorless, and lighter than air.

10.1.4 Personal Detection Device

Small personal gas detectors are pocket-sized analyzers that measure the gas concentration levels in the surrounding environment. They provide an audible and visual alarm when a measured concentration exceeds a preset threshold limit. These detectors are made in various configurations and are typically designed to detect and alert for one to four different gases. Gas detectors are intended for workers to wear in their breathing spaces (attached to clothing somewhere in the upper chest area) when they are working in potentially hazardous areas. The detectors are highly effective, are reasonably priced, and save lives. It is important to note that the detectors must be checked and recalibrated periodically. A slightly larger handheld version of these gas detectors is made to be used with extension tubing to check the environment around equipment, around suspected leak points, or inside a confined space before and during an entry.

10.1.5 Permanent Gas Detection

In confined areas where biogas is likely to be present, permanent gas detectors with a visible alarm function should be installed to prevent an accidental entry into a hazard zone. Areas of concern include enclosed post-digestion solids separation buildings, entrances to high solids AD vessels, confined space areas, and rooms attached to digesters such as pump rooms.

10.1.6 Toxicity Hazard Zones

Like flammability/explosion hazard zones, toxicity hazard zones are typically around the seams and joints between the digester tank and the biogas containment (cover) and the area immediately surrounding any PRV that discharges biogas to the atmosphere. Buildings, enclosures, pits, or vaults that house biogas processing equipment without adequate ventilation are also toxicity hazard zones. In addition, any O&M that results in the reactor being opened or any equipment or piping that causes biogas to be discharged or vented will cause that area to become a toxicity hazard zone.

10.2 General Safety Considerations

10.2.1 Material Handling

Material handling can include activities such as the periodic clean-out of the digester basin and the operation of excavation equipment. Material handling operations can also include bed material change-outs for the H_2S and CO_2 scrubbers, change-outs for the dehydration vessels, and the hoisting/lifting/moving of large or heavy process equipment. Injuries could result from standing under a suspended load; failing to stay within eyesight of a heavy equipment operator or signal person; overreaching from or being knocked off a ladder or elevated platform while attempting to handle and direct material; or being pinched or crushed between a moving object and fixed equipment. O&M personnel training and maintaining continuous situational awareness can minimize these hazards.

10.2.2 Confined Space

Personnel entry into any confined space requires specialized training and certification, using well-established procedures and proper equipment. Otherwise, there is a significant risk of severe injury or death. Examples of a confined space are any tank, vessel, pit, silo, bin, or underground vault. By OSHA rules, these are considered confined spaces if they are large enough for a person to enter and perform tasks in but have a limited/restricted means of entry and exit and are not designed for continuous occupancy. Three primary precautions must be taken for someone to enter a confined space:

1. The atmosphere inside the confined space must be checked before and during entry to confirm that it is not hazardous. O_2 levels must be at least 19.5 percent (normal air is approximately 21 percent). To avoid having an explosive mixture, CH_4 levels must be below 5 percent. Levels of H_2S must be below 20 ppm. If any of these three atmospheric concentration requirements are not met, it may still be possible to enter the confined space by using forced and continuous fresh air ventilation. If the CH_4 content is 5 percent or higher, then all electrical equipment (including the ventilation blower motor) should be rated as explosion-proof. Furthermore, all ignition sources (e.g., cigarettes, cell phones, and non-explosion-proof radios) must be kept well away from the confined space while the operation is underway. Using a self-contained breathing apparatus or a supplied-air respirator is also an option. However, these measures require additional training and specialized equipment and should be reserved for exceptional or emergency situations only.
2. The person entering the confined space must wear a safety harness with a lifeline connected to a hoist, winch, or pulley that is located outside of the confined space. This ensures the person can be safely and readily removed from the confined space without the need for another person to go inside to attempt a rescue.
3. There must be at least one other person located outside the confined space whose sole responsibility is to monitor the atmosphere inside the confined space, monitor the condition and health of the person inside the confined space, and if needed, call for help and operate the mechanical rescue equipment to safely remove the person from the confined space. Frequent verbal or radio communication with the person inside the confined space is an effective way to monitor their health and condition.

Improper entry into a confined space is one of the more common causes of accidental death in agriculture and the wastewater industry. Consult OSHA's website (www.osha.gov) for more complete information.

10.2.3 Ventilation

Providing adequate ventilation is an important way to reduce the likelihood of flammable/explosive or O_2-displacing vapors accumulating and to reduce toxic vapor inhalation. If the equipment or process being serviced is located outside of a building or enclosure, then adequate ventilation is usually not a problem. However, low-lying and bermed areas, including open pits, ponds, and sumps, may not receive enough natural ventilation and should be considered potentially non-ventilated areas. Even if outdoors with adequate natural ventilation, some specific areas should be treated with caution. Examples include areas immediately surrounding a digester system or areas surrounding a PRV discharging any biogas to the atmosphere.

The airspace inside a building or enclosure housing the engine-generator set or any biogas processing equipment is capable of accumulating flammable/explosive, O_2-displacing, or toxic vapors. Without adequate ventilation, it has to be presumed that a leak or other malfunction will eventually lead to a dangerous accumulation of undesirable vapors. Building ventilation with frequent air changes does more than prevent hazardous vapors from accumulating; it also helps cool the engine-generator equipment and maintain a comfortable temperature for personnel working inside the building.

In some areas, such as an enclosure for small equipment, it may not be practical to provide adequate ventilation. This type of situation normally requires the use of explosion-proof equipment and electrical devices within the enclosure, as well as gas detection and warning devices to alert operations personnel of any unsafe working conditions.

10.2.4 Slips, Trips, and Falls

Manure and other organic wastes are slippery. The keys to preventing slips, trips, and falls are employee awareness, good housekeeping, and proper equipment layout and design. Work surfaces and walkways should be kept clean and cords, tools, and supplies picked up. To the extent possible, all valves, instruments, and equipment should be operable and maintainable from ground level. Where this is not possible, consider using stairs with handrails, ladders with cages, and elevated platforms with handrails for routine work, and consider using a safety harness for non-routine work. Walkways should be designed with or covered with a non-slip surface. A good design allows for an adequate amount of clear area around equipment for O&M activities. This is especially important around electrical panels.

10.2.5 Electric Shock

Unexpected contact with electrical sources can be serious and sometimes fatal. Probably the greatest risk of electric shock occurs during routine maintenance, repair, or replacement of the various components of the electrical system, such as motors, disconnect switches, and motor controllers. This risk usually occurs during O&M or repair activities when protective guards have been removed, equipment is partially disassembled, electrical panel doors are left open, wiring is left exposed, or the equipment or process is otherwise falsely assumed to be in a safe condition.

Accidents are frequently caused by one person inadvertently energizing or turning on a piece of equipment or opening a valve, while another person is working on the equipment or process line. The risk of shock can easily be avoided by rigorously practicing "lockout/tagout" procedures. These involve the use of energy-isolating devices, such as circuit breakers or disconnect switches, and the locking or tagging of these devices to prevent accidentally re-energizing the item being maintained, repaired, or replaced.

10.2.6 Electrical Fire

There are many possible sources of electrical fires. One is increasing the electrical load on a circuit beyond its design capacity. Examples of this are replacing a pump with one of a higher horsepower or a circuit breaker with one of a higher amperage capacity. Another example is not replacing a disconnect switch or motor controller with one of the same voltage, amperage, or enclosure rating.

Only individuals with the necessary skills and training should be allowed to maintain and repair AD/biogas projects' electrical systems. Otherwise, a licensed electrician should be retained.

10.2.7 Entanglement

Entanglement in rotating equipment is an all-too-common safety problem. Typical areas of concern are unprotected blades, drive shafts, couplings, belts, and sheaves on augers, pumps, blowers, compressors, and impeller-type mixers. Safety guards should always remain in place unless inspection or O&M requires otherwise. For inspection or O&M while the equipment is operating, personnel should tie back long hair and beards and refrain from wearing jewelry or loose-fitting clothing.

10.2.8 High Pressure

Less common but just as dangerous accidents can happen when pressure-retaining devices, heavy objects, or springs held in place by bolts are released by removing the bolts without first relieving the pressure or tension. Training and strict adherence to a robust lockout/tagout program can mitigate these types of safety issues.

10.2.9 Extreme Temperature

Some parts of the AD/biogas system operate at very high temperatures. Equipment and piping associated with the boiler, IC engine jacket water and exhaust, CHP system heat exchangers and pumps, and possibly the compressor discharge piping can operate at temperatures well above 140 °F. Simply touching or accidentally leaning against a hot pipe or piece of equipment can produce a serious burn. Hot piping and equipment should be labeled as burn hazards. Insulation or expanded-metal screens should be installed around hot piping that is 140 °F or hotter and is less than 8 feet above grade or decking.

10.2.10 Noise

Excessively loud or chronically high noise is an insidious safety hazard. High noise levels can cause temporary pain, short-term hearing loss, and in extreme cases, permanent hearing loss. The IC engine-generator set is likely to be the equipment producing the most noise.

Compressors and blowers can also produce a lot of noise. Hearing protection should be provided for all personnel working in noisy areas, and the noisy areas should be properly identified with warning signs.

10.2.11 Drowning

Ponds and tanks used for liquid storage are locations for drowning risk. Covered anaerobic lagoon digesters and liquid manure storage areas are especially dangerous because of H_2S toxicity and elevated levels of the asphyxiants CO_2 and CH_4. The presence of these gases can quickly cause a person to lose consciousness and fall into the liquid. Equipment repair in these areas is usually the activity with the highest drowning risk. Access to these areas should be controlled and limited to personnel with appropriate training. In addition, ring buoys (with ropes attached) and ladders (if appropriate) should be provided in these areas to facilitate rescue.

10.2.12 Pests

Flies, birds, rodents, and other vermin usually inhabit the area surrounding an AD/biogas system and are naturally attracted to digester operations because of the availability of food, water, and shelter. These pests can transmit diseases, disturb the surrounding community, and cause building and equipment damage, and an infestation can negatively affect digester operations. Preventing an infestation is the primary goal of a pest control program.

The first step in a pest control program is good housekeeping. This limits the availability of food, water, and shelter, and doing so makes additional control measures more effective. Good housekeeping includes removing clutter from within and around buildings, cleaning dumpsters, and removing trash in a timely manner. Limiting food, water, and shelter also includes removing food waste; dead and decaying organic matter; puddles and items containing standing water; stacks of pallets, wood, and similar items; and tall weeds and grasses. Common pests and specific control measures used to address them are listed below:

- Flies carry diseases and can be a significant issue for both humans and animals. Effective fly control usually requires spraying approved insecticides in the general infestation area. Be careful when selecting and applying insecticides so that spraying does not adversely affect the microorganisms necessary for the AD process. Fly control also requires regular cleaning of and larvicide application to piles of wet or moist organic material, unattended manure piles, and the moist edges of silage and feedstock piles.
- Birds can bring diseases into the facility, can transfer diseases from one location to another within the facility, and are very difficult to control. The best way to control birds is to minimize the attractiveness of the facility as a habitat, which means reducing cover and available food sources. Where allowed, approved and regulated poisons can also be used to control birds.
- Rats and mice carry diseases and can also cause equipment and building damage by gnawing on wiring and other building materials. Rodent control is best done by minimizing their food sources and habitat. Poisons are also effective, but they are more effective when

combined with a reduction of food sources and habitat so that the poisons can be strategically located.

- Eliminating food sources and restricting entry where possible can control other vermin. Hunting and/or trapping may also be an effective means of controlling vermin populations.

10.3 Safety Conclusions

Biogas contains components that can be harmful or deadly to plant operators. Precautions and training should be implemented to focus on the safe operation of the AD/Biogas system, and proper care must be used to avoid injuries due to moving equipment associated with the system.

Safe operation of an AD/Biogas system is essential for the continued and beneficial use of the AD/Biogas system to protect this investment, facilitate the reliability of revenue from the system, and ensure that the operation is an asset to the community.