Final

Methane to Markets
International Guidance for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures

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The Methane to Markets Partnership

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PREFACE

This guidance was developed by the U.S. Environmental Protection Agency (EPA) at the request of the Agriculture Subcommittee of the Methane to Markets Partnership. The Methane to Markets Partnership is an initiative to reduce global methane emissions to enhance economic growth, promote energy security, improve the environment, and reduce greenhouse gases. The initiative focuses on cost-effective, near-term methane recovery and use as a clean energy source. The Partnership works internationally through collaboration among developed countries, developing countries, and countries with economies in transition, together with strong participation from the private sector. A separate guidance for quantifying and reporting the performance of anaerobic digestion systems for agro-industrial wastes may be developed in the future.

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1.0 INTRODUCTION

The Methane to Markets Partnership strives to reduce global methane emissions. Methane accounts for 16 percent of all greenhouse gas emissions resulting from human activities (M2M, 2008). Because methane is a potent greenhouse gas and is short-lived in the atmosphere compared to carbon dioxide, achieving significant reductions would have a considerable impact on atmospheric warming, especially in the near term.

The Methane to Markets Agriculture Subcommittee focuses on reducing methane emissions from agriculture. Globally, managed livestock manure contributes more than 230 million metric tons of carbon dioxide equivalents of methane emissions, roughly 4 percent of total anthropogenic methane emissions. To reduce methane emissions from the agricultural sector, the Agriculture Subcommittee promotes anaerobic digestion of manure and agro-industrial wastes.

Anaerobic digestion is a waste stabilization process. The stabilization of livestock manures occurs by the microbially mediated reduction of the carbon in complex organic compounds to methane and carbon dioxide. Because anaerobic digestion occurs under controlled conditions, it provides the opportunity for the capture and combustion of the methane produced. It is the capture and combustion of the methane produced, along with the ability to maximize the degree of waste stabilization, that differentiates anaerobic digestion from anaerobic decomposition, which occurs naturally in lagoons and other livestock manure storage structures and may provide only partial stabilization.

As a unit process in the management of livestock manures, anaerobic digestion can provide the following benefits:

1. Reduction in methane emissions to the atmosphere. Methane is a greenhouse gas with approximately 21 times the global warming capacity of carbon dioxide.

2. Reduction in emissions of noxious odors. Noxious odors associated with livestock manures result from the accumulation of products of incomplete anaerobic decomposition.

3. Reduction in water pollution potential. Oxygen-demanding organic compounds are removed by reduction to methane and carbon dioxide, and densities of enteric pathogenic micro-organisms are reduced with negligible or no energy input.

4. Renewable energy production. The captured mixture of methane and carbon dioxide, known as biogas, can be used as a fuel to produce mechanical power for purposes such as generating electricity, cooking, lighting, and water and space heating.

5. Revenue to offset costs. Revenue can be realized byselling carbon credits and using biogas to generate electricity or displace on-farm fossil fuel use. This energy use will partially offset costs or ideally provide an increase in net income.

Interest in anaerobic digestion as a livestock manure management option has expanded rapidly in recent years as concern about methane emissions and other environmental impacts from livestock wastes has increased, along with recognizing the potential to capture and utilize a renewable energy source. As interest has increased, a number of system design approaches have evolved and been followed by construction of full-scale systems. Many of these design approaches have been accompanied by claims of process superiority. Generally, data supporting these claims have been minimal at best and not collected following a standardized methodology. Thus, the ability to compare different system design approaches with respect to biogas production, waste stabilization, and cost-effectiveness on a uniform basis has been lacking. To address this situation, the Agriculture Subcommittee of the Methane to Markets Partnership determined that an international guidance for evaluating and reporting the performance of anaerobic digestion systems for livestock manure should be developed.

This guidance is intended to establish a uniform set of methods for evaluating and reporting the performance of anaerobic digestion systems for livestock manures developed to reduce methane emissions. It provides guidelines for anaerobic digestion system evaluations. Adherence to the guidance is voluntary and is not a compulsory requirement for countries participating in the Methane to Markets Partnership. The guidance, however, is applicable to all systems across all countries, including those countries not participating in the Partnership.

Initial efforts to develop this guidance included an international search for existing documents that could support its development. A number of documents were identified, most of which focused on estimating greenhouse gas reductions, reducing greenhouse gas emissions, or safety issues.

Based on this search, a number of relevant documents were identified, including:

1. Intergovernmental Panel on Climate Change (IPCC) *2006 IPPC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006), which includes methods for establishing baseline methane emissions estimates from livestock waste management systems and combustion efficiency, as well as and methane leakage rates and emissions from open and closed flare systems.

2. The United Nations Framework Convention on Climate Change (UNFCCC) methodology for Clean Development Mechanism (CDM) projects for methane recovery in animal manure management systems (UNFCCC, 2010); which includes calculations for estimating methane reductions.

3. *A Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manure* (AgSTAR, 2007), which provides a method for evaluating the performance of anaerobic digesters in the United States.

These documents and methods were used to develop various elements of this International Guidance document. The U.S. protocol (AgSTAR, 2007) formed the basis of the overall approach, which was expanded in this document to provide flexibility for an array of technologies, scales, and country-specific constraints. This protocol was based on mass-balance characterizations for livestock waste processes and provides guidance for sampling, data analysis, and reporting. These are critical components for evaluating digester systems, as they provide a standardized and credible approach to verify claims of process performance, which are readily applicable in an international context. Specifically, the U.S. protocol:

- Establishes prerequisites for performance evaluations.

- Lists required background information.

- Specifies acceptable methods for data collection and analysis to characterize performance with respect to biogas production and utilization and waste stabilization.

- Details the approach to be used to perform an economic analysis.

All the elements listed above are incorporated in this international guidance. Although it is most desirable to perform a comprehensive performance evaluation, evaluations including all of the elements listed above may not always be possible due to resource or other constraints. Therefore, , this international guidance provides four levels of performance evaluations, as outlined below:

- **Level I:** Assembly of background information, estimation of methane emission reductions, and measurement of biogas production and composition.
- **Level II:** Level I, plus measurement of biogas utilization for generating electricity or replacing fossil fuels by direct combustion or engine-generator set waste heat recovery, or some combination thereof.
- **Level III:** Level II, plus economic analysis.
- **Level IV:** Level III plus quantification of the degree of waste stabilization.

Adherence to this international guidance will provide an objective and unbiased assessment of individual system performance and provide vendors with the ability to demonstrate the validity of performance claims. Furthermore, it will provide a common basis for comparing the performance of different design approaches. It also will provide a standard for acceptance of performance evaluation reports if a central repository is created in the future and an appropriate basis for developing technology-specific certification programs. Such information should be useful to:

- Allow livestock producers considering construction of anaerobic digestion systems to make informed choices about which technologies to install.
- Provide consultants with the ability to compare various technologies to develop the best possible system or to improve their existing technologies to meet the standards of others.
- Provide policymakers with a basis for considering or developing incentives and public waste-to-energy or rural sanitation education programs.
- Furnish the financial community with information to quantify the benefits of anaerobic digestion projects.

Certification of specific design approaches for the anaerobic digestion of livestock manures by governmental agencies or non-governmental organizations should be based on the peer review of at least two, and preferably three or more, performance evaluation reports. There should be at least three peer reviews of each report by individuals with the requisite expertise, by virtue of a combination of education and experience. Only those performance evaluation reports judged to be complete and technically sound should be accepted as the basis for certification. All peer reviews should be retained in the permanent records of the certifying agency and be available for public inspection with the names of the peer reviewers deleted. The basis for certification—Level I, II, III, or IV—should be indicated and briefly described. It also is suggested that only Level II, III, or IV should be used as a basis for certification, as the evaluation is based on measured system performance.

2.0 PREREQUISITES FOR PERFORMANCE EVALUATIONS

Performance evaluations under this guidance should be conducted only for full-scale systems that serve commercial livestock operations. The evaluation should be at least 12 months in duration to capture any impact of seasonal ambient temperature variation. In addition, evaluations should be conducted after the startup phase of operation has been completed and the digester is operating under steady-state conditions, as defined below:

1. **Plug-flow and mixed digesters, such as above and below ground tanks:** Continuous operation for a period equal to the sum of at least five hydraulic retention times (HRTs) after startup phase.

2. **Unmixed systems, such as covered lagoons, and standard rate (unheated and unmixed) anaerobic digesters:** Continuous operation for at least 1 year after startup phase.

3. **Unheated or heated attached film and anaerobic sludge blanket digesters:** Continuous operation for at least 3 months after startup phase, with the 3 months of operation being the warmest 3 months of the year for unheated digesters.

3.0 REQUIRED BACKGROUND INFORMATION

The importance of assembling and reporting adequate background information cannot be overemphasized. Such information is critical for evaluating reported results in the proper context. Below are lists of information about the livestock operation (Table 1) and the anaerobic digestion system (Table 2) that should be assembled. This information should be included in all performance evaluation reports. If the performance of a centralized system is being evaluated, the information specified in Table 1 should be provided for each livestock operation served.

In addition to the background information about the farm, a site- and system-specific plan for data collection should be developed for each evaluation. This plan should identify the sampling locations, the sampling methods to be used, the frequency and number of samples to be collected, and any other data necessary to perform the evaluation described in this guidance.

Table 1. General Information.

1. Name of operation

2. Postal address and other contact information

3. Type of operation (*e.g.*, dairy, swine, layer, *etc.*)

4. If dairy,
    a. Breed (*e.g.*, Holstein, Guernsey, *etc.*)
    b. Average number of lactating cows
    c. Average number of dry cows
    d. Average number of heifers (females more than 6 months old)
    e. Average number of calves (females less than 6 months old)
    f. Respective fractions of manure from lactating cows, dry cows, and replacements collected for digestion
    g. Method(s) of manure collection (*e.g.*, scrape, flush, *etc.*) and frequency of manure collection

5. If swine,
    a. Type of operation (*e.g.*, farrow-to-wean, farrow plus nursery, farrow-to-finish, *etc.*)
    b. Average numbers of sows and pregnant gilts, litters per sow-year, and weaned pigs per litter if applicable
    c. Average number of nursery pigs and number of nursery stage cycles per year
    d. Average number of feeder pigs and number of grow/finish cycles per year
    e. Respective fractions of manure from sows and pregnant gilts, nursery pigs, and feeder pigs collected for digestion
    f. Method(s) of manure collection (*e.g.*, scrape, flush, pull-plug pit, *etc.*) and frequency of manure collection

6. If beef,
    a. Average number of feeder cattle and number of grow/finish cycles per year
    b. Fraction of manure collected for digestion
    c. Method(s) of manure collection (*e.g.*, scrape, flush, pull-plug pit, *etc.*) and frequency of manure collection

7. If layer,
    a. Average number of hens
    b. Method(s) of manure collection (*e.g.*, scrape, flush, pull-plug pit, *etc.*) and frequency of manure collection

8. If other livestock,
    a. Type
    b. Average number of animals
    c. Fraction of manure collected for digestion
    d. Method(s) of manure collection (*e.g.*, scrape, flush, pull-plug pit, *etc.*) and frequency of manure collection

Table 2. Anaerobic Digestion System Information

Biogas Production

1. Type of digester (i.e., plug-flow, mixed, attached film, or covered lagoon)

2. Name of system vendor, postal address, and other contact information

3. Digester design assumptions
    a. Average manure volume, m^3/day (ft^3/day)
    b. Average wastewater volume, m^3/day (ft^3/day) (e.g., none, milking center wastewater, confinement facility wash water)
    c. Other waste volume, m^3/day (ft^3/day) (e.g., none, food processing waste) with physical and chemical characteristics (e.g., concentrations of total solids, total volatile solids, chemical oxygen demand)
    d. Pretreatment before digestion (e.g., none, gravity settling, screening)
    e. Volumetric loading rate, m^3 per 1,000 m^3 per day (ft^3 per 1,000 ft^3 per day)
    f. Organic loading rate, kg total volatile solids per 1,000 m^3 per day (lb per 1,000 ft^3 per day)
    g. Hydraulic retention time, days
    h. Operating temperature, °C
    i. Average monthly ambient temperatures
    j. Rate of biogas production, m^3 per kg total volatile solids added (ft^3 per lb)
    k. Presence or absence of monensin or any other antibacterial growth promoters
    l. Expected methane content, percent
    m. Compliance (yes or no) with an established engineering design standard (e.g., an applicable U.S. Department of Agriculture Natural Resource Conservation Service Conservation Practice Standard)

4. Physical description
    a. General description, including types of construction materials (e.g., partially below grade, concrete channel plug-flow with flexible cover)
    b. Dimensions (length, width, and depth or diameter and depth or height)
    c. Type(s), location(s), and thickness(s) of insulation when applicable
    d. Operating volume and ancillary gas storage capacity, if present
    e. Digester effluent treatment (e.g., none, solids separation, phosphorus precipitation)
    f. Method of digester effluent storage (e.g., none, earthen pond)

5. Monthly summaries of operational details during the period of evaluation
    a. Numbers and types of animals
    b. Other waste volume(s) and physical and chemical characteristics
    c. Frequency of digester influent addition (e.g., hourly, twice per day, once per day)
    d. Average daily digester temperature and monthly range
    e. Use of monensin or any other antibacterial growth promoters
    f. Any deviation from digester design assumptions (e.g., change in manure volume, addition or deletion of an additional waste stream)

Table 2 (continued). Anaerobic Digestion System Information

Biogas Utilization

1. Biogas utilization (e.g., none; generation of electricity; use on site for cooking or lighting or as a boiler or furnace fuel; sale to a third party).

2. If generation of electricity:
   a. Type of engine-generator set (e.g., internal combustion engine, microturbine, fuel cell) with name of manufacturer, model, and power output rating (MJ or kW) for biogas and nominal voltage
   b. Component integration (i.e., vendor or owner)
   c. Origin of equipment controller (i.e., manufacturer integrated, third-party off shelf, or third-party custom)
   d. System installer with postal address and other contact information
   e. Stand alone capacity (yes or no)
   f. Pretreatment of biogas (e.g., none, condensate trap, dryer, hydrogen sulfide removal) with names of manufacturers and models
   g. Exhaust gas emission regulation (yes or no). If yes, type of control (e.g., none, catalytic converter)
   h. If interconnected to an electric utility:
      i. Name of utility
      ii. Type of contract (i.e., sell all/buy all, surplus sale, or net metering)
      iii. If engine-generator set waste heat utilization:
      iv. Heat source (i.e., cooling system or exhaust gas or both) and heat recovery capacity (kJ/hr or Btu/hr)
      v. Waste heat utilization (e.g., digester heating, potable water heating, space heating)

3. If use on site as a boiler or furnace fuel, description of the boiler or furnace, including manufacturer, model, and rate capacity for biogas (kJ/hr or Btu/hr).

4. If biogas sale to third party, description of method of processing, delivery, and end use.

Cost Information

1. System "as built" cost, excluding site cost.

2. Cost basis (e.g., turnkey by a developer, owner acted as general contractor, constructed with farm labor).

3. An itemized list of component costs (e.g., digester, biogas utilization system).

4.0 ESTIMATING METHANE EMISSION REDUCTIONS

Each performance evaluation must include an estimate of the gross and net reductions in methane emissions resulting from the use of anaerobic digestion for the production, capture, and combustion of biogas. Gross reductions are total reductions, not accounting for any project-related emissions, such as leakage of methane from the digester or biogas handling equipment. Net reductions are total reductions less losses due to leakage and combustion efficiency, among others.

Estimates of gross methane emission reductions should not be based on the mass of methane produced by the digester.This approach would overestimate the emission reduction because digesters are designed to optimize methane production and may produce more methane than the system that it replaced. Therefore, methane reductions should be based on estimated emissions from the manure management system that was in place before anaerobic digestion was added to the manure management system. These emissions are typically referred to as *baseline emissions* as specified in, the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. For example, if the farm had originally used an anaerobic lagoon, as the primary waste management system and added an anaerobic digester, the gross methane reduction would be based on the estimated emissions from the anaerobic lagoon that was in place prior to adding the anaerobic digester.

For new operations, baseline emissions would be based on the manure management system without anaerobic digestion, which is typical for the type of livestock operation in the region, unless an exception can be justified. For example, in some parts of the world, flush-type pig farms typically have anaerobic lagoons in place to provide recycled water for flushing waste from under slatted floors, while in other parts of the world this same pig farm would typically employ manual labor and fresh water for removing waste, which is then sent to a fish pond. When co-digestion with another waste is being practiced, the avoided methane emissions associated with this other waste can be included in the gross reduction estimate. The methods for determining baseline emissions from these sources are the IPCC methods for solid waste disposal, wastewater, land application, and composting.

To estimate net emission reduction, the gross reduction in methane emissions should be adjusted to account for leakage from the system, efficiency of combustion, and any additional fossil fuel used (adapted from the UNFCCC methodology), as follows:

$$EF_P = \left(\sum_{i=1}^{n} EF_M + \sum_{i=1}^{n} EF_W \right) - \left(LK_P + CE_P + FF_P \right) \qquad (1)$$

where: EF_P = Annual project net methane emission reduction, kg CH_4 per year
EF_M = Annual gross methane emissions from manure, kg CH_4 per year
EF_W = Annual gross methane emissions from co-digested waste, kg CH_4 per year
LK_P = Methane leakage, kg CH_4 per year
CE_P = Combustion-related emissions, kg CH_4 per year
FF_P = Fossil fuel-related carbon dioxide emissions on a methane equivalent basis, kg CH_4 per year

The net project methane emissions reduction may be converted to a carbon dioxide equivalent basis by multiplying by 21, which is the global warming potential (GWP) of methane. The GWP of methane represents the ability of methane to trap heat in the atmosphere as compared to carbon dioxide. The estimated carbon dioxide equivalents represent the carbon credits that the project is eligible to claim and market.

4.1 Manure-Related Reductions

At a minimum, the *2006 IPPC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006) Tier 2 method for estimating methane emissions should be followed for estimating gross reductions in methane emissions from manure. If possible, the Tier 3 method should be used. It is based on country-specific models or using measurement-based approaches to quantify methane emissions.

Using the Tier 2 method, methane emissions for each livestock category (T) and prior manure management system (S) and climate combination (k) should be estimated as follows:

$$EF_M = \sum_{T,S} \left[\left(VS_T \times H_T \times 365 \right) \times \left(B_{0,T} \times 0.67\ \text{kg/m}^3 \times \frac{MCF_{S.k}}{100} \right) \right] \qquad (2)$$

where: EF_M = Annual methane emissions from manure, summed by livestock category (T) and prior manure management system (S), kg CH_4 per year
VS_T = Daily volatile solids excretion rate for livestock category (T), kg VS per animal-day
H_T = Average daily number of animals in livestock category (T)
365 = Basis for calculating annual volatile solids production, days per year
$B_{0,T}$ = Maximum methane production capacity for manure produced by livestock category (T), m^3 CH_4 per kg volatile solids excreted
0.67 = Conversion factor, kg CH_4 per m^3 CH_4
$MCF_{S,k}$ = Methane conversion factor for manure management system (S) for climate (k), percent

The best way to estimate average daily volatile solids excretion rates is from measured digester influent volatile solids concentration and flow rate. Another option is to use country-specific published data or region-specific default values. Default values may be found in Tables 10A-4 through 10A-9 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). Finally, the following relationship (IPCC, 2006) can be used:

$$VS_T = \left[GE \times \left(1 - \frac{DE\%}{100} \right) + \left(UE \times GE \right) \right] \times \left[\frac{1 - Ash}{18.45} \right] \qquad (3)$$

where: VS_T = Volatile excretion rate for animal type (T) on a dry matter basis, kg VS per day
GE = Gross energy intake, MJ per day
DE% = Basis for calculating annual volatile solids production, days per year
(UE x GE) = Urinary energy expressed as a fraction of GE. Typically 0.04GE can be considered urinary excretion by most ruminants (reduce to 0.02 for ruminants fed 85% or more grain and for swine). Use country-specific values when available.
Ash = Ash (fixed solids) content of manure calculated as a fraction of dry matter feed intake (e.g., 0.08 for cattle). Use country-specific values when available.
18.45 = Conversion factor for dietary GE per kg of dry matter (MJ per kg). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

See Section 10.2, Equation 10.16 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006) for estimating GE intake and digestibility. The maximum methane production capacity (B_0) of manure varies by species and diet. If available, published country-specific data should be used. Otherwise, see Tables 10A-4 through 10A-9 of the *2006 IPCC*

Guidelines for National Greenhouse Gas Inventories for default values. The same source should be consulted for default MCF values (See Table 10.17).

4.2 Baseline Emissions From Co-Digested Wastes

When another waste is being co-digested with manure, there is an additional reduction in methane emissions if that waste previously was a source of methane emissions. For example, there will be a reduction in methane emissions if the waste being co-digested with manure was previously sent to a landfill or a conventional anaerobic lagoon. Conversely, there will be no reduction if the waste was previously treated using an aerobic process such as activated sludge or land application. These processes may also increase nitrous oxide emissions, which are not addressed in this guideline. Equation 4 should be used for estimating the reduction in methane emissions for each waste being co-digested with manure.

$$EF_w = \left(VS_W \times 365\right) \times \left(B_{0,W} \times 0.67\ \text{kg/m}^3 \times \frac{MCF_{S,k}}{100} \right) \qquad (4)$$

where: EF_W = Annual methane emissions from waste (W), kg CH_4 per year
VS_W = Mass of waste (W) digester influent volatile solids, kg dry matter per day
$B_{0,W}$ = Maximum methane production capacity waste (W), m^3 CH_4 per kg influent volatile solids
$MCF_{S,k}$ = Methane conversion factor for waste management system (S) for climate (k), percent

If a country-specific and verifiable published value for the maximum methane production capacity (B_o) of the waste is not available, this value must be determined experimentally using replicated long-term, bench-scale batch studies to be conducted at the operating temperature of the digester being evaluated to estimate the readily biodegradable and refractory fractions of VS. Such studies should be conducted for no less than 30 days and with the refractory fraction at infinity (VS_∞/VS_0) determined by plotting VS_t/VS_0 versus ($1/VS_0$*t), where t equals zero at the beginning of the study. The y-axis intercept should be determined using linear regression analysis.

4.3 Leakage and Combustion Emissions.

Very little information is available regarding methane leakage from anaerobic digestion systems. However, some leakage probably occurs from most systems and should be incorporated into estimates of net methane emission reductions from anaerobic digestion systems. The IPCC (2006) provides no guidance. Therefore, this guidance recommends using the default value for projects covered under the UNFCCC CDM, which is 10 percent of the B_0 of the manure fed into the management system, as follows (adapted from UNFCCC, 2010):

$$\mathrm{LK_P} = 0.10 \times 0.67 \times \sum_{S,T} \mathrm{B_{0,T}} \times \mathrm{N_T} \times VS_T \times MS\%_S \times 365 \qquad (5)$$

where:
- LK_P = Methane leakage, kg CH_4 per year
- 0.10 = Assumed amount of leakage
- 0.67 = Conversion factor, kg CH_4 per m^3 CH_4
- $B_{0,T}$ = Maximum methane production capacity for manure produced by livestock category (T), m^3 CH_4 per kg volatile solids excreted
- N_T = Number of animals in livestock category (T)
- VS_T = Daily volatile solids excretion rate for livestock category (T), kg VS per animal-day
- $MS\%_S$ = Fraction of manure handled in baseline manure management system (S)
- 365 = Basis for calculating annual volatile solids production, days per year

Because no combustion process is 100 percent efficient, and all captured methane should be disposed of by combustion, combustion-related methane emissions also should be accounted for in estimating a project's net methane emission reduction. For open and enclosed flares, methane emissions should be based on the measured volume of methane combusted and calculated as follows:

$$\mathrm{CE_P} = \left[\mathrm{CH_{4comb}} \times \left(1 - \mathrm{C_{eff}}\right)\right] \times 0.67 \qquad (6)$$

where:
- CE_P = Combustion-related emissions, kg CH_4 per year
- $CH_{4,\,comb}$ = Measured methane sent to flare, m^3 CH_4 per year
- C_{eff} = Combustion efficiency, decimal
- 0.67 = Conversion factor, kg CH_4 per m^3 CH_4

Unless higher combustion efficiency values can be justified by supporting documentation, the UNFCCC CDM default values listed in Table 3 should be used.

Table 3. Default Values for Methane Flare Combustion Efficiencies, Decimal

Combustion Process		Default Value, Decimal (C_{eff})
Open flare	Continually operational	0.50
	Not continually operational	0
Enclosed flare	Continuous monitoring of compliance with manufacturer's specifications* or continuous monitoring of methane destruction	0.90

*In any hour when there is noncompliance with the manufacturer's specifications, a 0.50 default value should be used for that hour.

Methane emissions associated with combustion in lean and rich burn internal combustion engines and boilers and furnaces also should be based on the measured amount of methane combusted and calculated using Equation 6, unless the IPCC default values listed in Table 4 are being used. In that case, methane emissions should be calculated as follows:

$$CE_P = CH_{4comb} \times 35{,}755{,}188\,\text{J/m}^3 \times CH_{4emitted} / 1 \times 10^{12}\,\text{J} \quad (7)$$

where: CE_P = Combustion related emissions, kg CH_4 per year
$CH_{4,\,comb}$ = Measured methane sent to combustion device, m^3 CH_4 per year
$CH_{4,\,emitted}$ = Methane emissions from combustion in lean burn and rich burn internal combustion engines and boilers and furnaces, kg CH_4 per TJ

Table 4. Default Values for Methane Emissions from Combustion in Lean Burn and Rich Burn Internal Combustion Engines and Boilers and Furnaces (IPCC, 2006)

Combustion Process	Default Value, kg CH_4/TJ ($CH_{4,\,emitted}$)
Lean burn internal combustion engine	597
Rich burn internal combustion engine	110
Boiler/furnace	1

4.4 Fossil Fuel Use Related Emissions

An anaerobic digestion project may result in increased fossil fuel use, such as use of gasoline or diesel fuel for manure transport to a centralized anaerobic digestion facility, transport of another waste to the facility for co-digestion, or use of compressors and other equipment required to process the biogas for use. The resulting increase in carbon dioxide emissions also should be accounted for using the default emission factors for fossil fuel use, as shown in Table 5.

Table 5. Default Values for Carbon Dioxide Emissions from Gasoline and Diesel Fuel Use (derived from values in IPCC, 2006)

Fuel	Default Value, kg CO_2/L (C_{factor})
Gasoline	2.4
Diesel	2.7

The values in Table 5 should be used with Equation 8 to estimate the carbon dioxide emissions resulting from increased fossil fuel use due to transportation and stationary fuel combustion.

$$FF_P = \frac{(FF_{use} \times C_{factor})}{21} \tag{8}$$

where:
- FF_P = Fossil fuel-related carbon dioxide emissions on a methane equivalent basis, kg CH_4 per year
- FF_{Use} = Additional fossil fuel use, L per year
- C_{factor} = Conversion factor, kg CO_2 per L
- 21 = GWP of methane as compared to carbon dioxide, kg CO_2/kg CH_4

5.0 BIOGAS PRODUCTION AND UTILIZATION

This guidance requires measurement of total biogas production and composition for all evaluations. Level II, III, and IV evaluations also require measurements related to biogas utilization for generating electricity or replacing fossil fuels by direct combustion or engine-generator set waste heat recovery.

5.1 Biogas Production

Total biogas production should be measured in all performance evaluations. The measurements must account for all biogas produced, including biogas used in an energy recovery device and all biogas that is flared (e.g., when biogas production exceeds engine capacity or when biogas is flared during periods of engine maintenance). Biogas production will need to be measured using an appropriate meter. Top inlet mechanical meters designed to measure corrosive gas flow are suitable for this measurement. Other types of gas flow meters, such as thermal mass flow meters, also are acceptable. Meters should be temperature- and pressure-compensated. Evidence of the verification of the precision and accuracy of all meters used to measure biogas production is required. All biogas production reporting should be under standard conditions (0°C, 1 atm) to allow direct comparisons of production among different systems.

5.2 Biogas Composition

The concentration of carbon dioxide by volume should be determined at least monthly using the detection tube appropriate for the expected concentration. Monthly determination of the biogas hydrogen sulfide concentration also is desirable. The concentration should be based on the average of at least three replicate measurements during each sampling episode. In addition, laboratory biogas analysis to determine methane, carbon dioxide, hydrogen sulfide, and ammonia content by volume should be performed at least quarterly to confirm the accuracy of the gas detection tube measurements. Each sample should be collected in a Tedlar™ gas collection bag and analyzed to determine methane, carbon dioxide, hydrogen sulfide, and ammonia composition by volume using gas chromatography ASTM Method D 1945-03 (ASTM International, 2009) for methane and carbon dioxide, ASTM Method D 5504-01 (ASTM International, 2009) for hydrogen sulfide, and EPA Method 350.1 for ammonia, or equivalent analytical methods. Results of samples containing more than 10 percent of unidentified gases, typically nitrogen and oxygen, should be discarded due to an unacceptable degree of atmospheric contamination reflecting a poor sample collection technique. Real-time electronic gas analysis (using continuous gas analyzers) is a requirement for CDM projects and is also an acceptable method for this evaluation, with evidence of precision and accuracy.

5.3 Biogas Utilization

Biogas utilization should be measured and recorded using the same type of meter used to determine total biogas production. When biogas is used to generate electricity, the electricity generated (MJ or kWh) also should be measured and recorded using a permanently installed utility-type meter or a comparable substitute. With these data and the biogas composition, the thermal efficiency of the conversion of biogas energy to electrical energy using the lower heating value (LHV) for methane should be calculated for reporting as follows:

$$TCE = \left[\left(\frac{MJ_E}{Biogas \times CH_4 \times LVH}\right)\right] \times 100 \quad (9a)$$

where:

TCE = Thermal conversion efficiency, percent
MJ_E = Rate of electricity generation, MJ per unit time
Biogas = Rate of biogas combustion, m^3/unit time
CH_4 = Biogas methane content, decimal
LHV = Lower heating value of methane, MJ/m^3

or

$$TCE = \left[\left(\frac{kWh \times 3{,}412}{Biogas \times CH_4 \times LHV}\right)\right] \times 100 \quad (9b)$$

where:

TCE = Thermal conversion efficiency, percent
kWh = Rate of electricity generation, kWh per unit time
3,412 = Btu/kWh
Biogas = Rate of biogas combustion, ft^3/unit time
CH_4 = Biogas methane content, decimal
LHV = Lower heating value of methane, Btu/ft^3

The LHV of methane is the heat of combustion less the heat of vaporization of the water formed as a product of combustion. The LHV of methane should be used in this calculation because condensation of any water with an engine-generator set is unlikely. The LHV of methane under standard conditions (0°C, 1 atm) is 960 Btu per ft^3 or 35,770 kJ per m^3 (Mark's Standard Handbook for Mechanical Engineers, 1978). However, the LHV of methane varies with temperature and pressure in accordance with the universal gas law, and the LHV of methane used to calculate thermal efficiency should be determined for the temperature and pressure at which biogas production is being measured. When reporting thermal conversion efficiency, the assumed heating value should be stated along with the time period involved.

Engine-generator set operating hours also should be measured and recorded at least monthly to calculate and report monthly and annual engine-generator set online efficiency, as shown in Equation 10.

$$\text{Online efficiency, \%} = \frac{\text{Engine - generator set hr per unit time}}{\text{hr per unit time}} \times 100 \qquad (10)$$

Average output should also be calculated as shown in Equation 11a or 11b.

$$\text{Average generator set output, kW} = \frac{\text{kWh per unit time}}{\text{Engine - generator set hr per unit time}} \qquad (11a)$$

or

$$\text{Average generator set output, MJ} = \frac{\text{MJ per unit time}}{\text{Engine - generator set hr per unit time}} \qquad (11b)$$

Capacity utilization efficiency should be calculated as shown in Equation 12a or 12b.

$$\text{Average capacity utilization efficiency, \%} = \frac{\text{Average generator set output, kW}}{\text{Rated maximum output for biogas, kW}} \times 100 \qquad (12a)$$

or

$$\text{Average capacity utilization efficiency, \%} = \frac{\text{Average generator set output, MJ}}{\text{Rated maximum output for biogas, MJ}} \times 100 \qquad (12b)$$

When there is utilization of engine-generator water jacket or exhaust heat for water or space heating , the heat energy (in Btu or kJ) beneficially used should be measured and recorded using appropriate meters. In addition, determination of any heat energy that is utilized for digester heating is recommended.

5.4 Data Collection

All meters used to measure biogas production and utilization, electricity generated, engine-generator set hours, and waste heat beneficially utilized should be calibrated by the manufacturer immediately prior to the beginning of each performance evaluation. In addition, each meter should have a totalizer that is not manually resettable to avoid accidental data loss, and all meter readings should be recorded during every sampling episode (or more often) with the date and time of the meter reading noted. Also, a copy of the digester operator records should be obtained monthly.

5.5 Reporting

If co-digestion of livestock manure and another waste or feedstock is being practiced, reporting biogas and methane produced and electricity generated on a per head basis is not applicable. This practice, which has been employed in the past, is misleading and will not be acceptable in submitted reports. When the performance of systems co-digesting manure and another waste or feedstock is being evaluated, biogas and methane produced and electricity generated should be reported as a function of the average daily loading of VS and COD over the duration of the study. In addition, the average daily loadings of VS and COD for manure and other wastes should be reported concurrently.

6.0 ECONOMIC ANALYSIS

It is generally accepted that the anaerobic stabilization of livestock manure under controlled conditions can significantly reduce the potential impacts of these wastes on air and water quality, while also recovering a substantial amount of usable energy. However, the decision to construct and operate an aerobic digestion system depends ultimately on the anticipated ability to at least recover any internally derived capital investment with a reasonable rate of return, and to service any debt financing over the life of the system. Therefore, all comprehensive system performance evaluations should include a financial analysis performed in accordance with the general principles of engineering economics, as outlined by Grant *et al.* (1976) and others.

In the past, several approaches have been used for assessing the economic attractiveness of these systems. One is the simple determination of the time required to recover the internally derived and borrowed capital investment from the revenue generated. This payback period approach is simple but does not consider the time value of money. Calculation of present worth or net present value is another approach in which the value of future revenue is discounted to present worth and compared to the required capital investment. The problem with this approach is that the result obtained is dependent on the assumption of a single discount rate over the life of the system. In addition, it does not account for annual net income or loss from the biogas production and utilization effort. Therefore, this guidance requires a cash flow approach, described below, in which total annual cost and annual revenue are calculated and compared to determine the annual net income or loss. However, results of payback period and present worth calculations also can be conveyed in performance evaluation reports if desired.

6.1 General Approach

Economic analysis of anaerobic digestion systems for Level III and IV performance evaluations should be performed from the perspective that the system is an independent enterprise, with annual net income or loss for the system being the single metric used to characterize financial viability. When the digester system is part of a livestock operation, as opposed to a centralized system, the biogas energy used by other parts of the operation is treated as a source of income for the biogas enterprise, along with payments received for any biogas energy sold to a third party.

6.2 Boundary Conditions

Because anaerobic digestion is an optional component of manure management systems, appropriate boundary conditions that exclude costs and revenue sources that are not dependent on the biogas enterprise must be defined. Only costs for system components that are required for the anaerobic digester should be included.

For example, costs associated with manure storage following anaerobic digestion should not be included as components of either biogas system capital or annual operation and maintenance costs, because biogas production and utilization does not require subsequent manure storage. Costs associated with manure storage are costs of an independent decision to store manure to minimize environmental impacts associated with current land application practices or to maximize manure value as a source of plant nutrients for crop production. However, when another waste that is not a byproduct of the farm enterprise is being co-digested with manure, the additional cost for storing and disposing the additional effluent should be included.

Another example of an inappropriate cost component would be including the cost of a pump to transfer manure to an anaerobic digester when a pump is required without digestion to transfer manure to a storage structure. However, if the anaerobic digester effluent cannot be transferred to the storage structure by gravity and a pump is needed to operate the anaerobic digester, then the cost of the pump should be included in the estimate.

With respect to complementary operations, such as the separation of coarse solids from anaerobically digested dairy or pig manure, there has been debate about the handling of costs and revenue. Commonly, the capital and operating costs of solids separation have been considered as part of the biogas production and utilization system total cost, and the sale or an onsite use of the separated solids (e.g., as bedding or soil amendment) is considered a source of revenue. However, this activity is not necessary for biogas production and utilization because separation of coarse solids from dairy manure can be accomplished without prior anaerobic digestion. Thus, solids separation should be considered as a separate enterprise in this context, with the caveat that any reduction in the final stabilization cost for the solids used on site or sold represents revenue to the biogas enterprise.

Similarly, the cost of separating coarse solids from dairy manure entering a covered lagoon digester should not be considered as part of the cost of biogas production and utilization, because removal of these solids is necessary for the satisfactory performance of conventional anaerobic lagoons, and the cost is the same. In addition, the revenue derived from the separated solids with and without biogas production will be the same.

This guidance recognizes that variation among biogas production and utilization systems and site-specific conditions may justify different boundary conditions for financial analysis, based on best professional judgment. When the rationale for the specified boundary conditions is not entirely clear, a brief explanation of the underlying logic should be included with the results of the economic analysis. In all cases, the report presenting the results of the performance evaluation must include a schematic that identifies the boundary conditions assumed for the economic analysis.

6.3 Methodology

This section describes the methodology to estimate annual capital cost, annual operating and maintenance cost, other annual costs, annual revenue, and net income.

6.3.1 Annual Capital Cost

The first step in determining annual net income or loss from biogas production is the calculation of the annual capital cost of the system using the annual cash flow approach. To do so, three initial assumptions are necessary. The first assumption is that the total capital cost is comprised of internally derived capital (e.g., monetary investment by the operator) and borrowed capital, not just the borrowed capital. The second assumption is that the retirement of total capital cost will occur by a uniform series of annual payments over the useful life of the system, or a shorter period if desired. The third assumption is an estimate of the useful life of the system. Although a useful life of 20 years generally is standard for structural components, it clearly is unrealistically long for some system components. Flexible covers generally have a useful life of about 10 years, and mechanical equipment has a useful life of 7 years. However, all system components can be considered to have a useful life of 20 years if the reconditioning or replacement costs for components having a useful life of less than 20 years are accounted for in the annual operation and maintenance costs. This assumption allows for simplicity and standardization. A more detailed approach is acceptable if reconditioning and replacement costs are not included in the estimate of annual operation and maintenance cost, as will the less conservative assumption of capital recovery over 10 instead of 20 years.

Generally, anaerobic digestion systems are financed with a combination of internally derived and borrowed capital. In some instances, projects may receive cost-sharing assistance in the form of a grant or a below-market interest rate loan. One of the objectives of this guidance is to establish a basis that allows the comparison of different types of anaerobic digestion systems and of similar systems in different geographical locations. Therefore, all determinations of the annual capital cost for individual systems should be based on the final total cost, not the net cost to the owner.

In calculating the annual capital cost of the system, it is recommended for simplicity that the rate of interest being paid for borrowed capital is a reasonable rate of return to the internally derived capital invested. Therefore, the annual capital cost is calculated simply by multiplying the turnkey cost of the system by the capital recovery factor for a uniform series of payments over 20 years, or 10 years if desired, at the interest rate being paid for borrowed capital.

6.3.2 Annual Operation and Maintenance Costs

One of the more uncertain aspects of the economic analysis of anaerobic digestion systems has been the ability to realistically estimate annual operation and maintenance costs. This lack of information is due, in part, to two factors. First, system owners generally do not maintain a detailed record of operation and maintenance costs during performance evaluations. Second, most performance evaluations will be for relatively new systems and it is unrealistic to assume that the operation and maintenance costs incurred during a 12-month performance evaluation will be representative of the average annual operation and maintenance costs over the life of the system, given that maintenance costs tend to increase with age. Therefore, the standard assumption that the average annual operation and maintenance costs will be 3 percent of the total capital costs should be used unless better information is available. However, management and labor requirements for routine system operation should be recorded and reported as part of all performance evaluations in an effort to delineate more clearly the cost of biogas system operation and maintenance.

6.3.3 Other Annual Costs

The construction of an anaerobic digestion system may increase the assessed value of a livestock operation and therefore increase annual real estate taxes. It also may increase the annual cost of insurance on structures and equipment and possibly the cost of liability insurance. In addition, other costs may increase, plus new costs may occur. For example, the cost of manure collection may increase if collection frequency increases. Also, an operating permit with an annual fee may be required. The magnitude of these increases should be determined and added to the estimated annual capital and operation and maintenance costs to determine the total annual cost of operating the system. Similarly, other annual costs in addition to operation and maintenance costs (e.g., insurance, real estate taxes, salaries, fringe benefits, transportation) will be incurred for centralized systems. All of these costs should be identified and included in the economic analyses of anaerobic digestion systems when possible, or their absence should be noted.

6.3.4 Annual Revenue

For some anaerobic digestion systems, the sale of carbon credits may be the sole source of revenue. However, electricity generated will be the primary source of revenue for many systems when it is financially attractive to reduce purchases of electricity from, and possibly sell electricity to, the local electric utility. For systems with sell all/buy all utility contracts, the annual revenue generated by the system simply will be the annual sum of payments received from the utility. The estimation of annual revenue from electricity generation for operations with surplus sale or net metering utility contracts is more difficult due to the problem of placing a value of the biogas-generated electricity being used on site. Because of the way rate schedules for electricity generally are structured, the average cost per kWh decreases as the amount of electricity purchased increases. Therefore, reducing the amount of electricity purchased can increase its unit cost. In addition, onsite use of biogas-generated electricity may either increase or decrease demand charges and may result in the addition of a stand-by charge. If there is no onsite use of biogas-generated electricity, assuming that the average value of biogas electricity is equal to the average cost per kWh of electricity purchased from the utility may result in either an over- or underestimate of the annual revenue from onsite biogas-generated electricity use.

The recommended approach for dealing with this issue is to compare the total amount of electricity purchased from the local utility for the 12 months prior to startup of the anaerobic digestion system with the total amount for the 12 months of the performance evaluation. The difference multiplied by the utility rate during the performance evaluation is the revenue generated by onsite use. If, however, the livestock operation is a new operation or there were significant changes, such as expansion when biogas production began, the cost of electricity without biogas production should be estimated. This should be done from the record of onsite biogas electricity consumption and purchases from the local utility for the 12 months of the performance evaluation. In all cases, the validity of the estimate should be confirmed by evidence that the period of the performance assessment is reasonably typical with respect to ambient temperature.

For combined heat and power systems where engine-generator set waste heat is being recovered for beneficial use, the revenue being derived from waste heat utilization should be calculated based on the cost per unit of energy for the conventional fuel being replaced and the waste heat energy being utilized. The same approach should be used to estimate revenue when using biogas as a boiler or furnace fuel. Costs of the conventional fuels most likely to be replaced (liquefied petroleum gas or No. 2 fuel oil) vary seasonally and therefore, the impact of seasonal variation in biogas use and value must be incorporated into revenue estimates.

6.3.5 Net Income

After calculations of total annual costs and annual revenue are made, calculate net income from the biogas enterprise before income taxes. An attempt to estimate net income after income taxes should not be made because income from the biogas system will be a component of total income only from the livestock operation, and livestock income may vary significantly over the life of the biogas system. In addition, the use of confidential business information will be avoided.

7.0 PROCESS PERFORMANCE CHARACTERIZATION

This section presents a summary of process performance characterization information, including waste stabilization parameters, pathogen reduction, sample collection, sample preservation, analytical methods, hydraulic retention time and temperature, and reporting.

7.1 Waste Stabilization Parameters

Level IV evaluations of the performance of anaerobic digestion systems include quantifying the degree of waste stabilization being realized by the anaerobic digestion process. For mixed, plug-flow, and attached film digesters, the degree of waste stabilization claimed should be based on differences—when statistically significant—between mean influent and effluent concentrations of the following parameters:

- Total solids (TS)
- Volatile solids (VS)
- Chemical oxygen demand (COD)
- Total volatile acids (TVA)

In addition, it must be demonstrated that the observed changes in concentrations of these parameters are due to microbial processes rather than settling of particulate matter by showing that there is no statistically significant difference ($P<0.05$) between influent and effluent fixed solids and preferably, total phosphorus (TP) concentrations as well. Ideally, changes in concentrations of the following chemicals should be determined but are not required:

- Total Kjeldahl nitrogen (TKN)
- Organic nitrogen (ON)
- Ammonia nitrogen (NH_4-N)
- Total phosphorus (TP)
- Total sulfur (S)

Mean influent and effluent pH values must be reported in conjunction with the other parameters listed above.

For covered lagoons, differences between influent and effluent concentrations for those parameters present in both particulate and soluble forms (i.e., TS, VS, and COD) represent changes due to the combination of microbial processes and settling and are not valid indicators of the degree of waste stabilization being achieved. Although these differences have value in characterizing effluent water pollution potential and should be reported, quantification of the degree of waste stabilization should be based on the difference between influent and effluent TVA concentrations and COD reduction, which are estimated based on methane production.

Stoichiometrically, 0.3496 m^3 of methane is produced per kg COD destroyed (5.60 ft^3 of methane is produced per lb of COD destroyed) under standard conditions (0°C and 1 atm) (Madigan et al., 1997). The assumed quantity of methane produced per unit COD destroyed under other than standard conditions must be adjusted to standard conditions using the universal gas law (See Metcalf and Eddy, Inc., 2003 and Appendix B). It is recommended that this approach for estimating COD reduction also be used in evaluating other types of digesters and comparing it to COD reduction estimates based on the difference between mean influent and effluent concentrations (see Appendix A for a discussion of the construction of materials balances).

Although methane production also can be expressed as a function of VS destruction, the nature of this relationship is variable depending on the chemical composition of the VS destroyed. The variation in chemical composition among different types of livestock manure as well as the impact of different feeding programs and possibly other variables within the different animal sectors, suggests that there is no single, generally applicable conversion factor as with COD. For example, the generally accepted degree of variation in total biogas production during the anaerobic digestion of domestic wastewater biosolids can vary from 0.7492 to 1.124 m^3 per kg VS destroyed (12 to 18 ft^3 per lb of VS destroyed) (Metcalf and Eddy, Inc., 2003). A defensible basis for estimating VS destruction during the anaerobic digestion of livestock manures based on methane production seems to be lacking at this time but may emerge in the future.

Finally, it is recommended that long-term, bench-scale batch studies be conducted at the operating temperature of the digester being evaluated to estimate the readily biodegradable and refractory fractions of VS. Such studies should be for no less than 30 days and with the refractory fraction at infinity (VS_∞/VS_0), determined by plotting VS_t/VS_0 versus ($1/VS_0*t$), where t equals zero at the beginning of the study, and determining the y-axis intercept using linear regression analysis.

7.2 Pathogen Reduction

Under this guidance, estimating pathogen reduction is optional. At a minimum, all claims of pathogen reduction potential must be supported by results of the analyses of the digester or covered lagoon influent and effluent samples collected and analyzed for the waste stabilization parameters previously listed. Claims of pathogen reduction potential may be based solely on reductions in the densities of the total coliform and fecal streptococcus groups of indicator organisms. It should be clearly explained that reductions in these groups of microorganisms are only indicative of the potential for pathogen reduction. If the demonstration of reduction of a specific pathogen is desired, preference should be given to *Mycobacterium avium paratuberculosis* in dairy manure and *Salmonella spp* in swine and poultry manures.

7.3 Sample Collection

Given the inherent variability in animal manures, care should be taken to ensure that all influent and effluent samples are collected under conditions that are representative of the average daily flow. While the most desirable approach would be to collect 24-hour flow-composite samples, this approach generally is impractical for collection of livestock manure samples. Thus, the following alternatives are recommended.

1. With influent and effluent lift stations, a series of at least five grab samples should be collected at different depths when the lift station is at maximum capacity and then combined into a single composite sample. When possible, the contents of the lift station should be mixed before sample collection.

2. When samples have to be collected from a continuously or periodically flowing influent or effluent stream, a series of at least six grab samples should be collected over a period of no less than 1 hour and combined into a single composite sample.

Composite samples should be no less than 20 L, and subsamples withdrawn for analysis should be no less than 1 L. To ensure that samples collected are representative, there should be an ongoing review of analytical results to determine if the degree of variability is reasonable. If not reasonable, a modification of the sample collection protocol is necessary.

Because of inherent variability over time, all claims with respect to waste stabilization must be based on the results of the analysis of a minimum of 12 monthly influent and effluent samples, with the following caveat: if the coefficient of variation for influent or effluent TS concentrations exceeds 25 percent, or there is more than one extreme observation that is statistically determined to be an outlier, more frequent sample collection and analysis may be necessary, with at least 24 semimonthly sampling episodes recommended.

With co-digestion of livestock manure and another waste or combination of other wastes or another feedstock, a sampling plan must be devised that will characterize the digester influent and effluent to accurately delineate the degree of waste stabilization being realized, as well as the relationship between waste stabilization and biogas production. If the same waste or combination of wastes or another feedstock is being combined with manure continually and at a constant rate, periodic sampling, as described above, should be sufficient. If, however, different wastes are being combined with manures at different times, or co-digestion is intermittent, adequate evidence must be provided that the mean values of the physical and chemical characteristics of the digester influent and effluent are representative.

An additional requirement for all performance evaluations involving co-digestion is that a record be maintained of all additions of other wastes for a period equal to at least five HRTs prior to and through the 12-month duration of the performance evaluation. This record must be included in the report of the performance evaluation and include at least the following information:

1. Type and source of the waste(s) or other feedstocks.
2. Date(s) of addition.
3. Volume added.
4. TS, VS, COD, and TVA concentrations and pH, using the same analytical protocols being used for determining digester influent and effluent physical and chemical characteristics.

7.4 Sample Preservation

All anaerobic digester influent and effluent samples should be collected, immediately iced or refrigerated, and delivered for analysis within 24 hours . Given the high concentrations of organic matter, subsamples should not be acidified for preservation.

7.5 Analytical Methods

Only analytical methods described in Methods for Chemical Analysis of Water and Wastes, EPA-600/4-79-020 (U.S. Environmental Protection Agency, 1983) or Standard Methods for the Examination of Water and Wastewater, 21st edition (American Public Health Association, 2005), or equivalent methods having the same degree of precision and accuracy should be used. Particular analytical methods are not specified because there may be more than one suitable option for a parameter. Influent and effluent samples should be analyed by a laboratory with appropriate certification to perform analyses of wastewater and with an ongoing quality assurance/quality control (QA/QC) program. In the event that an analytical laboratory without the appropriate certification, such as a university research laboratory, is used, that laboratory must have a QA/QC program that is comparable to such programs required for certification. The laboratory used should have previous experience in analyzing samples with high solids concentrations, and duplicate, or preferably triplicate, analyses of individual samples should be performed for all parameters.

The multiple-tube fermentation techniques described in Standard Methods for the Examination of Water and Wastewater, 21st edition (American Public Health Association, 2005) should be used to estimate fecal coliform, fecal streptococcus, and *Salmonella spp.* densities. For estimation of *M. avium paratuberculosis* densities, either the NADC or the Cornell Method (Stabel, 1997) is acceptable.

7.6 Hydraulic Retention Time and Temperature

Because the degree of waste stabilization will vary with HRT, and actual HRT might differ from the design value, the determination of actual digester or covered lagoon influent or effluent flow rate to calculate actual HRT is also a requirement of this guidance. Because of differences among digesters, no specific flow measurement techniques arespecified. However, the method used, as well as the underlying rationale, must be fully described in the performance evaluation report.

In addition, digester or covered lagoon operating temperature must be determined and recorded during each sampling episode. The concurrent measurement of influent and effluent temperatures is desirable, but not required. At least monthly, the accuracy of all thermometers and other temperature measuring devices should be checked using a precision thermometer with certification traceable to the National Institute of Standards and Technology (NIST) or a similar national standards organization. For covered anaerobic lagoons, the average daily ambient temperature over the duration of the performance evaluation also should be measured and recorded or obtained from the nearest official weather observation station.

7.7 Reporting

All reductions must be shown to be statistically significant at least at the $P<0.05$ level using the Student t test (Snedecor and Cochran, 1980.). Any suspected outliers in datasets should be tested at $P<0.05$ using Dixon's method (Snedecor and Cochran, 1980). For covered lagoons, claims of VS and COD reductions will have to be estimated based on observed biogas production. All densities of indicator organisms and pathogens should be reported and compared statistically on a $\log_{10}$ colony-forming unit (CFU) per 100 ml basis. If a reduction is claimed, it also must be statistically significant at least at $P<0.05$. When differences are found to be statistically significant, 95 percent confidence interval estimates should be reported.

8.0 REPORT FORMAT

Reports presenting results of performance evaluations of anaerobic digestion systems for livestock manures should contain the following sections:

- Summary and Conclusions—A brief overview of the performance evaluation and presentation of the major findings.
- Introduction— Descriptions of the location of the performance evaluation and the biogas system evaluated followed by the objectives of the evaluation.
- Methods and Materials—A description of methods and materials employed in the performance evaluation.
- Results—Summaries of the results obtained.

- Discussion—A discussion of the results obtained, especially with respect to similarities to and differences from previously reported results.

- References—A list of literature cited, following the format used in this document.

- Appendices
  - A copy of the QA/QC plan for the laboratory that performed digester influent and effluent sample analyses, when applicable.
  - A record of tests of the accuracies of meters and temperature measuring devices used.
  - All data collected in tabular form.

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APPENDIX A

Material Balances

A material balance (or inventory) is a simple accounting of any material in a system, which may be a single unit, a collection of units, or an entire system, and generally may be stated as:

Input (enters through the system boundary) +
Generation (produced within the system) –
Output (leaves through the system boundary) – (A-1)
Consumption (consumed within the system) =
Accumulation (buildup within the system boundary)

If there is no generation or consumption within the system boundary, as is the case with fixed solids (FS) and total phosphorus (TP) in an anaerobic digestion reactor, Equation A-1 reduces to:

Input (enters through the system boundary) –
Output (leaves through the system boundary) = (A-2)
Accumulation (buildup within the system boundary)

In the analysis of the performance of livestock and other waste treatment or stabilization processes, it generally assumed that no accumulation of any substance due to settling is occurring if the input of FS, and preferably also TP, is equal to the output. Therefore, any difference between input and output must be due to generation or consumption, and Equation A-1 reduces to:

Input (enters through the system boundary) +
Generation (produced within the system) = (A-3)
Output (leaves through the system boundary) –
Consumption (consumed within the system) +

If generation is zero or negligible in comparison to consumption, Equation A-3 reduces to:

Input (enters through the system boundary) –
Output (leaves through the system boundary) = (A-4)
Consumption (consumed within the system)

and treatment or stabilization efficiency is calculated as follows:

Treatment or stabilization efficiency, % = (A-5)
*(Consumption/Input) * 100*

The basis for material balances for continuous steady-state processes such as anaerobic digestion usually is mass flow rates (e.g., kg per hr). However, material balances to estimate treatment or stabilization efficiency also can be constructed using concentrations (e.g., mg per L) when volumetric flow rates (e.g., L per hr) are equal. Although, there is some reduction in volume during anaerobic digestion due to the saturation of the biogas leaving the reactor with water vapor, the reduction in volume is negligible and can be ignored.

For estimating chemical oxygen demand (COD) reduction in covered lagoons based on methane production under standard conditions, the relationship is:

$$COD_{reduction}\text{, kg/unit time} = (\text{Methane production, } m^3\ CH_4\ /\text{unit time})/(0.3496\ m^3\ CH_4/\text{kg}\ COD_{destroyed}) \quad \text{(A-6a)}$$

$$COD_{reduction}\text{, lb/unit time} = (\text{Methane production, } ft^3\ CH_4\ /\text{unit time})/(5.60\ ft^3\ CH_4/\text{lb}\ COD_{destroyed}) \quad \text{(A-6b)}$$

For nonstandard conditions, the universal gas equation should be used to determine the volume occupied by one mole of methane and the methane equivalent of COD converted under anaerobic conditions, assuming 64 g COD per mole of methane.

APPENDIX B

Biogas Production

To determine biogas production under digester operating conditions from COD destruction based on the stoichiometrically based estimate that 5.60 ft^3 of methane are produced per lb of COD destroyed (0.3496 m^3 per kg COD destroyed) under standard conditions (0°C and 1 atm), or to correct non-temperature- or pressure-compensated biogas production measurements to standard conditions, the following relationship (the general gas law) should be used:

$$V_2 = V_1 * (T_2/T_1) * (P_1/P_2) \qquad \text{(B-1)}$$

where: V_1 = gas volume (m^3) at temperature T_1 (°K) and pressure P_1 (mm Hg)
V_2 = gas volume (m^3) at temperature T_2 (°K) and pressure P_2 (mm Hg)