Development of a Methane Conversion Factor to Estimate Emissions from Animal Waste Lagoons

Joseph Mangino
U.S. Environmental Protection Agency, Methane and Sequestration Branch
1200 Pennsylvania Ave, NW (Mail Code 6202J), Washington, DC 20004
mangino.joseph@epa.gov

Deborah Bartram and Amy Brazy
Eastern Research Group, Inc., Engineering and Analysis Division
14555 Avion Parkway, Suite 200, Chantilly, VA 20151
deborah.bartram@erg.com
amy.brazy@erg.com

ABSTRACT

The management of livestock and poultry manure produces methane when organic material in the manure decomposes in an anaerobic environment. Many confined animal feeding operations, particularly swine and dairy operations, manage their manure and associated manure wastewater in anaerobic lagoon systems. These operations are a significant source of methane from agricultural operations. To develop a national estimate of methane emissions from these operations, the Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*[1] includes two possible estimation methodologies. The more detailed, "Tier 2" approach requires specific animal waste characteristics, including a methane conversion factor (MCF) that defines the portion of methane-producing potential achieved for each type of manure management system. The guidance provides a default MCF range from 0% to 100% for animal waste lagoons, which reflects the wide range of performance these systems may achieve. There exist relatively few data points on which to determine country-specific MCFs for these systems. Therefore, a procedure was developed for the United States to calculate MCFs based on the limited set of measurement data available, the results of laboratory-scale tests on methane production from animal waste, and knowledge on the performance of lagoon systems. This procedure accounts for temperature variation throughout the year, retention of volatile solids in a system, and management and design practices that may reduce the volatile solids available for conversion to methane.

INTRODUCTION

The management of manure waste can produce methane from the decomposition of manure. The manner in which animal manure is handled greatly impacts the amount of methane that is produced. Conditions are favorable for methane production when livestock or poultry manure are stored or treated in liquid systems, particularly anaerobic lagoons. Several operating conditions affect the amount of methane produced: 1) the ambient temperature; 2) the lagoon temperature; and 3) residency time of manure solids in the system. All of these factors affect the amount of methane produced because they influence the growth of the bacteria responsible for methane formation. Methane production generally increases with rising temperature and residency time.

In the U.S., the general trend in manure management, particularly for large dairy and swine producers, is one of increasing use of liquid systems. In the U.S. over 80 percent of methane emissions from manure management come from dairy and swine manure management[2]. IPCC 2000 strongly encourages countries to use the more detailed "Tier 2" approach to estimate methane emissions for livestock species/categories that represent a significant share of emissions. The Tier 2 approach requires the development of country-specific emission factors based on the volatile solids added to the system, the maximum methane-producing capacity for the specific type of animal manure (represented by B_o), and an MCF for the manure management system that reflects the percentage of volatile solids actually converted to methane compared to the theoretical maximum, B_o:

Equation (1) $$EF = VS \times 365 \text{ days/yr} \times B_o \times 0.662 \times \sum_{jk} MCF_{jk} \times MS_{jk}$$

where

EF	= annual emission factor for defined animal population (kg CH_4/yr)
VS	= daily volatile solids excreted for an animal within defined population (kg/day)
B_o	= maximum methane-producing capacity for manure produced by an animal within defined population (m^3 CH_4/kg VS)
0.662	= conversion factor of m^3 CH_4 to kilograms CH_4 (kg CH_4 /m^3 CH_4)
MCF_{jk}	= methane conversion factor for each manure management system *j* by climate region *k*
MS_{jk}	= fraction of defined animal population's manure handled using manure system *j* in climate region *k*

IPCC 2000 specifically notes that the MCF should account for the following factors:

- Influence of climate on methane production;
- Timing of storage/application;
- Length of storage;
- Manure characteristics;
- Determination of the amount of manure left in the storage facility;
- Time and temperature distribution between indoor and outdoor storage;
- Daily temperature fluctuation; and
- Seasonal temperature variation.

In the U.S., the majority of dairy and swine manure is managed in anaerobic lagoons. The default MCF values provided in IPCC 2000 for an anaerobic lagoon range from 0% to 100% and reflect the wide variation of performance that such systems may achieve. There exist relatively few data points on which to determine a country-specific MCF for these systems. In fact, in the United States, many livestock waste treatment systems classified as anaerobic lagoons are actually holding ponds that are substantially organically overloaded and therefore not producing methane at the same rate as a properly designed lagoon. In addition, these systems may not be well operated, contributing to higher loading rates when sludge is allowed to enter the treatment portion of the lagoon or the lagoon volume is pumped too low to allow treatment to occur.

Rather than setting the MCF for all anaerobic lagoon systems in the United States based on data available from optimized lagoon systems, an MCF methodology was developed that more closely matches observed system performance and accounts for the effects of temperature and retention time on system performance. To best account for climate differences throughout the United States, anaerobic lagoon MCFs were developed for each state. Methane production was estimated for each month of the year to account for the retention of volatile solids in the system, and a management and design practices (MDP) factor was developed using measurement data to calibrate the model to actual system performance.

OVERVIEW OF MCF DEVELOPMENT METHODOLOGY FOR ANAEROBIC LAGOONS

The anaerobic lagoon MCF calculation considers the effect of climate, retention of volatile solids, and the management and design practices through the use of a monthly calculation for each State.

The methodology calculates the amount of volatile solids generated, retained, and available for anaerobic digestion each month and then calculates a monthly estimate of methane production. The monthly methane estimates are then summed for the year and divided by the total yearly methane potential assuming no operational loss of solids (i.e., no accounting for management and design practices.) This calculation assumes that solids in the lagoon are completely cleaned out annually at the end of September. Therefore, the accumulation of volatile solids for a system begins in October of the preceding year and continues through September. The following calculation steps are used for each animal population:

1) Determine the average temperature for a given month and state using temperature data obtained from the National Climate Data Center[3] and county-level animal population data from the U.S. Department of Agriculture[4]. Only counties that have animal populations are used in determining the state-wide average monthly temperature.

2) Calculate a climate factor, f, using the van’t Hoff-Arrhenius equation for forecasting the performance of biological reactions. (f factor is described in more detail later in this paper.)

3) Calculate the volatile solids produced by that animal population in each state using the methodology outlined in the draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990 – 2000: Annex L[2].

4) Calculate the volatile solids monthly loading into the lagoon system by multiplying the volatile solids produced by the MDP factor.

5) Calculate the amount of volatile solids available for consumption by anaerobic bacteria in a given month, based on the monthly volatile solids loading rate plus the amount of volatile solids retained in the lagoon from previous months minus the amount consumed. Because it is assumed that lagoons are cleaned out yearly in September, there is no carry over of volatile solids in the month of October. For this month, the amount of volatile solids available equals the monthly loading rate.

6) Calculate the amount of volatile solids consumed in a month in the lagoon using the van’t Hoff-Arrhenius f factor to simulate biological activity as a function of temperature. The volatile solids consumed equals the volatile solids available multiplied by f.

7) Calculate the amount of methane produced monthly from the consumption of volatile solids using the maximum methane-producing capacity of the volatile solids, or B_o.

8) Calculate the annual lagoon MCF for each state, year, and animal type as follows:

Equation (2) $$MCF = \frac{\text{Annual Methane Production}}{B_o \times \text{Annual Volatile Solids Production}}$$

Figure 1 presents an example of this methodology used to calculate the annual MCF for breeding swine lagoon systems in Iowa for the year 2000. The following sections discuss in detail the use of the van’t Hoff-Arrhenius factor, the effect of retention time on methane production, and the development of the management and design practices factor.

Figure 1. Annual MCF calculation for anaerobic lagoons treating swine manure in Iowa (2000).

MDP Factor =	0.8	
Bo =	0.48	m3 CH4/kg VS added
VS Production =	216,235,125	kg/year
	592,425	kg/day

Month	Tavg (K)	Tavg (C)	f	VS Produced (kg)	VS Loading (kg)	VS Available (kg)	VS Consumed (kg)	CH4 (m3)	Annual MCF
October	283.3	10.1	0.17	18,365,190	14,692,152	14,692,152	2,512,574	1,206,036	**0.70**
November	279.8	6.6	0.12	17,772,765	14,218,212	26,397,790	3,204,631	1,538,223	
December	278.2	5.0	0.10	18,365,190	14,692,152	37,885,312	3,933,727	1,888,189	
January	278.2	5.0	0.10	18,365,190	14,692,152	48,643,737	5,050,802	2,424,385	
February	278.2	5.0	0.10	16,587,914	13,270,331	56,863,266	5,904,256	2,834,043	
March	279.1	5.9	0.11	18,365,190	14,692,152	65,651,162	7,461,372	3,581,459	
April	282.5	9.4	0.16	17,772,765	14,218,212	72,408,002	11,511,997	5,525,758	
May	290.0	16.8	0.32	18,365,190	14,692,152	75,588,157	24,075,574	11,556,276	
June	292.8	19.6	0.41	17,772,765	14,218,212	65,730,795	26,935,014	12,928,807	
July	295.4	22.2	0.51	18,365,190	14,692,152	53,487,933	27,535,896	13,217,230	
August	295.5	22.4	0.52	18,365,190	14,692,152	40,644,189	21,191,701	10,172,016	
September	290.9	17.7	0.34	17,772,765	14,218,212	33,670,701	11,613,640	5,574,547	
October	285.4	12.2	0.21	18,365,190	14,692,152	14,692,152	3,057,226	1,467,468	
November	278.2	5.0	0.10	17,772,765	14,218,212	25,853,138	2,684,396	1,288,510	
December	278.2	5.0	0.10	18,365,190	14,692,152	37,860,894	3,931,192	1,886,972	
SUMS				**216,235,305**				**72,457,471**	

$$\textbf{Annual MCF} = \frac{72{,}457{,}471.00}{0.48 * 216{,}235{,}305} = 0.70$$

EFFECT OF TEMPERATURE ON METHANE PRODUCTION

Safley and Westerman[5] discussed the close relationship between anaerobic lagoon activity and temperature while exploring the production of biogas from anaerobic lagoons. Barth and Hegg[6] also evaluated this relationship and reported that biological activity in anaerobic lagoons is lowest during winter months when the temperature is lowest.

The van't Hoff-Arrhenius equation is typically used to forecast the performance of biological reactions at one temperature based on performance at a known temperature[7]. Safley and Westerman[8] suggested that this relationship could be applied to anaerobic lagoons with lower concentrations of influent volatile solids and longer retention times, such as those managing animal wastes. One practical way of estimating MCFs for liquid manure handling systems is based on the mean ambient temperature and the van't Hoff-Arrhenius equation with a base temperature of 30°C, as shown in the following equation:

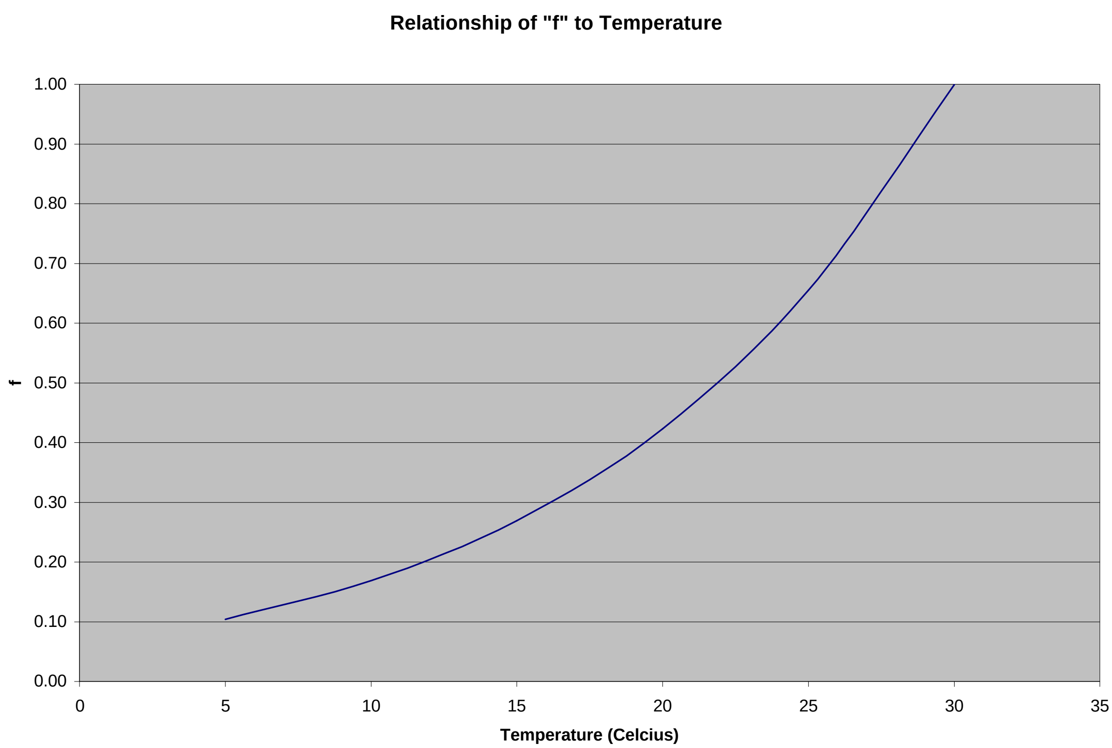
Equation (3) $$f = \exp\left[\frac{E(T_2 - T_1)}{RT_1T_2}\right]$$

where

T_1 = 303.16K
T_2 = ambient temperature (K)
E = activation energy constant (15,175 cal/mol)
R = ideal gas constant (1.987 cal/K mol)

The factor "f" represents the proportion of volatile solids that are biologically available for conversion to methane based on the temperature of the system. This factor accounts for increasing biological activity as temperature increases, as shown in Figure 2.

Figure 2. Relationship of "f" to temperature.



This factor can be used to estimate monthly methane production for an anaerobic lagoon managing animal waste. While Figure 2 shows an "f" factor of 1.0 theoretically achievable at 30°C, for practical modeling of field conditions, a maximum "f" factor of 0.95 is set for the MCF values used in the inventory. More research data are needed to confirm activity at the high end of the scale, but it is unlikely in field conditions that 100% conversion is achieved.

The ambient air temperature is used to simulate the change in lagoon temperature throughout the year. In reality, the lagoon will stay warmer than the ambient air temperature as temperature drops in the fall and will stay colder than the ambient air temperature as temperature rises in the spring. In addition, lagoons have sufficient biological activity to keep the temperature above freezing. Therefore, a minimum lagoon temperature of 5°C is assumed in the calculation of monthly methane production.

For the U.S. Inventory, temperature data from the National Climate Data Center representing individual weather stations across the country were used to develop average monthly temperatures for each state. These average temperatures were estimated based on the counties in which the specific animal population was located (using 1997 Census of Agriculture data).

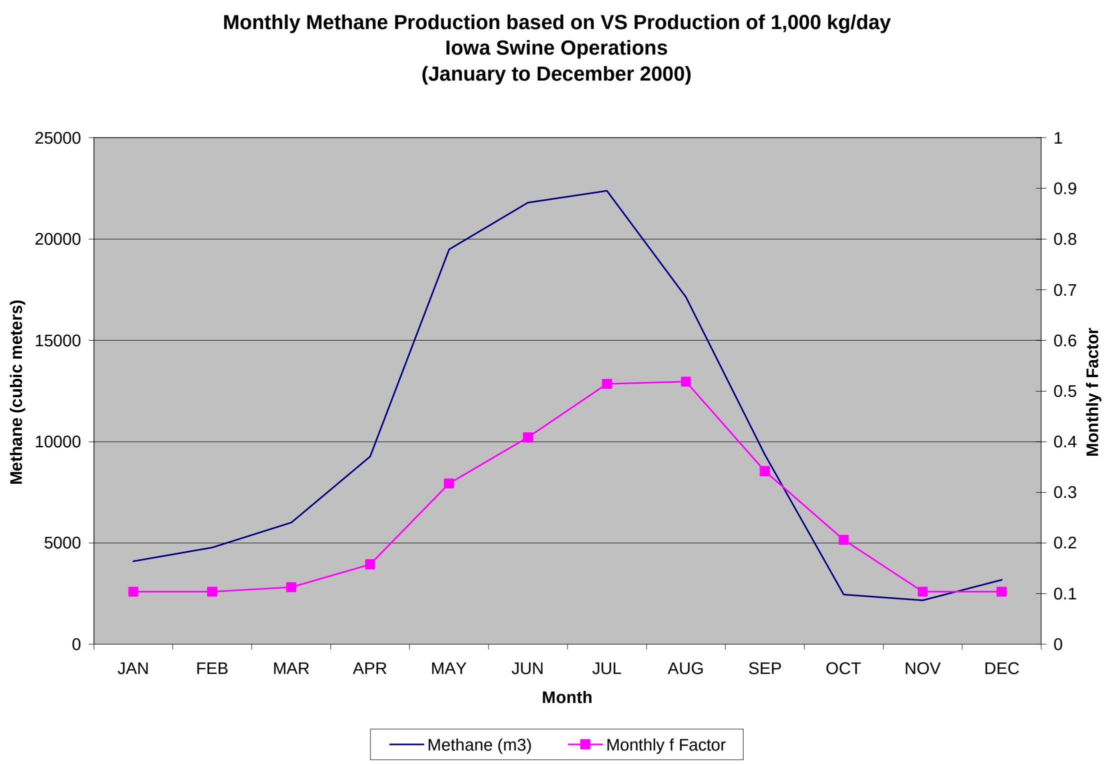
EFFECT OF RETENTION TIME ON METHANE PRODUCTION

The MCF methodology considers the seasonal variation of volatile solids destruction, and therefore, volatile solids retention in the system. The methodology assumes that a constant daily mass of volatile solids enters the system, and the destruction of volatile solids is dependent on the temperature of the anaerobic lagoon. During cooler months, not all of the volatile solids that enter the lagoon may be consumed.

The MCF methodology accounts for this circumstance by calculating the unconsumed portion of volatile solids and adding that portion to the amount of volatile solids available for consumption in the following month. The amount of volatile solids available for consumption in a given month is equal to the normal monthly volatile solids loading plus any volatile solids remaining from the preceding month. The methodology assumes that all solids (and therefore all volatile solids) are cleaned out of the system annually, at the end of September. Therefore, volatile solids are either consumed or accumulate from October through September.

The monthly calculation procedure captures the fluctuation in methane production throughout the year due to both climate changes and longer retention time, as shown in Figure 3.

Figure 3. Comparison of monthly methane production and “f”.



EFFECT OF OPERATIONAL CONDITIONS ON METHANE PRODUCTION

The MCF methodology used in the inventory includes a factor to account for management and design practices that result in the loss of volatile solids from the management system. This factor, equal to 0.8, is estimated based on data from anaerobic lagoons in North Carolina and accounts for other mechanisms by which volatile solids are removed from the management system prior to conversion to methane (e.g., solids removed from the lagoon for application to crop land).

Methodology

Data collected at two anaerobic lagoons were used to develop the MDP factor. One of the anaerobic lagoons manages swine manure, while the other manages dairy manure. Both lagoons are located in North Carolina. The MDP factor was calculated for each anaerobic lagoon system, based on the predicted optimal methane generation (calculated using the algorithm described in this paper) versus the measured methane generation at that facility. The MDP for the swine waste lagoon was calculated as 0.79, and the MDP for the dairy waste lagoon was calculated as 0.79. Based on these data, the default MDP for the MCF calculations was estimated to be 0.8. The following discussion provides specific details of this calculation.

Swine Farm, North Carolina

Dr. John Martin reported on the performance of a covered anaerobic lagoon system that was monitored for 12 months in central North Carolina[9]. The lagoon system was used to collect waste from a swine farrow-to-wean operation with an average of 3,600 gestating and 640 lactating sows. The reported average sow weight was 135 kilograms. Data were collected daily characterizing the influent, effluent, and biogas recovery. The average influent loading of volatile solids was 1,194 kg/day. Table 1 presents the monthly biogas production. From these data, the monthly methane generation was estimated by assuming the biogas contains 70% methane. Table 1 also presents the monthly and annual estimate of methane generation, based on these data. The volatile solids reporting rate from this swine operation was used to estimate the optimum methane generation for this farm. Table 2 presents the assumptions made to complete this calculation.

Table 1. Monthly biogas and methane production at swine farm in North Carolina.

Month	**Biogas Production (m^3/month)**	**Methane Production (m^3/month)**
January	6,863	4,804
February	15,450	10,815
March	17,047	11,933
April	18,424	12,897
May	24,468	17,128
June	27,361	19,153
July	25,900	18,130
August	23,069	16,148
September	16,372	11,460
October	16,303	11,412
November	14,752	10,326
December	14,646	10,252
Annual	220,655	154,458

Table 2. Data inputs to estimate the optimal methane generation at swine farm.

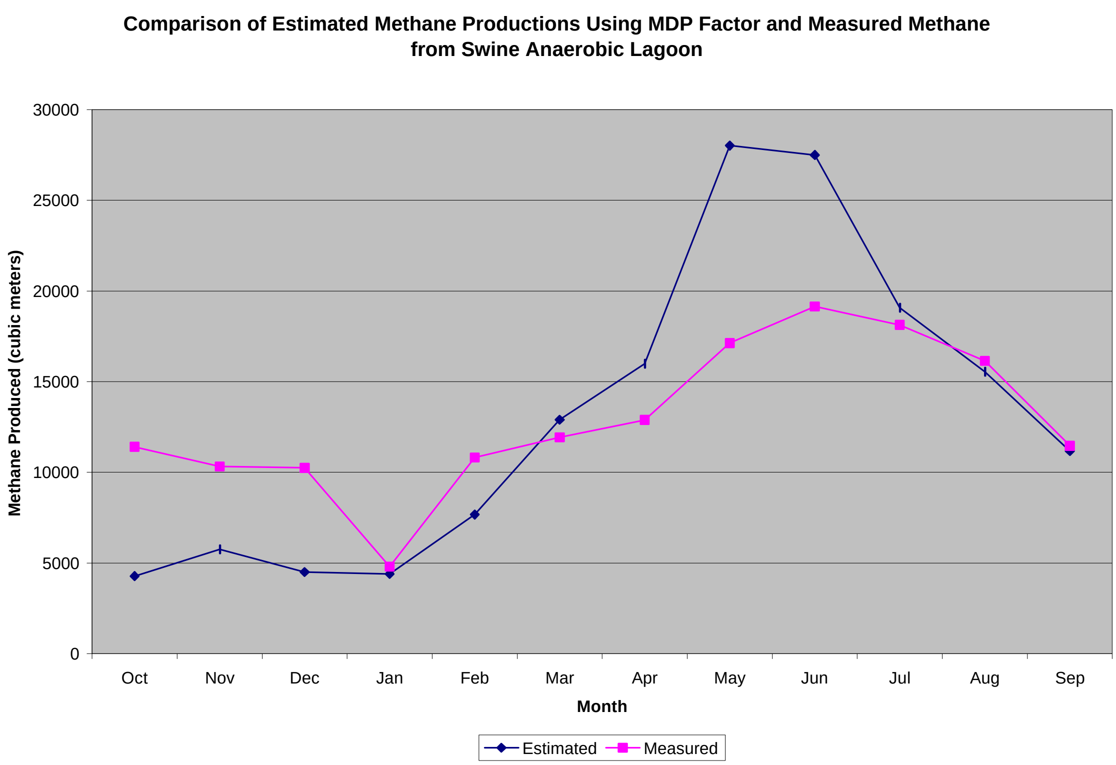
Parameter	**Value**		**Source**
Number of Head	4240 head		Martin 2000
Average Weight	135 kg		Martin 2000
Volatile Solids Loading Rate	1194 kg VS per day		Martin 2000
Maximum Methane Producing Capacity (B_o)	0.48 m^3 CH_4 per kg VS added		Hashimoto, 1984
Monthly ambient temperature in North Carolina for year 2000	January	282K	NOAA, 2001
	February	282K	
	March	283K	
	April	290K	
	May	293K	
	June	297K	
	July	300K	
	August	300K	
	September	295K	
	October	289K	
	November	287K	
	December	281K	

The optimal annual methane production of this system was predicted using these data inputs with the van=t Hoff-Arrhenius factor. Table 3 presents the results of these calculations. The MDP factor for this system, 0.79, is equal to the ratio of the measured methane generation (154,459 m^3) to the optimal predicted methane generation (196,062 m^3) for this lagoon. Figure 4 presents a comparison of the measured methane (calculated as 70% of the biogas) to the estimated methane, applying the MDP factor to the MCF methodology. While the difference between the estimated and measured methane production varies on a monthly basis, the overall annual trends are consistent.

Table 3. Predicted optimal methane generation at swine farm.

Month	f	Average Ambient Temperature (Kelvin)	VS Produced (kg)	VS Optimally Available (kg)	VS Consumed (kg)	Methane Produced (m^3)
Oct	0.30	289	37,014	37,014	11,150	5,352
Nov	0.24	287	35,820	61,684	14,975	7,188
Dec	0.14	281	37,014	83,722	11,740	5,635
Jan	0.11	278	37,014	108,997	11,482	5,511
Feb	0.15	282	34,626	132,141	19,993	9,597
Mar	0.23	286	37,014	149,162	33,604	16,130
Apr	0.28	288	35,820	151,378	41,640	19,987
May	0.50	295	37,014	146,752	72,962	35,022
Jun	0.65	298	35,820	109,610	71,624	34,380
Jul	0.66	298	37,014	74,999	49,693	23,853
Aug	0.65	298	37,014	62,320	40,491	19,436
Sep	0.50	295	35,820	57,649	29,107	13,971
TOTAL						196,062

Figure 4. Comparison of measured and predicted methane production.



Dairy Farm, North Carolina

Safley and Westerman[10] reported on the performance of a covered in-ground anaerobic lagoon system in central North Carolina. The lagoon system was used to collect waste from a 150-milking-cow dairy. They estimated that, from December through March, an average of 68 cubic meters of methane was generated per day.

The number of head from this dairy operation was used to estimate the optimum methane generation for this farm. Table 4 presents the assumptions made to complete this calculation. The optimal annual methane production of this system was predicted using these data inputs with the van't Hoff-Arrhenius factor. Table 5 presents the results of these calculations. Safley and Westerman report that the lagoon produced an average of 68 cubic meters of methane per day during the months of December through March. For the same period, the predicted optimal methane generation is 86 cubic meters of methane per day, which equates to an MDP of 0.79 for this lagoon.

Table 4. Data inputs to estimate the optimal methane generation at North Carolina dairy.

Parameter	**Value**		**Source**
Number of head	150 head		Safley and Westerman, 1992
Average weight	604 kg		ERG, 2000
Volatile solids production rate	8.45 kg VS per 1,000-kg cow		USDA, 1998
Maximum methane producing capacity (B_o)	0.24 m^3 CH_4 per kg VS added		Morris, 1976
Monthly ambient temperature in North Carolina for year 2000	January	282K	NOAA, 2001
	February	282K	
	March	283K	
	April	290K	
	May	293K	
	June	297K	
	July	300K	
	August	300K	
	September	295K	
	October	289K	
	November	287K	
	December	281K	

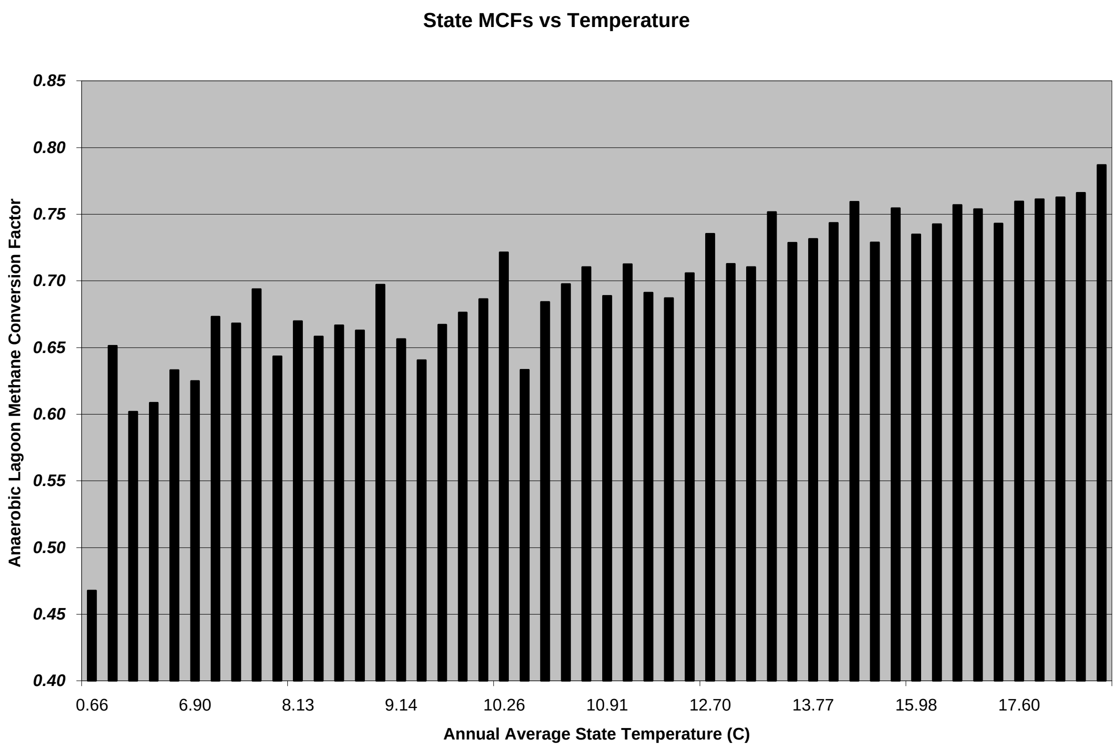
Table 5. Predicted optimal methane generation at North Carolina dairy.

Month	f	Average Ambient Temperature (Kelvin)	VS Produced (kg)	VS Optimally Available (kg)	VS Consumed (kg)	Methane Produced (m^3)
Oct	0.24	287	23,733	23,733	5,698	1,368
Nov	0.20	285	22,967	41,002	8,171	1,961
Dec	0.11	279	23,733	56,563	6,408	1,538
Jan	0.09	276	23,733	73,888	6,344	1,523
Feb	0.12	280	21,436	88,980	11,011	2,643
Mar	0.19	285	23,733	101,702	19,646	4,715
Apr	0.23	286	22,967	105,022	23,917	5,740
May	0.42	293	23,733	104,838	44,340	10,642
Jun	0.58	297	22,967	83,465	47,998	11,519
Jul	0.59	297	23,733	59,200	34,724	8,334
Aug	0.57	297	23,733	48,209	27,465	6,592
Sep	0.41	293	22,967	43,711	18,012	4,323
TOTAL						60,896

CONCLUSIONS

The specific MCF for an animal waste anaerobic lagoon is a function of temperature, retention time, and operational practices. The approach developed to calculate MCFs for anaerobic lagoons accounts for the effect of temperature by using the van't Hoff-Arrhenius equation to predict biological activity at different temperatures. The effect of prolonged retention is addressed by using a monthly calculation procedure that models solids carryover from month-to-month. Actual system performance data are used to develop a management and design practices factor to account for operational variability. Figure 5 presents the state-specific methane conversion factors calculated for the treatment of swine anaerobic lagoon systems in the United States in 2000 relative to average annual temperatures. The MCF values provided in Figure 5 are plotted against annual average temperatures for each state, and are shown for illustrative purposes only (actual MCF calculations are performed using monthly temperature data). Figure 5 shows that the general trend is for the MCF to increase with higher temperatures. The monthly VS retention cycle and seasonal temperature variations from state to state results in the non-linear relationship shown in Figure 5.

Figure 5. Comparison of State-specific MCFs to temperature.



However, there is uncertainty related to the new methodology. The MCF methodology includes a factor to account for management and design practices that result in the loss of volatile solids from the management system. The MDP factor is estimated based on data from covered anaerobic lagoons in temperate climates, and from only two systems. However, this methodology is intended to account for systems across a range of management practices. Future work in gathering measurement data from animal waste lagoon systems across the country will contribute to the verification and refinement of this methodology, including reevaluating the MDP factor for various types of anaerobic lagoon systems.

REFERENCES

[1] IPCC. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Intergovernmental Panel on Climate Change, NGGIP, 2000. Chapter 4, Agriculture.

[2] U.S. EPA. *Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*, U.S. Environmental Protection Agency, Office of Atmospheric Programs, 2002.

[3] NCDC. National Oceanic and Atmospheric Administration (NOAA), National Climate Data Center. Downloaded “0106.tmp” on July 27, 2001 from <ftp://ftp.ncdc.noaa.gov/pub/data/cirs/> (for all states except Alaska and Hawaii); downloaded “all-1994.tar”, “all-1995.tar”, “all-1996.tar”, “all-1997.tar”, “all-1998.tar”, and “all-1999.tar” in April 2000 and “all-2000.tar” in July 2001 from <ftp://ftp.ncdc.noaa.gov/pub/data/globalsod/> (for Alaska and Hawaii). Documentation for Dataset: “Time Bias Corrected Divisional Temperature-Precipitation-Drought Index”; TD-9640; March, 1994. <http://www.ncdc.noaa.gov/onlineprod/drought/ftppage.html>.

[4] USDA. *1992 and 1997 Census of Agriculture* (CD-ROM), U.S. Department of Agriculture, National Agriculture Statistics Service, Washington, DC, 1999.

[5] Safley, L.M.; Westerman, P.W. “Biogas Production from Anaerobic Lagoons”, *Biological Wastes*. 1988, 23, 181-193.

[6] Barth, C.L.; Hegg, R.O. "Poultry Lagoon Odor Correlations". ASAE, St. Joseph, MI, 1984; paper 84-4088.
[7] Metcalf and Eddy. *Wastewater Engineering: Treatment, Disposal, and Reuse*; McGraw-Hill, Inc.; New York, NY, 1972.
[8] Safley, L.M.; Westerman, P.W. "Psychrophilic Anaerobic Digestion of Animal Manure: Proposed Design Methodology", *Biological Wastes*. 1990, 34, 133-148.
[9] Martin, J.H., Jr. "A Comparison of Three Swine Waste Stabilization Systems"; Submitted to Kurt Roos, AgSTAR Program, U.S. Environmental Protection Agency, Washington, DC. 2002.
[10] Safley, L.M., Jr.; Westerman, P.W. "Performance of a Low Temperature Lagoon Digester", *Biological Wastes*. 1992, 9060-8524/92/S05.00.

KEYWORD

Manure Management
Anaerobic Lagoons
Animal Waste
Emission Inventories