COMPARISON OF METHANE EMISSION MODELS

AND METHANE EMISSION MEASUREMENTS

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ABSTRACT

Quantification of methane emission from landfills is important to evaluate reduction measures. Both the United Nations and the European Union have adopted protocols to enforce among others quantification of methane emission from individual landfills. The most widely applied methods for quantification are based on models. The suitability and accuracy of six models is explored. The modelling results are compared with whole site methane emission measurements. The comparison with waste data of one single landfill shows that current models do not supply a reliable tool to estimate methane emissions from individual landfills. Further development of measurement techniques may provide a more reliable quantification tool.

INTRODUCTION

Methane emission from landfills is a major contributor to the greenhouse effect. World wide regulators implement waste management strategies, policies and regulations aiming at reduction of methane emission from landfills. Because landfills are a diffuse source it is not easy to measure the methane emission. In order to determine the effectiveness of the resulting measures on landfills quantification of the methane emission either per country or per landfill is essential.

In May 2003, the United Nations (UN) have adopted the Protocol on Pollutants Release and Transfer Registers (also known as PRTR's- or Kiev-protocol). Among others this protocol requires landfills receiving more than 10 tons per day or with a total capacity of 25,000 tons to individually determine their methane emission and report it to the general public and their national government from 2007 onwards. The European Union (EU) is currently considering adaptation of the European Pollutants Emission Register (EPER) into the E-PRTR's to comply with the UN PRTR's-protocol. Apart from E-PRTR's and PRTR's national governments are also required to report to the IPCC with respect to the Kyoto protocol. It is obvious that one method that is suitable for reporting in all cases has advantages and will prevent confusion. Unfortunately this is not reality. Several governments are considering or have already given guidance to their landfill operators to determine their methane emission. The recommended approaches all involve modelling of methane production. The overall emission is calculated by introducing aspects as methane extraction and oxidation. This paper explores the suitability and accuracy of the methods currently available for quantification of methane emission on individual landfills.

CASE STUDY OBJECT AND MODELS

In the EU countries guidance should preferably take into account a situation that EU waste policy is aiming for i.e. diversion of organic waste from landfills and consequently landfills that contain small amounts of organic matter. In the last two decades, waste policy in the Netherlands resulted in a reduced amount of landfilled waste and a change in the composition of the landfilled waste. The landfill Nauerna in the Netherlands is a perfect case study object for the comparison of methane emission models and emission measurement techniques. The Nauerna landfill has a total surface of 72 hectares. Landfilling of waste started in 1985 and the site is still in operation. Up to 2002 a total

amount of 9.5 Mtonnes of waste is landfilled at Nauerna. The waste is characterised by a low content in organic matter. Table 1 shows the composition of the waste landfilled at Nauerna. At this landfill whole site measurements with the best available techniques were carried out annually starting in 1997. In 2001 a very extensive measurement program comparing different measurement techniques was carried out.

A lot of different models to predict methane emissions originating from landfills are used nowadays. The most common type of models use single or multi phase first order kinetics that describe the decay of biodegradable waste and the production of landfill gas (LFG). LFG production in combination with the oxidation capacity of the top cover and LFG extraction data enables calculation of the methane emission. Most landfill gas (LFG) models are based on municipal solid waste (MSW). They are therefore not automatically suitable for situations with reduced amounts of organic waste. In most cases emission model validation has been carried out using LFG extraction data and assumptions for extraction efficiency and methane oxidation. Thus major uncertainties are introduced. The authors have the opinion that a proper validation of LFG emission models requires comparison with whole site emission measurement data. Only two studies (Oonk & Boom, 1995; Huitric & Soni, 1997) have applied validation based on whole site methane emission measurements.

In 1994 a study (Oonk et al., 1994) was performed at several landfills in the Netherlands. Both first order and multi phase models showed low mean relative errors in contrast to zero order models. This study resulted in the development by the TNO research institute of the first order model used by the Dutch government to calculate and report national methane emissions as if the waste were deposited at one landfill. The UK Environment Agency prefers GasSim as the model for individual landfill operators to calculate and report their methane emission. Recently new models were developed in order to calculate landfill gas emission in Germany and France. In this present case study six different models are used to calculate the methane emission of Nauerna landfill:

1. First order model (TNO) (Oonk and Boom, 1995);

2. Multi phase model (Afvalzorg);

3. GasSim (Environment Agency UK and Golder Associates) (Gregory et al., 2003);

4. EPER model France (ADEME) (Budka, 2003);

5. EPER model Germany (Umwelt Bundesamt and State Institute for Environmental protection Baden – Würtemberg) (Wielenga, 2003) and

6. LandGEM (US-EPA) (US-EPA, 2001).

MODEL SPECIFICATIONS

First order model (TNO)

The effect of ageing of waste is accounted for in a first order model (Oonk et.al., 1994) LFG formation in a certain amount of waste is assumed to decay exponentially in time. The first order model can mathematically be described by:

$$\alpha_t = \varsigma 1.87 A C_0 k_1 e^{-k_1 t} \hspace{3cm} \textbf{(Eq. 1)}$$

Where:

α_t	= landfill gas formation at a certain time	$[m^3.yr^{-1}]$
ς	= dissimilation factor	[-]
A	= amount of waste in place	[tonne]
C_o	= amount of organic carbon in waste	$[kg.tonne\ waste^{-1}]$
k_1	= degradation rate constant	$[y^{-1}]$
t	= time elapsed since depositing	[y]

In order to derive a methane emission based upon the production prognosis a very straight forward calculation is used:

$$CH_4\ emission\ [m^3.hr^{-1}] = CH_4\ production - CH_4 recovery - CH_4\ oxidation \hspace{1cm} \textbf{(Eq. 2)}$$

This calculation can be and is used in many approaches, e.g. first order (TNO), multi phase (Afvalzorg and GasSim) or LandGEM model. It is apparent that not only the accuracy of the production model is an important factor in this type of approach. The recovery can be measured accurately. But the oxidation of methane is usually the great unknown and in general a default value is used. With emission measurements the appropriateness of the default value can be checked.

Multi phase model (Afvalzorg)

In the multiphase model a number of fractions are distinguished. For each fraction LFG formation is described separately. The advantage of the multi phase model is that the typical waste composition

can be taken into account, since all types of waste contain typical fractions of slow, moderate and fast degradables (see Table 1). The multiphase model is a first order model and can mathematically be described by:

$$\alpha_t = \varsigma \sum_{i=1}^{3} 1.87 A C_{0,i} k_{1,i} e^{-k_{1,i}t}$$ **(Eq. 3)**

Where:

α_t = landfill gas formation at a certain time $[m^3.yr^{-1}]$

ς = dissimilation factor   [-]

i = waste fraction with degradation rate $k_{1,i}$ $[kg_i.kg_{waste}^{-1}]$

A = amount of waste in place   [tonne]

C_o = amount of organic carbon in waste $[kg.tonne\ waste^{-1}]$

$k_{1,i}$ = degradation rate constant of fraction i $[y^{-1}]$

t = time elapsed since depositing   [y]

GasSim

The GasSim model (Version 1.00, June 2002) (Gregory et al., 2003) comes equipped with two mathematical approaches to calculate a methane emission prognosis (GasSim manual Version 1.00). The first approach uses the GasSim multi phase equation, which is similar to the multiphase model as described above. The second approach to estimate LFG formation is the LandGEM model. LandGEM determines the mass of methane generated using the methane generation capacity and the mass of carbon deposited. The quantity of LFG generated is determined using the methane generation capacity and the proportion of methane to carbon dioxide. LandGEM can mathematically be described by:

$$L_1 = \frac{L\left[\dfrac{1}{([CH_4]/100)}\right]}{V_m} M$$ **(Eq. 4)**

Where:

L_1 = LFG generation capacity   [g/tonne]

V_m = molar volume (at STP) $[2.241 \times 10^{-2}\ m^3 mol^{-1})$

M	= relative molar mass of carbon	[m^3Mg^{-1}]
$[CH_4]$	= methane concentration within LFG	[%]

By obtaining L_1 the available mass of degradable carbon can be determined by:

$$C = C_I * L_1 \qquad \textbf{(Eq. 5)}$$

Where:

C	= mass of degradable carbon	[Mg]
C_I	= mass of waste deposited	[Mg]

To determine the formation of methane L_1 and C are applied in a first order model as described earlier and the methane emission is determined by eq. 2.

EPER model France

The French EPER model (Budka, 2003) combines two approaches to estimate methane emission.
The model is divided into two calculations:

1. Methane emission prognosis for landfill cells connected to LFG recovery system by use of data of recovered LFG by the landfill operator

2. Methane emissions prognosis of landfill cells not connected to LFG recovery system by a conventional multiphase model (ADEME version 15/12/2002)

The methane emission for landfill cells connected to the LFG recovery system can be calculated with the following formulas:

$$A = F * H * \left[CH_4\right] \qquad \textbf{(Eq. 6)}$$

Where:

A	= recovered amount of LFG	[m^3y^{-1}]
F	= extraction rate of LFG	[m^3h^{-1}]
H	= compressor yearly hours in operation	[h]
$[CH_4]$	= methane concentration in LFG	[%]

A is then corrected to Nm³y⁻¹ taking into account the ambient pressure and temperature (STP) at the moment of the gas quality sample. The surface area of cells connected to the LFG recovery system and the type of top cover present on that particular cell determine the recovery efficiency. The model can calculate the production of methane. For example a zone in operation which has no top cover and is connected to a LFG recovery system has an LFG collection efficiency of 35%. 65% of LFG will eventually emit to the atmosphere. The production of methane for cells connected to LFG recovery system is calculated by:

$$P = \frac{A}{\eta}$$
(Eq. 7)

Where:

P	= production of methane	[m³y⁻¹]
η	= recovery efficiency	[%]

The formation of LFG of landfill cells which are not connected to a LFG recovery system are calculated by a multi phase equation following the ADEME model, which can be described as:

$$FE_{CH_4} = \sum_{x} FE_0 * \left(\sum_{1,2,3} A_i * p_i * k_i * e^{-k_i t} \right)$$
(Eq. 8)

Where:

FE_{CH4}	= annual methane production	[Nm³y⁻¹]
FE_0	= LFG generation potential	[m³$_{CH4}$.tonne waste⁻¹]
p_i	= waste fraction with degradation rate k_i	[kg$_i$.kg$_{waste}$⁻¹]
k_i	= degradation rate of fraction i	[y⁻¹]
t	= age of waste	[y]
A_i	= normalisation factor	[-]

The model describes three categories of waste and every category has a specific LFG formation capacity per tonne waste. The three categories are given in Table 2.

The EPER model assumes an oxidation capacity of the top cover of 10%. The total methane emission is calculated by

$$CH4_{emission} = P(1-\eta) * 0,9 + FE_{CH4} * 0,9 \qquad \textbf{(Eq. 9)}$$

EPER model Germany

The EPER model (Wielenga, 2003) used in Germany is a zero order model and can mathematically be described by:

$$Me = M * BDC * BDC_f * F * D * C \qquad \textbf{(Eq. 10)}$$

Where:

Me	= amount of diffuse methane emission	[Mg.y^{-1}]
M	= annual amount of land filled waste	[Mg]
BDC	= proportion of biodegradable carbon	[MgC.Mg waste^{-1}]
BDC_f	= proportion of biodegradable C converted into LFG	[%]
F	= calculation factor of carbon converted into CH4	[-]
D	= collection efficiency	active degassing 0.4; no recovery 0.9; active LFG recovery and cover 0.1
C	= [CH$_4$]	[%]

LandGem US EPA

The US EPA model (US-EPA, 2001) is based on the LandGEM model and uses eq. 2, 4 and 5.

RESULTS CALCULATED METHANE EMISSIONS

For comparable results the usage of equal values for every model is important. For instance, slight variations in applied k values can have great influence on methane emissions calculated. Therefore equal values based on the experience of the landfill operator were used for every model in which k values could be altered. In Table 3 applied values for each model are shown. After data input each model was run and prognoses were calculated. The results are given in Table 4. Results shown in Table 4 reveal a huge variation in calculated methane emission. The difference between the largest

and smallest emission is 4,018 $m^3CH_4.h^{-1}$. The LandGEM models in both the GasSim as the US EPA package calculate methane emissions which may be considered extremely high. The difference in methane emissions between the two LandGEM models can be explained by the fact that LandGEM US EPA assumes Municipal Solid Waste (MSW) as the total amount of waste land filled. MSW is known to contain far more organic carbon and thus produce far more methane in comparison to waste mixtures landfilled in the Netherlands. LandGEM in the GasSim package uses the waste composition as shown in Table 1 and therefore takes into account the differences in organic carbon per waste stream, which eventually degrades into methane. Furthermore GasSim LandGEM uses a lower value for k_1, which also results in a lower methane emission. Both factors explain the somewhat lower methane emission calculated by GasSim in contrast to LandGEM (US EPA) model.

The lowest methane emission is calculated by the French EPER model, which is 192 $m^3CH_4.h^{-1}$.

The methane emissions calculated by the multi phase and German EPER model are comparable and respectively 483 and 375 $m^3CH_4.h^{-1}$ which is rather remarkable. An earlier Dutch case study (Oonk et al., 1994) showed a large mean relative error of 44% in methane production prognoses generated by zero order models in contrast to first order and multi phase models.

Higher emissions of 853 and 965 $m^3CH_4.h^{-1}$ are calculated by the first order and GasSim multi phase model respectively. The higher calculated emission for the first order model can be explained by the difference in the used amount of organic carbon in each specific waste stream. The model uses larger amounts of organic carbon, which eventually degrade into methane and therefore the calculated methane emission is also higher.

QUANTIFYING METHANE EMISSIONS

In 2001 and 2002 a large scale project was performed by several Dutch landfill owners in the framework of the program Reductie Overige Broeikasgassen (Reduction other Greenhouse gasses) (Scharff et al., 2003) at several landfills among which Nauerna. The project aimed at developing simpler measurement techniques for methane emissions.

During the project three measurement techniques were used, which are:

- Mobile Plume Measurement with Tuneable Diode Laser (TDL);
- Stationary Plume Measurement (SPM) and
- Mass Balance Measurement (MBM)

The mobile plume measurement technique is internationally accepted and gives an estimation of the methane emission of a complete landfill site. In this method the methane concentration downwind of the site is measured in a transect through the plume, that is composed by all the small methane emission spots on the landfill surface. The concentration measurements are performed driving a tuneable diode laser along a transect through the methane plume. A plume transect takes approximately 5 to 7 minutes. For determination of the whole landfill emission 8 to 12 transects are made. Due to fact that the emission of methane by degradation of waste will not be constant in time and the short period of time of actual measuring, a TDL measurement only gives a good estimation of the emission level on the day of measurement.

There is a similarity between the SPM and TDL measurement method. Both quantify methane emissions by use of the downwind plume originating from the landfill site. The SPM uses four fixed gasbag sampling stations around the landfill. Combining meteorological data and computer modelling the four receptor stations can be activated whenever predicted methane concentrations surpass a certain threshold level. Once activated, air samples are taken for a 30 minute period of time at two computer selected stations. One station is activated for background methane concentrations and the second station is activated to measure plume concentrations. The samples are analysed using the GC-FID technique. A Gaussian model is used to calculate expected methane concentrations at the receptor stations.

In the MBM a vertical methane concentration profile is measured along with a wind velocity profile. The profiles are gathered by means of sampling points in a pole up to 26 meters in height. In order to asses the temporal variation of the landfill methane emission a landfill is divided in several sections. With changing wind directions the contribution of each sector to the methane emission of the landfill can be assessed.

Both SPM and MBM measurement techniques can obtain an annual methane emission for a particular landfill in contrast to the TDL technique. Both techniques have advantages and disadvantages and are suitable in different situations. In combination the SPM and MBM techniques are complementary to the TDL measurement technique and give more insight in the temporal variation of the emission originating of the landfill.

RESULTS METHANE EMISSIONS MEASURED

In total three TDL campaigns were carried out. The SPM and MBM were stationed at Nauerna during 8 weeks. Measured methane emission by different measuring techniques is presented in Table 5. The results of the different methane measuring techniques are in the same order of magnitude. If the first TDL campaign is considered an outlier and omitted, the average measured emission of Nauerna for 2001 is 515 $m^3CH_4.h^{-1}$.

DISCUSSION

The comparison in this case study is based on one landfill site. It is possible that this landfill site is not representative. This case study clearly shows a huge difference in methane emission prognoses obtained from six different methane emission models. In comparison to the average measured methane emission of a single landfill the first order (TNO), GasSim multi phase, the LandGEM and LandGEM US EPA model seem to overestimate the methane emission. The multi phase (Afvalzorg), German EPER and French EPER model seem to have a tendency to underestimate methane emissions at Nauerna.

The largest deviation between measured and calculated methane emission is 3,695 $m^3CH_4.h^{-1}$ and was calculated by LandGEM (US EPA). The assumption in the model, that the total amount of land filled waste is MSW, does not represent the waste mixture of Nauerna. The smallest deviation between measured and calculated emission is only 31 $m^3CH_4.h^{-1}$ and was calculated by the multi phase model of Afvalzorg. The applied values as shown in Table 3 used in the multi phase model describes the methane emission at Nauerna fairly accurate, but may be inaccurate for other landfills. The first order TNO model calculates a methane emission that is 370 $m^3CH_4.h^{-1}$ larger than the multi phase model (Afvalzorg). This is remarkable as an earlier study (Oonk et al., 1994) showed good agreement between a first order and multi phase model. One must keep in mind that the similar results were found on landfills before 1994 and could resemble MSW more than Nauerna in 2001. The first order model does not take into account the difference in readily and slowly degrading carbon. And the used amount of organic carbon per waste stream differs from the applied values (Table 1) by the Afvalzorg multi phase model. Therefore the model could calculate a larger methane emission and show a larger deviation with respect to the measured emission of this particular site.

GasSim (multi phase) seems to overestimate the methane emission by 368 $m^3CH_4.h^{-1}$. It was not possible to describe the waste composition in the GasSim model. This resulted in a higher amount of degradable organic carbon than actually present and consequently a higher methane emission. With GasSim it is very difficult to come to a waste mixture which represents the case at Nauerna, i.e. poor in organic waste. In order to use the package application of default waste mixtures was inevitable. This will represent a British waste mixture and clearly not the waste mixture at Nauerna. Furthermore a considerable amount of industrial waste (585,533 tonnes until 2002) is landfilled at Nauerna. Industrial waste does contain a certain amount of organic carbon. In case large quantities are involved it contributes significantly to the formation of methane and to the methane emission of the landfill. However in the GasSim model, industrial waste does not contain any organic carbon. Instinctively methane emission should even be higher than the presented emission in this study, as the methane contribution due to industrial waste is disregarded.

The French EPER model seems to underestimate the methane emission by 323 $m^3CH_4.h^{-1}$. The model calculates an average LFG production of 7.68 $m^3.(tonne\ waste.y)^{-1}$ for category 1 waste, which seems low. Also the second category produces a rather small amount of LFG, namely 3.84 $m^3.(tonne\ waste.y)^{-1}$. In addition the model has a fixed extraction rate for the landfill cells that are connected to a gas extraction system. And the production is calculated by means of the extraction not the available organic carbon. Because the Nauerna landfill has a large surface, a limited depth and a low organic carbon content it is extremely difficult to design an efficient extraction system and simultaneously prevent intake of atmospheric air. The extraction efficiency at Nauerna landfill is approximately 20%. This is much lower than the 65% in the French model. This results in a lower total methane emission and the underestimation by the ADEME model.

A 140 $m^3CH_4.h^{-1}$ deviation is obtained with the German EPER model. This model seems to underestimate methane emissions. As mentioned earlier zero order models appeared not to describe methane formation very accurately. Nevertheless the German EPER model in this case study gives a rather good approximation of the methane emission in contrast to several more complex models. One must bear in mind that this may be a good approximation for operational landfills. But once a landfill is closed a zero order model calculates a constant production or emission. This is in contradiction with reality as the evidence that LFG production decreases after closure of a landfill is overwhelming.

CONCLUSION AND RECOMMENDATION

The intention of the UN-PRTR's and E-PRTR's is to disclose emission data to the general public and the regulators. In itself this is a positive trend. We should however bear in mind that a number in a database represents the absolute truth in the eyes of the reader. There is no room for explanation what the number means or caution about its accuracy.

The huge differences in results indicate that current models do not supply a reliable tool to estimate landfill methane emissions. It can not be concluded that the minimum accuracy has been achieved that might be considered necessary before admission in a database can be regarded useful. The authors do not consider it useful or fair to compile and compare data that have such an incomparable origin.

The difference in results between the various measurement techniques is smaller than between the different models. A further development of these techniques may provide a more reliable tool in the near future than modelling.

The comparison has however been made for one landfill. This site may not be representative. It is recommended that more data sets are compared before a draft guidance model is proposed in the Netherlands. It is also recommended that an attempt is made to harmonise the different existing models in order to enable a fair review of the future methane emission data reported to UN- or E-PRTR's.

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Table 1: Age and amount of waste landfilled at Nauerna landfill (tonnes).

Year	Soil & Gravel	Construction & demolition waste	Commercial waste	Shredder waste	Street cleansing waste	Coarse Household waste	Sewage sludge	Annual Total
1985	238,765	3,227	53,153	2,695	3,601	1,223	10,347	*313,011*
1986	358,148	4,841	79,729	4,044	5,400	1,835	15,521	*469,518*
1987	425,061	7,239	119,225	6,047	8,076	2,743	23,210	*591,601*
1988	514,590	10,858	178,836	9,070	12,115	4,115	34,815	*764,399*
1989	306,198	13,820	110,098	28,366	15,420	872	34,050	*508,824*
1990	188,314	8,914	110,836	9,442	12,930	51,398	55,762	*437,596*
1991	217,746	7,794	121,350	5,436	21,534	61,915	34,824	*470,599*
1992	290,651	27,137	138,885	1,943	10,563	20,329	53,467	*542,975*
1993	243,840	66,810	151,971	28,005	25,339	12,201	117,386	*645,552*
1994	239,961	55,385	72,313	27,596	29,807	10,563	161,345	*596,970*
1995	309,100	72,950	76,022	35,663	25,426	5,941	136,718	*661,820*
1996	188,629	29,945	41,559	26,020	11,885	116	43,308	*341,462*
1997	130,545	22,769	26,340	17,980	8,319	0	25,970	*231,923*
1998	207,571	83,836	40,359	27,861	13,645	16,688	29,381	*419,341*
1999	374,714	47,273	64,524	35,590	13,023	2,707	28,356	*566,187*
2000	461,598	48,802	48,197	40,518	10,939	15,856	16,995	*642,905*
2001	590,204	56,227	49,878	39,183	5,116	18,805	6,540	*765,953*
2002	415,807	17,506	9,390	30,630	2,597	770	3,604	*480,305*
Total	**5,701,442**	**585,333**	**1,492,665**	**376,089**	**235,735**	**228,077**	**831,599**	*9,450,941*

Table 2: Waste categories according to ADEME model

Category 1	Category 2	Category 3
Municipal solid waste	Industrial waste	Inerts
Sludges	Commercial waste	Non biodegradable waste
Yard waste	Biological pre treated waste	

Table 3: Default values used in each model

Parameter		First order (TNO)	Multiphase model (Afvalzorg)	GasSim Multi phase& LandGEM	EPER France	EPER Germany	LandGEM (US-EPA)
k_{FAST}	$[y^{-1}]$	-	0.1873	0.1873	0.1873	-	-
$k_{MODERATE}$	$[y^{-1}]$	-	0.099	0.099	0.099	-	-
k_{SLOW}	$[y^{-1}]$	-	0.0301	0.0301	0.0301	-	-
k_1	$[y^{-1}]$	0.094	-	0.04*	-	-	0.094
BDC	$[MgC.Mgwaste^{-1}]$	-	-	-	-	0.107**	-
L_1	$[m^3.Mg^{-1}]$	-	-	100		-	100
C_0	$[m^3.kgOC^{-1}]$	1.87	1.87	1.87	-	-	-
FE_{CAT1}	$[m^3CH_4.tonne\ waste^{-1}]$	-	-	-	100	-	-
FE_{CAT2}	$[m^3CH_4.tonne\ waste^{-1}]$	-	-	-	50	-	-
FE_{CAT3}	$[m^3CH_4.tonne\ waste^{-1}]$	-	-	-	0	-	-
A_1	$[-]$	-	-	-	0.15	-	-
A_2	$[-]$	-	-	-	0.55	-	-
A_3	$[-]$	-	-	-	0.30	-	-
ζ	$[-]$	0.7	0.7	-	-	0.7	-
Infiltration	$[mm.yr^{-1}]$	-	-	800	-	-	-
T_{LFG}	$[°C]$	-	-	-	27	-	-
$P_{MEASUREMENT}$	$[mbar]$	-	-	-	93	-	-
$[CH_4]$	$[\%]$	56.3	56.3	56.3	56.3	56.3	-
CH_4 RECOVERY	$[Mm^3.yr^{-1}]$	1.27	1.27	-	1.27	-	-

$\eta_{RECOVERY}$	[%]	-	-	-	65	65	-

*GasSim will not accept any value for k1 other than 0.04, therefore this AP-42 (US EPA Compilation of Air Pollutant Emission Factors) default value is used during LandGEM modulation.

** The value for BDC is comparable to L_1, indicating the ability to form 100 m^3LFG.Mgwaste^{-1}.

Table 4: CH_4 emission prognoses landfill Nauerna obtained by type of model

Model		Methane emission prognosis ($m^3CH_4.h^{-1}$)
First order		853
Multi phase		483
GasSim	Multi phase	883
	LandGEM	2,683
EPER France		192
EPER Germany		375
LandGEM (US EPA)		4,210

Table 5: Methane emission by different measuring techniques at Nauerna landfill

Measurement technique		CH$_4$ emission (m^{3}CH$_4$.h^{-1})
TDL	1st	900*
	2nd	550
	3rd	540
SPM		440
MBM		530
Average		515**

*The higher emission, in relation to the two other campaigns, observed with the TDL at the first

campaign was partially originating from a extra source (opening of the topcover) located on the landfill.

The contribution was estimated to be 15%.

** The first TDL campaign is considered an outlier and is therefore not accounted for.