Quantifying landfill gas emissions in the Netherlands

Definition study

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SHORT SUMMARY

The present method to quantify national methane emissions of landfills in the Netherlands probably results in an overestimation. The Dutch Ministry of Housing, Spatial Planning and Environment (VROM) could benefit from better methods to quantify the methane emission of Dutch landfills. For Afvalzorg as an operator of landfills not containing household waste adequate tools with respect to methane production and emission estimates do not exist. Therefore it is difficult to design proper reduction measures.

To improve methane emission assessments in this study two strategies have been identified:
a) improvement of the present method;
b) estimates based on emission measurements at all relevant landfills.
In both strategies emission measurements as well as modelling is important. Only the emphasis is different. Also in the first strategy it is more important to improve the knowledge about methane oxidation in top covers. Because of the nature of methane emission on landfills it is argued that measurements at a certain landfill should be carried out during longer periods (1 to 3 weeks) several times per year (preferrably in all four seasons). The mass balance method and the stationary plume method have been identified as most practical to fulfil this requirement.

The interests of VROM and Afvalzorg can to a large extent be combined. This study concludes with a proposal to develop more suitable methods in consecutive and interelated steps.

Keywords: landfill, landfill gas, methane, emission, measurement, method, development.

VERKORTE SAMENVATTING

De huidige methode om nationale methaan eMissies van stortplaatsen in Nederland vast te stellen leidt waarschijnlijk tot een overschatting. Het Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer (VROM) zou baat hebben bij betere methodes om de methaan emissie van Nederlandse stortplaatsen te kwantificeren. Afvalzorg als beheerder van stortplaatsen met hoofdzakelijk bedrijfsafval en verontreinigde grond beschikt niet over doeltreffende methoden om methaan productie en emissie te schatten. Om die reden is het moeilijk om juiste reductie maatregelen te treffen.

Om vaststelling van methaanemissie te verbeteren zijn in deze studie twee strategiën geïdentificeerd:
a) verbetering van de huidige methode;
b) schatting gebaseerd op emissiemetingen op alle relevante stortplaatsen.
In beide strategiën zijn zowel metingen als modellering belangrijk. Alleen het accent verschilt. Daarnaast is het in de eerste strategie belangrijker om de kennis inzake methaan oxidatie in de afdeklaag te verbeteren. Vanwege de aard van methaan emissie op stortplaatsen is beargumenteerd dat metingen op een bepaalde stortplaats bij voorkeur gedurende langere periodes (1 tot 3 weken) en meerdere keren per jaar (bij voorkeur in alle vier seizoenen) uitgevoerd worden. De massa balans methode en de stationaire pluim methode lijken het meest geschikt om hieraan te voldoen.

Het invullen van de belangen van VROM en Afvalzorg kan grotendeels worden gecombineerd. De studie besluit met een voorstel om in opvolgende en samenhangende stappen meer geschikte methodes te ontwikkelen.

Trefwoorden: stortplaats, stortgas, methaan, emissie, meting, methode, ontwikkeling.

CONTENTS

SUMMARY

Measurements of methane emissions might be an option to improve the methane emission assessment. In this definition study an inventory is made, how emission measurements can contribute to a better quantification for both the Netherlands and the landfills of Afvalzorg and to what extent measurement methods applied at selected measurement locations are the same for the Dutch gouvernment and Afvalzorg. In this way, this study is intended to evaluate the possibilities for a joint project.

Due to a successful gouvernment policy the amount of organic materials processed on Dutch landfills has significantly decreased. Less biodegradable material and less moisture in the waste influences formation prcesses in Dutch landfills. Therefore the present method to quantify national methane emissions of landfills probably results in an overestimation. Consequently the effect of emission reduction measures could be underestimated. The Dutch Ministry of Housing, Spatial Planning and Environment (VROM) could benefit from better methods to quantify the methane emission of Dutch landfills. New methods however do need acceptance by the international community.

Afvalzorg as landfill operator has indications that landfill gas formation models lose their value in landfills with a differtent composition than the traditional household waste landfills. Afvalzorg by means of an ISO 14001 certified environmental management system has committed herself to quantify the emissions of her landfills and where possible to reduce the emissions. For landfills other than household waste landfills adequate tools with respect to methane emission do not exist and therefore it is difficult to design proper reduction measures.

To improve methane emission assessments of VROM two strategies have been identified:
a) improvement of the present method;
b) estimates based on emission measurements at all relevant landfills.
In both strategies emission measurements as well as modelling is important. Only the emphasis is different. Also in the first strategy it is more important to improve the knowledge about methane oxidation in top covers.

Because of the nature of methane emission on landfills it is argued that measurements at a certain landfill should be carried out during longer periods (1 to 3 weeks) several times per year (preferrably in all four seasons). The mass balance method and the stationary plume method have been identified as most practical to fulfill this requirement.

The interests of VROM and Afvalzorg can to a large extent be combined:
- both parties can benefit from improved methane emission measurement methods;
- 4 out of 7 Afvalzorg landfills are relevant to national emission assessment.

Validation and international acceptance of methods is more an interest of VROM. Extending research to more landfills is a combined interest of VROM and other landfill operators. This can however be postponed to a later stage in the project. This study ends with a proposal to develop more suitable methods in consecutive and interelated steps.

1 INTRODUCTION

Why monitoring methane emissions from landfills
Landfills are recognised as an important source of methane. Dutch 1990-emissions of methane from landfills are estimated to be about 560 ktonne (VROM, 1998). When expressed in CO_2-equivalents, this is a substantial part of total 1990 emissions of the greenhouse gases mentioned in the Kyoto protocol (see table 1). In this Kyoto protocol, the Netherlands committed themselves to a substantial emission reduction. Due to existing waste policy, methane emissions are expected to decrease, thus contributing significantly to the total Dutch effort to reduce greenhouse gas emissions. Since landfills play such an important role in the Dutch effort to meet the Kyoto target, this source should be well monitored.

Table 1: Greenhouse gas emissions in the Netherlands (in 10^6 CO_2-eq. y^{-1})

	1990	**expected 2010**	**objective 2010**
methane from landfills	12	4	4
other methane	15	10	
other greenhouse gases	190	241	200
total	217	255	204

Afvalzorg is one of the major waste management companies in the Netherlands. In its ISO-14001-system, Afvalzorg takes the obligation to monitor its emissions and also to strive for a continuous improvement of its environmental effects.

Changes in waste-treatment
In the last few years waste policy in the Netherlands has led to major changes in amounts and composition of waste that is landfilled. Besides, landfill management practices are improved as well. So existing knowledge on methane generation in landfills and the subsequent capture, oxidation and emission might not be applicable anymore. As a result, the Dutch Government (i.e. the Ministry of Housing, Spatial Planning and Environment - VROM). is less well able to quantify the national emissions and the emission reduction achieved in the period 1990-2010, while Afvalzorg has problems to quantify their emissions and assess the effects of measures for emission reduction.

Objective of this definition study
Measurements of methane emissions might be an option to improve the methane emission assessment. In this definition study an inventory is made, how emission measurements can contribute to a better quantification for both the Netherlands and the landfills of Afvalzorg and to what extent measurement methods applied at selected measurement locations are the same for both parties. In this way, this study is intended to evaluate the possibilities for a joint project.

Approach
The approach in this definition study is as follows. First the problem of both the Dutch Government and Afvalzorg are carefully defined and a step-wise strategy to solve this problem is made. Subsequently, suitable measurement activities are identified and conditions applying to these measurements.

2 DEFINITION OF THE PROBLEM

2.1 Background- waste policy leads to lack of knowledge on processes in landfills

Current waste policy in the Netherlands aims at both the reduction of amounts of waste to be treated as well as reducing the environmental effects of waste treatment. With respect to methane emissions of landfills, the most important developments are:

- the separate collection of paper and organic materials at households is almost fully implemented and quite effective at the moment;
- the capacity of municipal solid waste incineration is doubled in the last decade, so alternatives to landfilling are being developed;
- landfilling of combustible wastes is in principle forbidden and special allowances are required to continue the landfilling of this waste; on top of that landfill taxes are being superimposed thus rendering incineration price-competitive with landfilling.

As a result it is expected that the amount of organic waste that is ultimately landfilled is going to decrease significantly (AOO, 1999). On top of that other important factors that influence biochemical processes in landfills will change as well. The humidity of the landfill will drop, since a large part of the water in the landfill comes in with the organic waste. The nature of the organic material will change from relatively rapidly degradable to a more woody, less well degradable nature. The sharp initial increase in temperature will be less due to the lack of rapidly degradable materials.

In the Netherlands a lot of knowledge is gathered about landfill gas formation and design and operation of landfill gas extraction schemes. This knowledge has lead to the development of landfill gas formation models, that proved to be a sound basis for the design of many landfill gas extraction schemes and are at the basis of the estimate of 1990-methane emissions from Dutch landfills. But all this knowledge is based upon the old traditional household waste, landfilled before this new policy came into effect. It is not clear to what extent this knowledge still applies for the newer generation of landfills. Most likely under these changed conditions waste decomposes less rapidly and less complete, thus complicating the assessment of landfill gas generation rates.

2.2 Problem definition of Dutch Government

The Dutch government under the Kyoto protocol is obliged to assess and report its emissions of greenhouse gases, a.o. methane emissions from landfills. Of special importance are the following topics:

- what were the 1990-emissions of methane form landfills;
- what are current emissions and (in 2011) what are the 2010-emissions of methane from landfills;
- what is the emission reduction achieved in the period 1990-2010 ;
- besides, estimates of expected 2010-emissions are required for policy definition.

The current estimate of 1990-emissions proceeds according to internationally accepted guidelines and can be regarded as satisfactory. However, as described in 2.1, Dutch waste policy results in a decrease of organic materials on landfills and changed conditions in the landfill (humidity, temperature) most likely results in a less rapid and less complete conversion of organic materials to methane. The effect of a decreased amount of organic materials to landfills is well monitored and its resulting methane emission is expressed in the Dutch emission estimate. The effect of changed conditions on methane emissions *is not*. The use of the existing methodology in quantifying current and 2010-emissions will result in an overestimation of the real emissions and the emission reduction achieved in the period 1990-2010 will be underestimated.

Another problem of the existing methodology for estimating methane emissions from landfills is that it is not able to monitor some specific measures that are proposed for furthergoing emission reduction. An example of this is the enhanced oxidation in top-layers. This option is widely recognised as a promising method to reduce methane emissions (ECN/RIVM, 1998). Emission reductions achieved in this way can at present not be monitored, due to lack of a suitable monitoring methodology (either a measurement method or an accepted reduced emission factor) and the results obtained can not be incorporated in the national assessment.

So there are some arguments in favour of improvement of the national method of assessing methane emissions from landfills.

An important prerequisite of the national emission estimate is that it is accepted in international negotiations. This means that the methodology and parameters used should meet certain requirements. Methodologies and default factors for model parameters are defined in the '1996 IPCC-Revised Guidelines' and the forthcoming 'IPCC-guidelines on good practice'. Use of other model parameters compared to the defaults and even other methods than the methods defined by IPCC is possible on a few conditions:

- the result should be an improved, more accurate emission estimate;
- the definition of methodology or model parameters should meet certain standards of quality control: it must be based on a number of observations on real landfills; it must be able to withstand criticism of international experts; results should preferably be published in double-peer reviewed journals;
- attention should be paid to base-line correction: any change in methodology or model-parameters along the way must be accompanied by considerations about the necessity of adapting the methodology of estimating 1990-emissions as well.

So any attempts of the Dutch government to improve their emission estimate is subject to rather strict preconditions, which imply that every activity and result should be carefully communicated with e.g. international experts, IPCC and UN-FCCC.

2.3 Problem definition of Afvalzorg

Afvalzorg in its ISO-14001-system takes the obligation to monitor its emissions and also to strive for a continuous improvement of its environmental effects. Afvalzorg has a detailed overview of the characteristics of the landfilled waste at most sites. Up to 60 different species of waste are defined and a 3-D database is kept up to date of what waste is where in the landfill, so making a fair prognosis of landfill gas formation should be no severe problem. But the waste composition at the landfills of Afvalzorg differ from what was landfilled in the Netherlands before 1990, so landfill gas formation models don't apply anymore and methane emissions are hard to predict. The results of a number of emission measurements result in methane emissions that deviate from the expected ones (see below). Besides for monitoring purposes, information on methane generation is also of importance for design and operation of landfill gas recovery schemes. Less accurate prognoses of landfill gas formation may lead to over- or underdimensioned extraction schemes and utilisation equipment and may render a project economically unfeasible.

Afvalzorg therefore seeks for ways to frequently or continuously monitor the emissions from its landfills. Besides Afvalzorg is interested in improved prognoses of landfill gas formation in its sites to enable improved design and operation of their schemes for landfill gas recovery.

Prerequisites of Afvalzorg for its monitoring system are: reliability, costs of monitoring and suited to be taken care of by landfill operators.

Two examples illustrating the problems of Afvalzorg:

- at the Landfill Nauerna, to the north west of Amsterdam the emission level was obtained using plume measurements downwind of the landfill (Hensen 1997, 1998) In 1997 the gas extraction system was not yet in operation. The production of the site was estimated to be 650 m^3 CH_4 h^{-1} using the landfill gas production model. The emission estimate was 310 m^3 CH_4 h^{-1} so apparently the oxidation of CH_4 in the top layer at this location was almost 50 %: 340 m^3 CH_4 h^{-1}.

In the next year, the extraction system recovered about 100 m^3 CH_4 .h^{-1}. Emission measurements showed a significant emission reduction of about 50 % down to a level of 155 m^3 CH_4 h^{-1}. The production estimate for this period was 600 m^3 CH_4 h^{-1}. This implies that the oxidation was about 345 m^3 CH_4 h^{-1}, which is almost identical to the 1997 level. The oxidation level is very high, almost 50-60% in the two subsequent years. This is significantly different from the 10 % level used in the national emission inventory. So either the oxidation level is high indeed, or the actual production level is overestimated or the emission estimate is to low. In November 1999 an emission level was found that seems higher than the production level. An oxidation level can of course not be negative. It should be noted however that the inaccuracy of both the production prognosis and the emission estimate is approximately 20%. In winter oxidation is likely to be zero. Matching levels of production and oxidation can be found within the range of inaccuracy.

Table 2. Emissions from Nauerna and Braambergen (all levels in m^3 CH_4.h^{-1})

Nauerna	**year**	**emission measured**	**production**	**extraction**	**oxidation**
	April 1997	310	650	0	340
	April 1998	155	600	100	345
	Nov. 1999	600	550	50	?

Braambergen	**year**	**emission measured**	**production**	**extraction**	**oxidation**
	Nov. 1999	240	250	110	?
	Dec. 1999			245	

At the site Braambergen, near Almere a production estimate was calculated for November 1999. A level of 250 m^3 CH_4.h^{-1} was obtained. Emission measurements using the plume method yielded an emission level of 240 m^3 CH_4.h^{-1} , which is almost equal to the total production level. Furthermore the gas extraction system recovered 110 m^3 CH_4.h^{-1} at the day of measurements. So even with oxidation of 0% the sum of emission and extraction exceeds the production estimate. This discrepancy could be caused by some error in the emission measurements, but in December 1999, the extraction system was able to recover 245 m^3 CH_4.h^{-1} (using extra wells). Therefore there is no doubt that the estimate of the production level is too low. This is surprising since for this landfill there is detailed information of age and composition of the waste.

3 STRATEGIES TO IMPROVED EMISSION ESTIMATES

3.1 Government

Current methodology
The current methodology for estimating Dutch methane emissions is based on the material balance in figure 1:

emissions = formation - recovery - oxidation

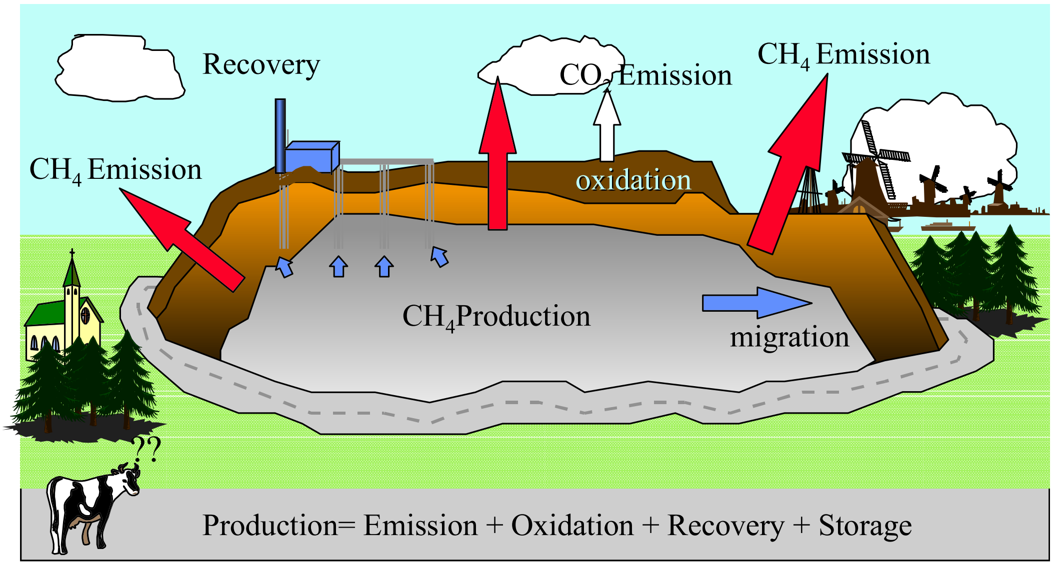

Figure 1: methane formation, recovery and emissions in a landfill

Formation is calculated using a first-order decay model as proposed by IPCC, using the default rate-constants for biodegradation, and applying specific input-parameters for carbon-content of the waste and dissimilation. Regarding 1990-formation this methodology can be considered about as accurate as possible with existing knowledge. Regarding formation in waste in the Netherlands due to the reason described in chapter 2.1, existing models are not suited to make an accurate estimate of methane formation in waste landfilled after 1993.
The amount of recovered methane from the landfill is well monitored and accurate compared to the other factors.
The uncertainty in the oxidation efficiency of the landfill cover in contrary is large. At the moment the methodology was made only little information was available on this topic and still it is difficult to extract a reliable oxidation factor from field data. One key problem is that no large scale measurement programme has been conducted. Estimated oxidation capacities on a larger number of landfills related e.g. to site specific parameters, or seasonal conditions are not available.

Two strategies
For the Dutch Government two strategies are identified to improve the emission estimates. Performing measurements of emissions at real landfills is an important part of both strategies. In the first strategy, measurements are used to improve current methodology based on modelling landfill gas formation and insight in methane oxidation. The second strategy ultimately aims at an emission assessment based on frequent or continuous measurement of methane emissions at all relevant Dutch landfill sites.

a) Improving current methodology

Methodologies for quantifying emissions are based on estimating formation, recovery and oxidation. Improving the existing methodology can imply both improving landfill gas formation models and improving oxidation factors.

b) Emission inventory based on measurements
In 2010 a limited number of landfills will be responsible for the major part of Dutch methane emissions: over 95 % will be caused by a group of 25 landfills. This implies that an inventory of Dutch methane emissions from landfills might be based on direct measurements from this group, on the condition that an accurate measurement methodology is available, that is affordable as well.

It must be stated however that whatever the choice is to obtain future estimates for CH_4 emission levels from landfills, a combination of both model evaluation and measurements will be needed. If we choose to update the methane formation models in order to improve the emission inventory, new measurements are needed to see if the models are able to describe the landfills now. If alternatively we decide to evaluate the emissions in 2010 using emisison measurements at the individual landfills, the new emission data will provide information that can be used to improve the available models. This might lead to an revision of the emission estimates for 1990.

Nevertheless it is usefull to evaluate the steps that should be taken in order to improve emission estimates using either option a or b.

Option a. *improving current methodology*
A stepwise approach for improving the formation model might be:
1.1 Choice of a suitable model. The existing first-order model might be a good starting point. Possibly the multi-phase model might be even better, since this model is in principle better suited to describe a decrease in rate of degradation of the organic wastes. Application of the multi-phase model however requires a further elaboration of this model.
1.2 Selection of an appropriate method for determining landfill gas formation on landfills. Since landfill gas formation in the landfill can be estimated from the sum of measured methane and carbon dioxide emissions, this activity will most likely comprise the identification of a suitable method for determining these emissions.
1.3 Real-scale observation of landfill gas formation on a number of landfills. For this purpose amounts of waste and waste composition of the landfills under study should be fairly accurately known. Since landfill gas formation models have a limited accuracy, deviations of measured and calculated emissions were also observed for older landfills. So a larger number of measurements are required in order to conclude, whether or not newer landfills deviate significantly from the older landfills. To illustrate this: in figure 1 and 2 calculated and observed formation at Dutch landfills in the years 1992/1993 (Oonk et al, 1994; Oonk and Boom, 1995) are depicted along with hypothetical results of emission measurements from newer landfills. Figure 1 depicts the situation, where the new landfills seem to behave in the same way as the older waste, where in figure 2 a clear difference exists between the group of older and newer landfills.

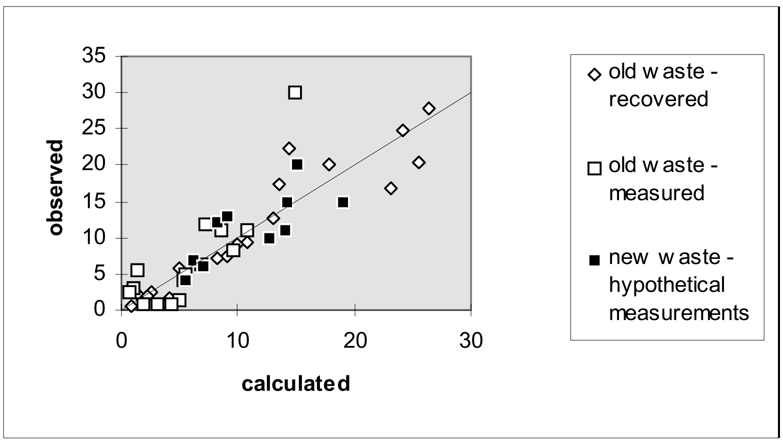

Figure 2: Example: hypothetical results of measurements indicate new landfills are comparable to older landfills

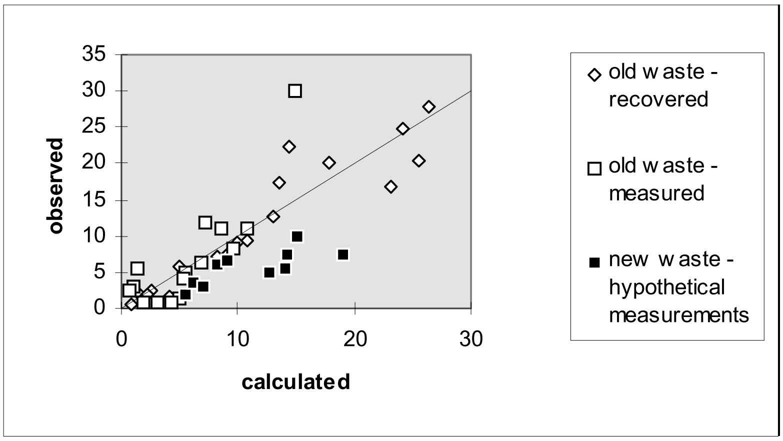

Figure 3:Example: hypothetical results of measurements indicate newer landfills produce less landfill gas compared to old landfills

1.4 Validation of existing models: measured formation can be compared with landfill gas formation as obtained from the formation model.

1.5 Adaptation of models. Based on the findings, methane formation models might be adapted.

A step-wise approach for improving the oxidation factor might be:

2.1 Development of a method to observe oxidation on a real landfill. This method should give a reliable estimate of oxidation on a real landfill, and its conclusions should be representative for the variation in methane oxidation on this landfill throughout the year.

2.2 Validate this method using an accepted technology for determining methane oxidation. Accepted methodologies for assessing methane oxidation do exist, but are rather expensive and give only an impression of a single day. So these methods are not that well applicable when trying to obtain an impression of the mean methane oxidation in the Netherlands. The methodologies however might be used to validate the method obtained under 2.1.

2.3 Measuring oxidation at a large number of landfill sites to obtain a representative mean value of oxidation.

Option b. *emission inventory based on measurements*
A shift in monitoring methodology from the existing model-based approach to an approach based on measurement requires some additional attention:

- The methodology should be internationally accepted. This means that both the fact that emission estimates might be based on emission measurements should be accepted and that the specific method for measuring emissions should be accepted. Since IPCC-methodology leave the opportunity for application of more accurate methodologies, the first part might not be such a large problem. The second part implies careful communication of measurement methods and results with IPCC, UN-FCCC and other international experts in the field.
- An emission inventory directly from measurements implies a discontinuity in emission monitoring in the period 1990-2010. Special attention should be paid to base-line correction. For example: if methane emissions in 2010 are lower than previously expected one can question the cause: is formation less than expected or is the oxidation higher than expected. If the latter is the case, this might have implications for the oxidation assumed in the 1990-emission estimate.

A stepwise approach for improving the formation model might be:

3.1 Development and validation of a suitable methodology in a series of measurements at selected landfills.

3.2 International discussion about the methodology and its results. At the moment there is no stage for this discussion. IPCC does not pay attention to measurement methods and there is no other expert group on this topic. The key researchers however are known and might be approached for disussion and comments. There is an iniatiative to organize an international

workshop on methane emissions form landfills (Bogner, 1999). Such a workshop could be used to promote a discussion on the subject. Publication of results should meet high standards and preferably in highly qualified peer-reviewed journals.
3.3 Measurement of emissions from all relevant Dutch landfills.
3.4 Interpretation of results. What impact has the gathered results for the Dutch estimate of 1990-emissions.

Requirements
It is essential that both strategies, their methods and results should be scientifically sound and accepted by international experts. This implies the publication in appropriate journals and discussion with international experts.

3.2 Afvalzorg

As described in chapter 2, Afvalzorg has taken the obligation to estimate emissions from their landfills and strive for continuous improvement of their environmental impact.
But current experiences of Afvalzorg indicate that due to changes in waste composition, landfill gas formation models are not applicable anymore. Therefore emissions can no longer be estimated from

$$\text{emissions} = \text{formation} - \text{recovery} - \text{oxidation}$$

while using the existing formation models. If an accurate method becomes available to measure emissions and estimate oxidation, emissions are diectly monitored and landfill gas formation (and the amounts of methane that might be recovered) can be calculated from emissions and oxidation.

A step-wise approach to the Afvalzorg problem is:
4.1 Development of a low cost monitoring system, based on the characteristic of the landfill landscape and the knowledge about the source distribution on the landfill, which should:
- provide an representative yearly average emission level for the whole landfill including its slopes, taking into account the daily and seasonal variation in emissions;
- not interfere with the normal operations of the landfill, i.e. landfilling.

The system probably does not have to be at one site during each day of the year. In order to evaluate the seasonal variation 4 episodes of 3-4 weeks or so in different seasons should provide the most important information about the emission behaviour of the site. This data can be compared with meteorological conditions and with gas extraction data to estimate the annual emission level.
4.2 Implementation of the method for Afvalzorg on all 7 landfills

Requirements
Sofar methane emission measurements have not been a widely applied tool to quantify landfill emissions. Therefore any method will be acceptable to inform the local authorities and the general public about landfill methane emissions, either direct or through an environmental annual report. Nevertheless scientific acceptance will be helpful.
Afvalzorg considers to use a low cost monitoring system in order to monitor the methane emissions at their landfills for the years to come. This system should improve the evaluation of the annual emission levels for the different sites. Since formation might be estimated from the sum of methane and carbon dioxide emissions, it would be extremely useful when CO_2 can be measured as well.

4 POSSIBILITIES FOR MEASURING EMISSIONS

4.1 Variability of emissions

Emission from landfills can be measured in various ways. Important aspect of the evaluation of techniques is the duration of the measurement. All techniques have typical durations: some give methane emissions as a point in time; others give an impression of emissions at a certain day, where a third category measures emissions during substantially longer times. The variability of the emission level in time provides constraints on the measurement methodology. Important question is: how representative are the emission levels obtained during the campaign for the annual average emission level? Over the last few years quite a number of emission experiments were performed at landfills. These different experiments showed that :

- the emission per m^2 on a single landfill shows a variability of three orders of magnitude;
- emissions from landfills with comparable size can be different by about an order of magnitude;
- the oxidation of the top layer, and therefore also the CH_4 emission of landfills shows a seasonal variation;
- the amount of emitted methane is depending on meteorological conditions: rainfall and pressure changes.

In the next paragraphs some results obtained from literature will be listed.

4.2 Spatial variation

Several researchers illustrate the high spatial variation in emissions, caused by the high heterogeneity of waste. Several examples: Verschut et al. measured emissions at three Dutch landfills using dynamic closed chambers and reported spatial variations of more than a factor 1,000. Czepiel et al. (1996) studied the spatial variation at a landfill in New England and found no correlation between emissions from two points when the distance was larger than 6 meters.

Figure 4: Methane emissions from the Kuchino landfill surface (Nozhevnikova et al., 1993)

4.3 Hourly or daily variations

There are several factors influencing landfill gas emissions on a relatively short time.

Climatological phenomena are very important. E.g. (Czepiel et. al 1996a) show a correlation between the changes in atmospheric pressure and the emission of the landfill. Measurements of emissions at a landfill in the US show that a change of 30 mbar over a 5 day period gives a fluctuation in the emission level with a factor 2 (see figure 5).

Other authors (e.g Verschut et al., 1991) mention pressure-variations to be of importance: increasing atmospheric pressure will lead to a reduced outflux of methane, and methane is accumulated inside the landfill. When the ambient pressure drops a significant increase in the emission can be observed. Variations in wind can have the same effect, because an increase in wind locally causes a decrease in pressure (Bernoulli-effect). Rainfall also influences landfill gas emissions, since it reduces the permeability of the top-layer.

Emission events can be related with the gas extraction system as well: in the US a 10 * fold increase in the emissions of methane into the atmosphere was found at a landfill site where the compressor unit of the extraction system failed for some days (Shorter et al, 1998; see figure 6). When the compressor unit came into operation the old low emission level was reached again after 1-2 weeks. This kind of events can be evaluated when performance of the gas extraction

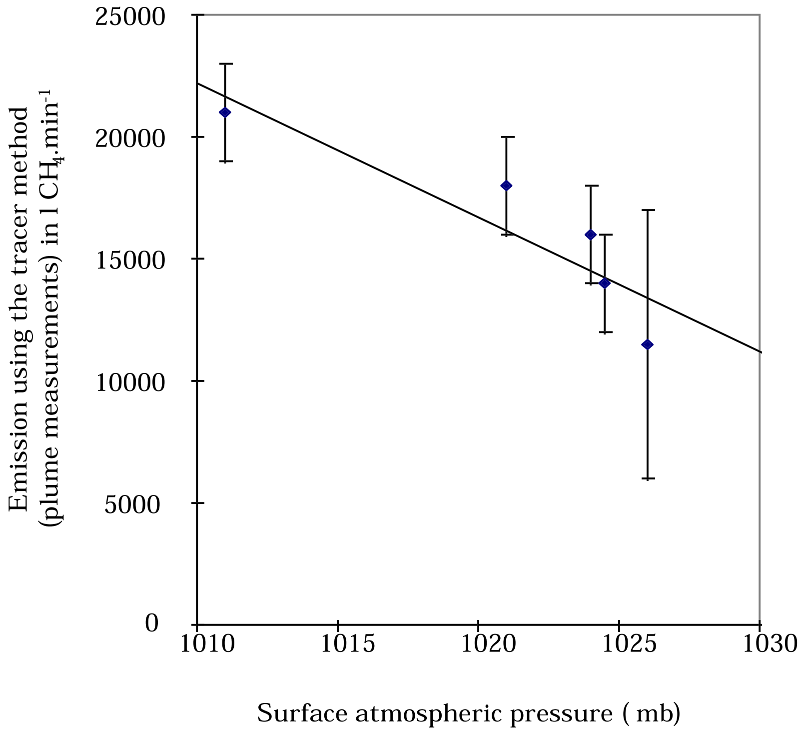

Figure 5: The CH_4 emission at a landfill in the USA, measured on 5 subsequent days. Higher emissions occur with a decrease in the atmospheric pressure. (After Czepiel et. al. 1996a)

system is well documented. It should be noted however that the gas extraction systems in the Netherlands on average are in operation during more than 90% of the year. Therefore the relative importance of emission events that are related to failure of the extraction system is probably low. When the average emission level at a site is to be evaluated in a measurement campaign however, it is necessary to know that the extraction system worked well (keeping a stationary extraction level) for a period of about 2 weeks before the measurements take place.

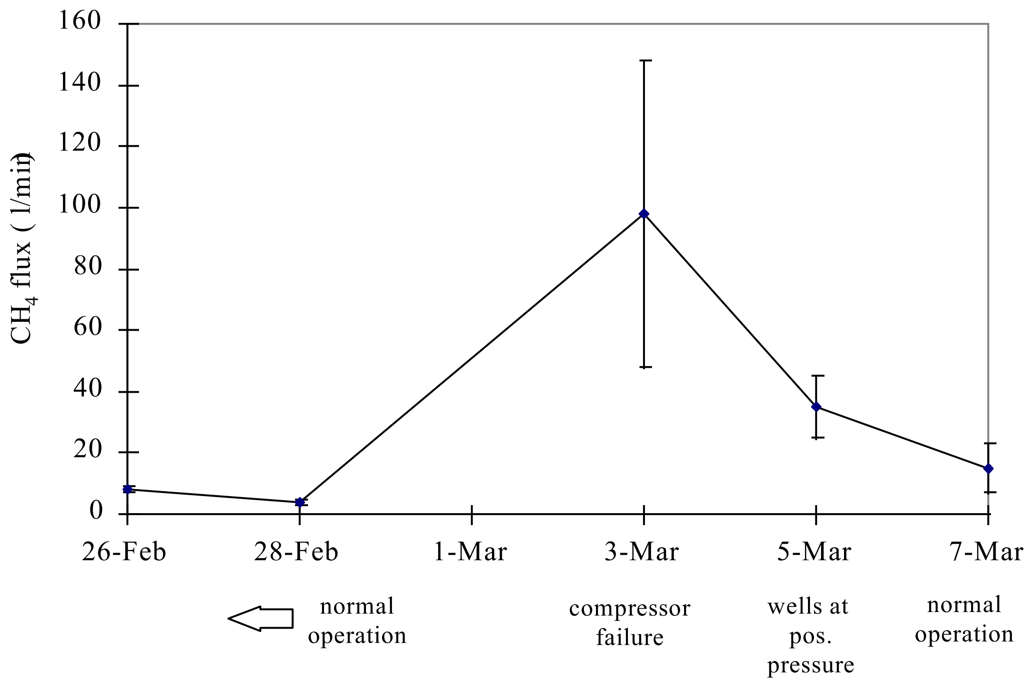

Figure 6. *The emission of a landfill before, during and after a technical failure of a compressor unit in the gas extraction system*. (Shorter, et al 1998)

4.4 Seasonal variation of the emission level.

The conditions (temperatures, humidity) for the methane producing bacteria inside the landfill most likely will not change during the season. So most likely formation will not fluctuate too much over the year. But there are several indications methane oxidation in top-layers *is* affected, resulting in a seasonal variation in the methane emissions from landfills. This phenomenon is reported in Denmark (Christophersen and Kjeldsen, 1999) , Sweden (Maurice and Lagerkvist, 1997), Belgium (Boekx et al., 1996) and in the US (Czepiel et al., 1996 b). Figures 7 and 8 illustrate this seasonal influence. This seasonal effect is caused by changes in both ambient temperature and rainfall. Ambient temperature is of great importance: all results show that oxidation efficiency is 0 below about 5° C and very slow roundabout 10-15 °C. Increased oxidation activity is found with increasing temperature and effective oxidation can take place at temperatures in excess of 20 °C. Furthermore a clear dependence on the soil moisture level is observed. A maximum in the oxidation is obtained at a moisture level of about 50% of the water holding capacity (Czepiel et.al., 1996b). Increased moisture levels of the soil reduce the fraction of methane that diffuses homogeneously through the top-soil and will lead to an increased emission through cracks in the surface. So not all the bacteria are in contact with methane anymore and methane oxidation will be relatively low. Low moisture levels will decrease the activity of the bacteria as well.

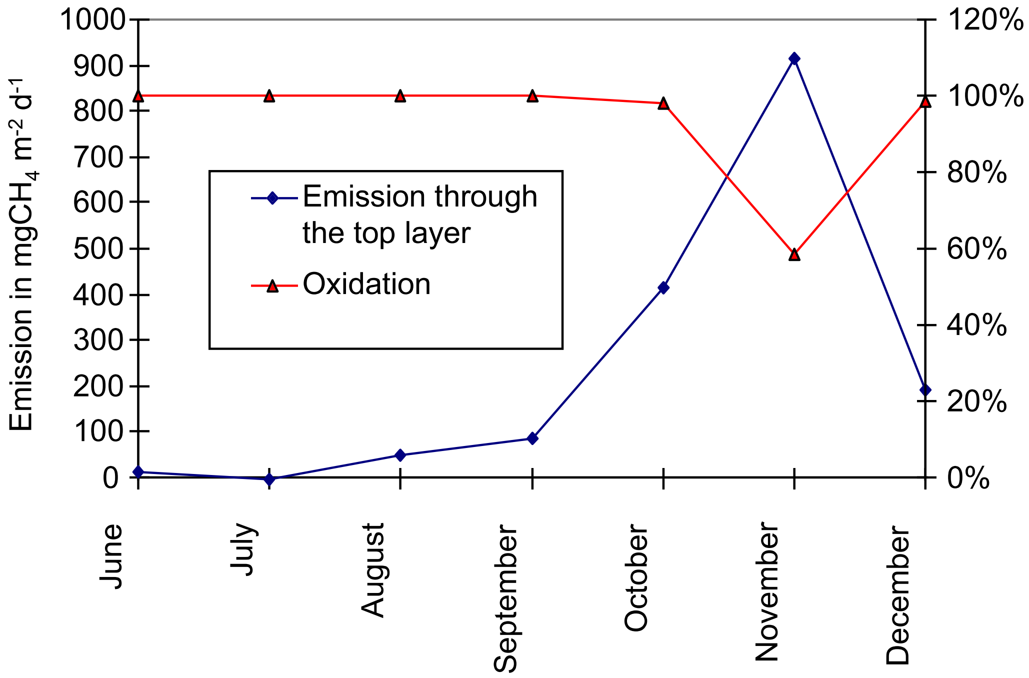

Figure 7. *Emission estimated in different months at a landfill in Belgium show a clear seasonal variation caused by a variation in the oxidation in 30 cm top soil layer. (after Boekx et al., 1996.)*

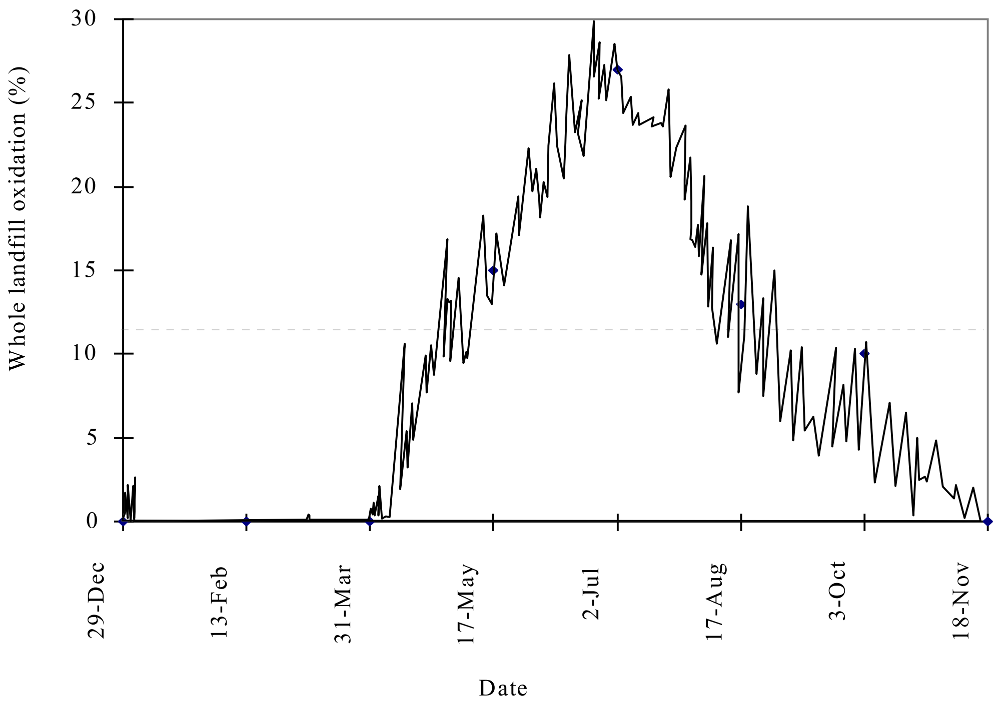

Figure 8. *The seasonal variation in the oxidation level is estimated based on changes in temperature and soil moisture. The model calculations show that the oxidation can change from almost 0% in winter to 40 % in summer. (free-style copy after Czepiel et al., 1996b)*

4.5 Overview existing measurement methods

a) Soil core measurements.
Measurements in the top-layer may give useful mechanistic information about the fundamental steps leading to methane emissions: diffusion and oxidation. Methane and concentration gradients in the soil may give an indication of methane and carbon dioxide diffusion through the layer (Bogner et al., 1995). Landfill soil cores may be collected and transported to the lab for determining bacteriological activity of methanotrophes. The latter is done by exposing the soil sample to a high concentration of CH_4 and measure the decrease of the CH_4 concentration in time, thus giving an indication of the oxidation capacity of the soil. These experiments may be carried out for further study of oxidation process at different temperatures or soil moisture levels etc..
The advantage of soil-core measurements is that it gives insight in the fundamental steps leading to emissions. The method however also has some disadvantages: it is does not take into account emissions caused by convection and its spatial and temporal resolution are low (one gets an impression of emission and oxidation of a very small spot on a single moment). Besides, the methodology is very labour-intensive.

b) Static closed chambers
Static closed chambers are the most simple method to measure fluxes through a surface and are most frequently used in literature. A sampling device consists of a box with a surface area of roundabout ½ m^2 in which the increase in concentration of methane in time is measured. Methane fluxes through the surface are directly obtained from the rate in increase of concentrations.

Advantages of this closed chamber method are:
- It is simple, easy to understand and often applied world-wide.
- Although the sample area is small (see disadvantages below, a number of literature references mention 'good agreement' with other methods, provided that sufficient measurements are conducted on the landfill (Bogner and Spokas, 1995; Mosher et al., 1996; Savanne et al., 1997). Such a good agreement is not obtained by Verschut et al. (1991), using dynamic closed chambers (see below).
- Since it is often applied, the method is a good candidate for international acceptance. E.g., in the UK plans exist to base the British estimate of methane emissions from landfills on measurements using these closed chambers (Gregory et al., 1999).

Disadvantages are:
- Small sampling area (in most cases less than 1 m^2) so less appropriate to measure inhomogeneous emissions and landfills prove to be very inhomogeneous. Mosher et al. (1996) conclude that there is no correlation between emissions from two sampling points located further than 6 meters apart. The good correlation they observe, using the box sampling method (see above) is much to their surprise.
- In order to get this good correlation, a large number of measurements are required: more than 20-30 on a typical landfill according to Mosher et al. (1996).
- So the method requires continuous attention and is therefore very labour intensive.
- Upon measurement, concentrations in the chamber are being increased. Assuming diffusion to be the prime mechanism of methane transport, this build-up of concentration influences fluxes again, thus limiting the duration of a single measurement. To overcome this problem, Perera et al. (1999) propose a correction method for determining emissions.
- On surfaces with vegetation, CO_2-emissions can not be measured, since the closed chamber influences assimilation-dissimilation patterns of the vegetation.

c) Dynamic closed chambers
Dynamic closed chambers resemble static closed chambers, except for one aspect: in a dynamic chamber a continuous air-flow is maintained through the box, thus avoiding the build-up of concentrations and the influence of fluxes. In dynamic closed chambers, fluxes are obtained from the air-flow through the chamber, the inlet and outlet concentrations. Upon performing closed chamber measurements, maintaining the pressure in the chamber at comparable levels

as ambient pressures is of utmost importance (Verschut et al., 1991). In order to have an optimum control of internal pressure, Verschut et al. (1991) therefore used inlet and outlet-fans to maintain the air-flow.
Dynamic chambers have in general the same advantages and disadvantages as static closed chambers.

d) Mass-balance method
In the mass-balance method, methane and carbon dioxide emissions can be obtained from an interpretation of wind velocity and the methane concentrations at different heights over the landfill surface. At each level the product of concentration and wind velocity provides the horizontal flux and is subsequently related to the landfill area upwind of the sampling point. If the measurements are performed to a sufficient height over the landfill the whole methane plume is sampled and the emission flux is obtained. At varying wind directions, emissions from all part of the landfill are sampled, so this method also provides some spatial information about high and low emission areas. With this method automated, continuous measurement is possible. Experience with this method exists in the Netherlands at almost 30 landfills (e.g., Oonk and Boom, 1995) and in France (Savanne 1997).

Advantages of the mass balance method:
- Gives representative emission levels for large parts of the landfill.
- Continuous measurements over a longer period are feasible.
- The interpretation is straightforward.
- CO_2-emissions can be measured as well on the condition that suitable analysing equipment is present. The combination of methane emission and carbon dioxide emissions give a better indication of landfill gas formation and methane oxidation, since formation can be obtained from the sum of methane and carbon dioxide emissions and methane oxidation from the ratio of methane and carbon dioxide emissions, compared to the ratio in extracted landfill gas[1].
- Compared to the box method only one measurement location is needed.

Disadvantages:
- The geometry of the landfill can limit applicability of the method: at larger landfills problems might occur, since the upper sample points have to be mounted at impratical heights on a pylon.
- The method shows a combination of spatial and temporal variation in the signal.
- Upscaling to obtain the emission level for the whole site is in some cases still needed.

e) Micrometeorological methods
Micrometeorological methods are often proposed to measure emissions from larger surfaces (e.g. Fowler and Duyser, 1991). In these measurements concentration gradients are measured and recalculated as vertical fluxes using information about air transport and mixing at the scale of a few m^3 (this explains the name micrometeorology).These techniques however can only be applied on terrain that is rather flat over a large distance (several hundreds of meters), and where emissions occur in a rather homogeneous way. There are almost no landfills that are entirely flat and where the distance to the slope is in excess of 200-300 m. Moreover the slope itself will be a major source of emissions. This makes emission measurement with these techniques impossible (Oonk and Boom, 1995, Savanne et al., 1997) and further discussions about advantages and disadvantages superfluous.

f) Mobile plume measurements
In the mobile plume method, emissions from the landfill are obtained from the difference in the methane fluxes through a transect screen downwind and upwind from the landfill. Using a fast response methane monitor (TDL) the concentration upwind of the landfill is determined. Downwind of the landfill a methane plume is found that originates from the landfill. In this plume the methane concentrations are higher than the background level. Using a dispersion model the concentration pattern can be used to estimate the emission level of the landfill . Simultaneous release of a tracer (N_2O for example) at the landfill can be used to either calibrate the dispersion model, or to, directly, calculate the methane emission level by comparison of the

[1] The authors of this report are aware of the formation of exopolymers (Hilger et al., 1999), making the results of measurements less easy as described above. Upon performance of measurements it shouldbe discussed, whether and how results have to be adapted for the formation of exopolymers.

plumes obtained from the landfill and the tracer. This type of measurement provides an integrated estimate of the emission of the whole landfill. The spatial differences of the emission level on the landfill automatically taken into account. The method was used in the US by Czepiel et al (1996) and by Shorter & McManus (1997)
In Europe experiments were performed in France (Savanne,1995) and in the Netherlands at the landfills at Nauerna, (Hensen 1997 & 1998) Hollandse Brug and at Braambergen (Almere) (Hensen, 2000)

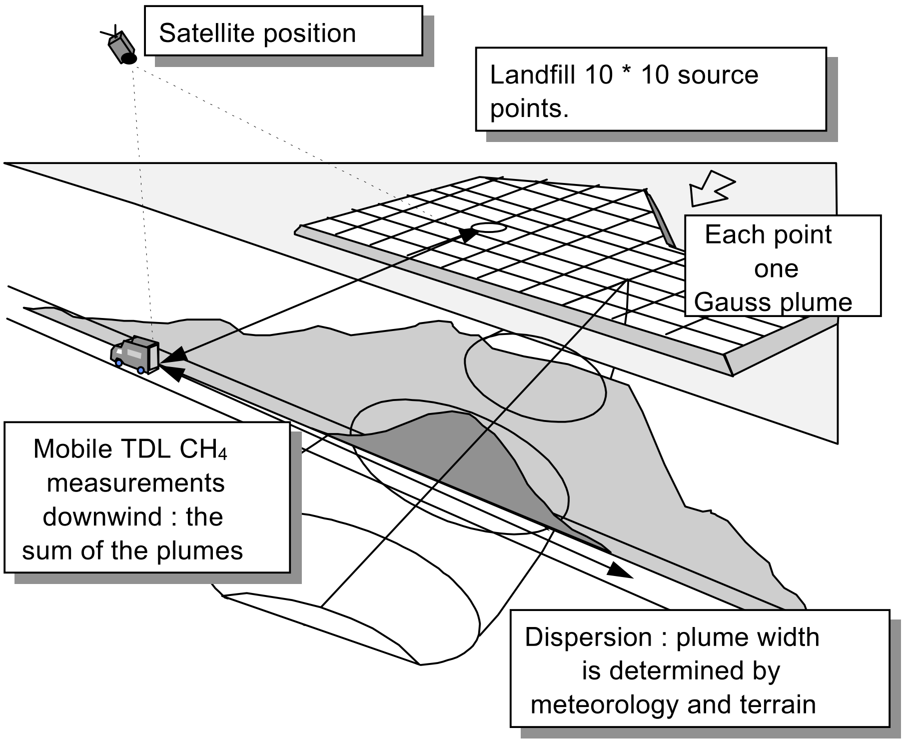

Figure 9: Schematic representation of the plume measurement

Advantages of plume measurements:
- An emission estimate for the whole landfill is obtained, spatial inhomogeneity of the source is accounted for.
- Especially when using a tracer with a known source strength the interpretation of the data is straightforward.

Disadvantages of plume measurements:
- The method can only be applied when a measurement transect is available downwind of the site.
- Mobile plume measurements can not be performed continuously (like for example the mass balance or box measurements).
- Since mobile measurement need manpower continuously this type of experiments is relatively expensive.

g) *Stationary plume measurements*
In stead of mobile plume measurements stationary plume measurements can be also be performed. Air samples are collected in canisters downwind of the landfill during a period of time. Experiments in the USA have shown a good agreement between these plume measurements and mobile measurements (Czepiel et al., 1996a) In the Netherlands this method was used to evaluate the emission of NH_3 from manured plots. Here also mobile plume measurments and stationary plume measurements were performed. A dispersion model is used to obtain the concentration variation versus time at the location of measurement. This modelled time series is avaraged over the period in which sampling takes place. Comparison of the modelled and measured concentration levels provide the estimate of the source strenght that causes the plume.

The method was tested for NH_3 using an artificial source and the emission estimates compared well with the amount of NH_3 released.

Advantages of stationary plume measurements:

- An emission estimate for the whole landfill is obtained, spatial inhomogenity of the source is accounted for.
- The method does not need attendance in while sampling so a monitoring system based on this method will be relatively low cost.

Disadvantages of stationary plume measurements:

- The method is new and needs evaluation.
- Sampling locations outside the landfill are needed, permission to use these locations is required.

h) Isotope measurements

Isotope measurements of CH_4 give insight in the fraction of methane that is oxidized in the top-layer (Bergamaschi et al., 1998). Methane that is formed inside a landfill has a specific isotope contribution ($^{12}C/^{13}C$) which is different from ambient air. When this methane passes the top-layer of the soil part of the methane is oxidized. In this process again the ($^{12}C/^{13}C$) ratio changes. This change is determined by the preference for ^{12}C of the oxidizing bacteria. The emitted CH_4 is "enriched" with ^{13}C. When the latter effect is determined (for example in the lab using cores-samples) the oxidation fraction can be obtained using the isotope composition measurements. The isotope composition measurement of the landfill gas itself is relatively easy to determine. More difficult is to determine the average isotope composition of the gas that is actually emitted into the atmosphere. This is done by filling gas-flasks downwind of the landfill different mixtures of background air and emitted gas are obtained. From these samples the isotope composition of the emitted gas is calculated. Since this method also uses samples downwind of the landfill, the average of the oxidation over the whole site is obtained. The major drawback of the method is the cost for the sample preparations.

Advantages of isotope measurements

- An oxidation level for the whole landfill is obtained, spatial inhomogenity of the source is accounted for.

Disadvantages of isotope measurements

- The sample preparation is expensive.

4.6 Discussion

The applicability, advantages and disadvantages of the various methods to measure methane emissions are once again depicted in table 3.

Table 3: comparison of measurement techniques

technique	spatial resolution	temporal resolution	compo-nents	costs	experience (world-wide)	other advantages/draw-backs/ limitations
soil core	m^2	hour	CH_4, CO_2	high	few	especially suited for mechanistic studies of oxidation, possible interference with normal landfilling activities
closed chambers	m^2	hour	CH_4	high	many	many samples required to obtain emission from an entire landfill, possible interference with normal landfilling activities
mass balance	few ha	continuous	CH_4, CO_2	moderate	few	well-suited for automation
micro-meteorology	few ha	continuous	CH_4, CO_2	moderate	few	demonstrated not to be applicable
plume measurement	entire landfill	hour	CH_4	high	some	considered most accurate
isotope measurement	entire landfill	hour	$^{13}CH_4$	very high	some	intended to measure amount of oxidation

As described in chapter 4.1, the spatial variation in emissions is very high. Emissions at a single landfill site may vary over three orders of magnitude. Temporal variation is also of great importance and emissions may range significantly over a range of weeks. On top of that the annual variation in oxidation activity plays a role. When emission measurements are used to get data about annual emissions of a whole landfill site, the surface area sample and the temporal resolution of the selected measurement method are of utmost importance. Taking this in account, the following conclusions can be made about the various methods:

- When emissions are to be measured using closed chambers, the low spatial and temporal resolution request a large number of relocations (more than 30 a day) on several days throughout the year (no experience how many measurement days are required here). This makes this method very labour-intensive and very expensive.
- The mass-balance method seems to be better suited to measure emissions from larger surfaces during longer times. Its capability to measure CH_4 and CO_2 gives insight in the primary processes leading to emissions: methane formation and oxidation. For larger sites however, this method might bring about some problems and further developments are required to enable measurements from the whole of a larger landfill site. Developments might comprise the application of longer poles (16 meters poles are commercially available) and the application of more accurate CO_2-analysers. Draw-back of the mass-balance method is that since there is not so much experience with the method, validation might be considered a requirement.

Mobile plume measurements can be considered the most accurate method to measure emissions from an entire site. But the draw-backs of this method (complexicity, low temporal resolution and high costs of prolonged measurement campaigns) render this method not suitable to give a reliable impression of the annual emission.

- Since a mobile plume measurement gives an indication of emissions at a single day, its costs will in practice reduce its temporal resolution. But since the method is generally accepted as being accurate it might be the best method for validation of other methods.
- The last drawback of the mobile plume method may be avoided when a suitable stationary plume method can be developed.
- $^{13}CH_4$ -measurements are widely recognised for their applicability in quantifying the amount of methane oxidized in the top-layer, so this method might be the primary candidate to validate the suitability of the mass-balance method to get an impression of methane oxidation.

In conclusion: the best option to obtain a proper estimate for an annual emission level at a

certain location will be a method with a good resolution in time, in combination with spatial integrative techniques.
The mass balance method method can provide emission data of methane and carbon dioxide with a high spatial and temporal resolution and is therefore a good candidate. Another good candidate might be a low-cost system, derived from the stationary plume method.
Both methods however are not internationally accepted and need further validation. Mobile plume measurements seem to be a good candidate for validation of emissions. Isotope measurements can be applied to estimate the average oxidation effect at the landfill.

5 COMBINING VROMS AND AFVALZORGS INTERESTS

5.1 Contributing to the accuracy of the Dutch national estimate

At present the methane emission estimate of landfills in the Netherlands is based on a model calculation. The mean inaccuracy of landfill gas formation models for a single landfill from waste deposited before 1993 is approximately 20% (on the condition that accurate information is available of amounts and compostion of the waste, Oonk et al., 1994). Since the uncertainties of the sum of formation in a group of landfills decreases, average Dutch formation per tonne of waste in 1990 is assumed to be known with an accuracy of 15%. Amounts of waste in 1990 and the years before is also assumed to be about that accurate.

Due to the changing nature of landfilled waste the inaccuracy in amounts of methane produced per tonne of waste have increased. At the same time knowledge about amounts of waste landfilled has gained considerable accuracy. Observations of Afvalzorg support this hypothesis. It is assumed that the sum of both uncertainties at a national level have remained about the same. But in the near future, when waste landfilled after 1993 becomes dominant in Dutch national emissions, uncertainties will increase.

With regards to methane oxidation in top-layers, a 10% reduction factor is assumed according to default values provided by IPCC. Since scientific background of this figure is very poor, this figure has to be considered inaccurate. More recent information (e.g. Boeckx et al., 1996) indicate oxidation might even be as high as 60%. This could have an emormous impact on the accuracy of the methane emission. It might be overestimated by 30-50%.

Improvement of the landfill gas formation models might improve the accuracy of methane formation per tonne of waste from newer waste on Dutch landfills to about 15-20%. Since knowledge about amounts of waste are accurate, this automatically will result in accuracies in total emissions of the same order of magnitude. If more knowledge of oxidation could improve the inaccuracy of the oxidation to a similar level, the inaccuracy of the methane emission estimate would be significantly reduced.

Emission measurements at individual landfills will be about 25% accurate. Since the total inaccuracy of several inaccurate measurements decreases, it might be possible to obtain total Dutch methane emissions from landfills at about 10-15% accurate by measuring all individual landfills. To obtain an even lower inaccuracy continuous fence-line monitoring at all relevant landfills might be an apprioriate option. At this stage it is to early to comment on its technical and economical feasibility. By development, validation and evaluation of a stationary plume method it will be possible to determine the feasibilty of continuous fence-line monitoring.

5.2 Measurement related activities

In chapter 3 approaches are defined towards different targets: how the Dutch government can improve the existing methodology for emission inventory; how an emission inventory might be based on direct measurements and how Afvalzorg can improve its inventory. In all approaches, emission measurements play an important role. Below the measurement-related activities are summarised.

Table 4: Overview of measurement related activities

	Target	activity	measurement	prerequisites
1.2	improvement of existing methodology	development of method for determining landfill gas formation		methodology should be: • suited for its scientific purpose
1.3		validation of formation models	CO_2 and CH_4-emissions	site-selection: • waste amounts and composition must be known and representative
2.1		development of method for determining oxidation on a single landfill		methodology should be: • compromise between accuracy and costs • suited for its scientific purpose
2.2		validation of determining oxidation from CO_2 and CH_4-emissions	comparison CO_2 and CH_4-emissions with conclusions drawn from ^{13}C-measurements	site-selection: • a limited number of sites
2.3		measuring oxidation at several landfills	CO_2 and CH_4-emissions	site-selection
3.1	emission inventory based on measurements	development of suitable measurement method		methodology should be: • affordable • accurate (e.g. < 25%) • internationally accepted for monitoring purposes
3.3		continuous monitoring effort	CH_4-emission measurements. CO_2 might be required as well for base-line correction of emissions	site selection: • on basis of gas formation, e.g. > 1 $Mm^3\ yr^{-1}$
4.1	improving Afvalzorgs inventory	development of suitable measurement method		methodology should be • affordable • accurate
4.2		measuring Afvalzorgs landfills	CH_4-emission measurements. CO_2-emissions might provide additional information about degree of oxidation	site selection: • Afvalzorg owned

Developing suitable measurement methods and subsequently measuring CH_4 and CO_2-emissions is mentioned several times. But is the measurement method and the selection of locations where to measure the same for both parties and in every situation ?.

5.3 Choice/development of measurement method

In the table above a number of activities are defined, related to choice or development of a suitable measurement method. Criteria that are defined for this method differ:

- In activity 1.2, the method has to be suited for its scientific purpose: the validation will be used for the validation of formation models. Scientists and others working on validation of formation models are the first ones involved and the first persons to be persuaded. Since landfill gas formation models have an inherent inaccuracy, caused by natural variability and by uncertainties in input-data for the model, it is useless to strive for measurements with

much higher accuracy than the expected accuracy of a formation model.
- In activity 2.1, the method should be accurate to enable an estimate of oxidation at a single landfill. The resulting information has to be acceptable for scientists and others working in the field of oxidation.
- In activity 3.1, the method has to be acceptable for experts of IPCC and UN-FCCC. Proof that the new method is superior to existing methodologies for emission assessment, transparency of results and possibilities for base-line corrections (re-evaluation of 1990-emissions) are important requirements.
- In activity 4.1, the accuracy and applicability in the field (complexity, interference with daily activities) has to be sufficient for Afvalzorg.

Emission measurements using the mass-balance method or static plume measurements should in principle be able to meet all requirements. However validation of the method through comparison with other more accepted methods might improve the applicability of the mass-balance method under activity 1.2, 2.1 and 3.1. In activity 3.1, international discussion is required, whether direct measurements can be used in making an international inventory of emissions form landfills and what measurement method is preferred for this purpose. At the moment this discussion is not being held, nor at IPCC, UN-FCCC or in other groups.

5.4 Selection of locations

The citeria that are defined for the sites where measurements are being performed differ as well:
- In activity 1.3 landfill gas formation models have to be validated for newer landfills. For this purpose landfills have to be selected that are representative for Dutch landfills where waste is landfilled of changed composition and where sufficient background-data are available to make an accurate prognosis of methane formation using the existing formation models. Carbon content might be a criterion for this. Older waste typically contained 110-130 kg C per tonne waste, where the carbon-content is expected to drop to about 80 (60-100 kg C per tonne) in future waste.
- In activity 2.3 landill sites are selected where the expected methane flux is representative for landfills that contribute significantly to national methane emissions, so sufficient gas generation is a prime objective.
- In activity 3.3 landfills have to contribute significantly to total methane formation in 2010. Formation in excess of 1 million m^3 can be used as a criterion.
- In activity 4.2 sites have to be Afvalzorg-owned.

Table 5: Overview of Afvalzorg locations

location	waste characteristics	quality waste data	C-content (kg/tonne)	estimated 2010 formation
Braambergen	a.o. polluted soil, domestic waste, industrial waste, demolition waste	good	80	3,50 Mm³
Hollandse Brug	demolition waste, industrial waste, sludges	poor	70	0,87 Mm³
Nauerna	polluted soil, industrial waste, sludges	good	50	5,25 Mm³
Schoteroog	demolition waste household waste, industrial waste	poor	80	0,87 Mm³
Velsen	demolition waste; industrial waste	poor		0,4 Mm³
Wieringermeer	industrial waste	moderate	90	2,63 Mm³
Zeeasterweg	pollutedsoil, household waste	good	60	2,50 Mm³

Based on the criteria described above and this table, Braambergen, Nauerna, Wieringermeer en Zeeasterweg seem to be locations of Afvalzorg, where emission measurements also contribute to the objectives of VROM.

5.5 Conclusions

Activities, requirements of a measurement method and site-selection for meeting the objectives of VROM meet those of Afvalzorg to a large part:

- Both parties seem to be interested in developing an accurate and applicable method for measuring methane emissions and in both cases the mass-balance method and static plume measurements seem to be a good candidates.
- Validation of methane emissions with plume-measurements and oxidation with $^{13}CH_4$-measurements is primarily aiming at acceptation of the method by international scientists and seems therefore to be mainly of interest of VROM.
- 4 out of 7 Afvalzorg landfills seem to be suited for measurements, aiming at the objectives of VROM.
- Regarding validation of landfill gas formation models, 4 landfills is a rather small group and preferably 4-6 other sites should be identified as well.

6 HOW TO PROCEED

In the previous chapters it is argued that the activities to improve methane emission estimates of landfills on behalf of Afvalzorg and of the Dutch government (i.e. the Ministry of Housing, Spatial Planning and Environment (VROM)) are to a large part the same. Activities in a joint research and development trajectory might consist of the following consecutive and interrelated phases :

a) Further development of the mass-balance method to a method, suited for the purposes defined in this study. This phase consists of design, verification with parties involved, acquisition of components and construction of equipment. Time required is approximately 8 weeks.
b) Development of a stationary plume method. This phase consists of design, verification with parties involved, making a calculation model and comparison with the mobile plume method model, acquisition of components and construction of equipment. Time required is approximately 6 weeks.
c) Verification of suitability by a measurement campaign with methods developed under a) and b) on a well known landfill. During the campaign on three occasions mobile plume measurements will be carried out for comparison of the data. The results will be evaluated and reported. Recommendations for following phases or adaptations will be given. Time required is approximately 3 weeks for preparation, 8 weeks for the measurement campaigns and 3 weeks for evaluation and reporting.
d) Validation of measurements methods developed under a) and b), using the mobile plume method. A validation on three landfills also using the data acquired during phase c) is recommended. Validation thus preferrably is to combined with additional measurement campaigns as mentioned under c). The 4 Afvalzorg locations selected in chapter 5 are an obvious choice for phases c) and d). The results will be evaluated and reported. Time required is approximately 3 weeks for preparation, 4 weeks for the measurement campaigns and 3 weeks for evaluation and reporting.
e) Validation of oxidation obtained from the method under a) and b) using $^{13}CH_4$-emission measurements at one or more locations. The results will be evaluated and reported. Time required is approximately 4 weeks for preparation, 1 week for sampling, 3 weeks for laboratory measurements and 3 weeks for evaluation and reporting.
f) Publication of results and discussion with international experts to ascertain acceptance of the method(s). This phase comprises submission of abstracts and papers, preparation of presentations, presence at symposia and workshops and feedback on the conclusions of discussion with international experts. Time required is in the order of 5 to 6 weeks spread over a period of a year or longer.
g) Measuring methane and carbon dioxide emissions from a larger group of landfills using a method that seems acceptable to international experts. Time required for each landfill is approximately 3 weeks for preparation, 4 weeks for the measurement campaigns and 3 weeks for evaluation and reporting.
h) Validation of landfill gas formation models using the results of phases c), d), e) and g). This phase is meaningfull when data of phases c), d), e) and g) are available of at least 8 landfills. For this phase it is assumed that all the necessary data with respect to waste age, amounts, composition, landfillgas extraction etc. are made available by the landfill operator in a format as prescribed by the project team. Time required is approximately 1 week.
i) Publication of results and discussion with international experts to assure acceptance of the method(s). As in phase f) this phase comprises submission of abstracts and papers, preparation of presentations, presence at symposia and workshops and feedback on the conclusions of discussion with international experts. Time required is in the order of 5 to 6 weeks spread over a period of a year or longer.

It is recommended that the Ministry of Housing, Spatial Planning and Environment and Afvalzorg discuss nature and extent of phases a) to c) in order to define the boundary conditions for a proposal for a joint project. After completion of this project information on the practical applicablity of the methods will be available. The results can be used to adapt methods, to decide to continue or to abort methods, and to supply more detailed information about expected results of phases d) and e). This will facilitate a decision to continue the project. Phases d), e) and f) will supply information on the validity and reliabilty of methods and a first indication with respect to international acceptance. The evaluation of phases d), e) and f) will facilitate a decision to start a subsequent project involving phases g) to i) at more landfills of different landfill operators. Preferably the consortium of the earlier projects will act as initiator.

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