 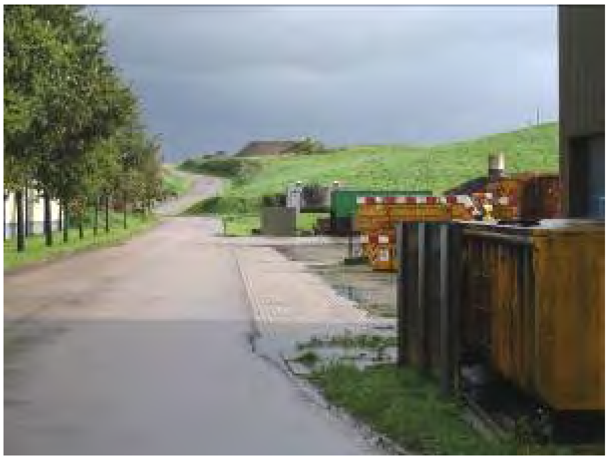

Feasibility study sustainable emission reduction at the existing landfills Kragge and Wieringermeer in the Netherlands

Generic report: Processes in the waste body and overview enhancing technical measures

Dutch Sustainable Landfill Foundation

20 March 2009

Final Report

9T6764

IFAS

Consultants for Waste Management

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1 INTRODUCTION

Environmental effects of landfills

When solid waste is landfilled, a number of biochemical and geochemical processes occur in the waste body, which can lead to undesirable and unacceptable emissions to the environment. So landfills can threaten the environment. On one hand landfill gas is generated, which may contribute to odour nuisance. Methane in the landfill gas contributes to global warming. On the other hand, organic components and heavy metals in the leachate might contribute to soil and groundwater pollution.

Current European policy on the landfilling of waste

The European Landfill Directive discriminates three classes of landfills: landfills for inert waste, for non-hazardous waste and for hazardous waste. For each class of landfill environmental protection measures and a set of acceptance criteria are given. Given the soil protection measures, the acceptance criteria were being calculated with a model in order not to pollute drinking water at a certain distance from a landfill.
The Landfill Directive was put into Dutch regulation in 2001. Annex II, in which the criteria are given, will be put into Dutch regulation shortly.

Current Dutch policy on the landfilling of waste

The current Dutch policy concerning modern landfills in the Netherlands is developed around 1990 and based on isolation of the waste from its environment after the operational period and is the same for all classes of landfills. Infiltration of rain water into the waste body, which causes a water flow through the waste body, is limited by means of an impermeable top liner to such an extent that emissions to ground- and surface water are reduced to acceptable levels. In addition measures to capture and process landfill gas have to be installed.
This approach however is not a sustainable solution. The pollution potential stays in place and will become imminent, whenever the isolation measures fails. Therefore the isolation requires eternal aftercare. The isolation measures on top of the landfill have to be kept in good condition and must be periodically replaced. The landfill operator is required to accumulate the necessary funding for isolation measures and to buy off the eternal aftercare.
Although it is Dutch policy to consider European law sufficient unless Dutch circumstances require stricter protection of the environment, the Dutch soil protection level was not adapted while putting the European Landfill Directive into Dutch regulation, because the acceptance criteria were still to be decided upon. The level currently given in the Landfill Decree is comparable to that for landfills for hazardous waste
Other soil protection regulations in the Netherlands have recently changed from strict prevention of pollution to a more risk based approach. Discussion on actualization of the Dutch landfill decree was recently started.

Sustainable landfilling of future landfills

A group of Dutch landfill owners, combined in the Dutch Sustainable Landfill Foundation (DSLF) consider isolation and eternal aftercare not a real and sustainable solution for the mitigation of unacceptable emissions due to landfills. They initiated a project 'Sustainable Landfilling' (lit. 1) to develop ways to reduce the emission potential of the waste, rather than just isolating the emission potential from the environment.

The goal of sustainable landfilling in terms of the European regulatory framework is to meet the emission thresholds for a landfill for inert waste within about 30 years as well as not to exceed the threshold values for groundwater quality. Main conclusion of this research (lit. 1) was that when biochemical and physical processes are allowed to complete, emission potential is reduced significantly. The project 'Sustainable Landfilling' however aimed at landfills, yet to be constructed and concluded with design rules for these future landfills.

Sustainability at existing landfills
The success of the project 'Sustainable Landfilling' led to the follow-up questions:

- *Is it possible to retrofit existing landfills in such a way, that they become more sustainable?*
- *Is it possible to stimulate the natural biochemical and geochemical processes at existing landfills?*
- *Does this also lead to a significant reduction of the potential emissions?*
- *Does this significant emission reduction also lead to admissible emission levels?*

If these questions can be answered positively, less stringent aftercare or discharge from aftercare would be possible. The DSLF is convinced that the EU Landfill Directive provides the possibility for aftercare that is tailor-made to the real risk of emissions from the waste body.

Initiative and main goal
In order to answer the above mentioned questions, the DSLF took the initiative to evaluate the possibilities and effects of sustainable landfill-methodologies at existing landfills. The main goal of this initiative can be formulated as follows:

The full scale demonstration of sustainable emission reduction at one or more existing landfills in the Netherlands

An independent risk analysis is essential for the assessment of the achieved extent of the sustainable emission reduction and the corresponding remaining emission potential. So the results of the demonstration project have to contribute to the creation of an accepted risk assessment method that includes both environmental and geotechnical aspects.

Within that framework the DSLF requested the Dutch landfill owners to submit landfills, which meet the requirements for a suitable landfill site as described in the Terms of Reference (annex 1). Finally two landfills could be selected:

- the landfill "Wieringermeer" in the province of North-Holland (NL) and owned by the landfill operator Afvalzorg;
- the landfill "Kragge" in the province of North-Brabant (NL) and owned by the landfill operator Essent Environment South.

Besides the technical requirements, these two landfills also comply with two other important conditions, which are:

- the willingness of the landfill owner to invest in the demonstration project.
- consent and approval of the competent authorities (provinces of North-Holland and North-Brabant) with respect to the selected pilot landfills.

The first step of the initiative is the execution of a feasibility study with respect to the suitability of the two selected landfills. The present generic report is a part of this feasibility study.

2 OBJECTIVES FEASIBILITY STUDY

The primary goal of the feasibility study is to draft a well substantiated project proposal for the two demonstration landfills Wieringermeer and Kragge, that comprises generic as well as site-specific aspects.

2.1 Generic objectives

- Description of the biochemical and geochemical **processes** occurring in the waste body with respect to microbiological requirements for degradation in waste bodies.
- **Development** of a **data analysis methodology** to analyse available data time series of leachate and biogas of the two pilot-landfills.
- An **overview** and assessment of often applied and proven **methods and technologies** in the Netherlands, Europe and the rest of the world (i.e. worldwide) for measures to stimulate and/or accelerate these natural processes in the waste bodies. It concerns infiltration and/or recirculation of water and/or leachate as well as injection of air (aeration), but also stimulation of moisture transport, pre-treatment of leachate before infiltration, etc.
- Establish which **environmental and geotechnical risk assessment** methods are suitable for the evaluation of potential emissions. Establish which types of results are required to substantiate such a risk assessment method.

2.2 Site specific objectives

- **Application** of the developed **data analysis methodology** to analyse available data time series of leachate and biogas of the two pilot landfills in order to establish a reference situation and to confirm or not the suitability of the two selected landfills as a pilot landfill.
- **Forecast** to the long term developments of leachate quality and biogas-production by means of extrapolation of the reference situation as well as by means of modelling.
- Draft design of a **basic project plan** at both pilot-landfills with respect to measurements and tests, which are able to stimulate/accelerate the occurring natural biochemical and geochemical processes (infiltration, recirculation, aeration).

- Draft design of a **research, measurement and monitoring protocol** (key performance indicators). Think of geophysical investigation methods, nutrient dosage, etc. It is extremely important to have a proper set of measurements to establish the situation before starting the stabilisation project (reference situation) to be able to determine unambiguously the reductions in potential emission due to the applied measures during the execution of the pilot-landfills.
- Determination of a draft **project budget** to support the investment decision by the operators of both pilot-landfills.

3 BASIC APPROACH OF FEASIBILITY STUDY AND DELIVERABLES

The basic approach is outlined in figure 3.1, which comprises three main parts of the feasibility study.

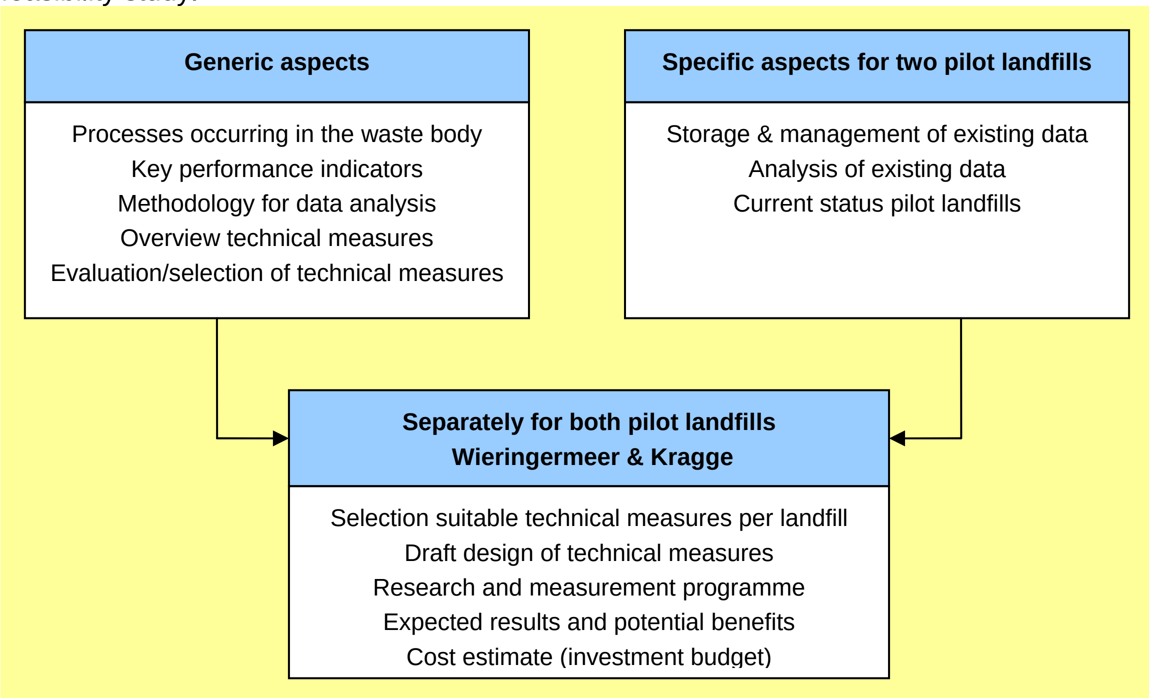

Figure 3.1: Basic approach feasibility study

These three main parts correspond to the required final deliverables, which means the following three section reports:

1. Generic report, comprising a general description of natural processes in the waste body and a general overview of technical measures to be able to enhance these processes.
2. Specific reports, separately for both demonstration landfills, comprising a description of the current status of the landfill with respect to emission potential and stabilization process (reference situation).
3. Specific reports, separately for both demonstration landfills, comprising a preliminary design of enhancing technical measures, a forecast of the achievable level of emission reduction due to autonomic and enhancing developments, and measurement program and cost estimate.

This document represents the generic report.

4 STARTING POINTS AND LIMITING CONDITIONS

1. The effect of the applied technical measures should be visible at short notice (3 to 5 years); the measurement protocol should be based on that target. This can not be guaranteed in advance, because it depends on the site specific conditions to what extent the final state of a mineralized waste body poor in emission will be reached.
2. The project aims at reduction of potential emission. Emission reduction down to acceptable emission levels may not (always) be achievable. In that case it is acceptable to rely on NA-processes in the downstream groundwater plume influenced by leachate. However, NA in the downstream groundwater is not a part of the feasibility study in this stage.
3. Analysis of chemical data with respect to waste and groundwater is not included in the feasibility study.
4. The required overview, evaluation and assessment of technical measures, which can stimulate/accelerate the occurring natural biochemical and geochemical processes in the waste body is based on knowledge and experience, present with the client, contractor (Royal Haskoning and IFAS) and involved external specialists.

5 ORGANIZATION OF THE PROJECT

In the assignment of the DFSL, represented by Mr. Hans Woelders as the chairman of the project group, the feasibility study is executed by the Dutch consultant Haskoning Nederland B.V., a company of Royal Haskoning in Nijmegen (NL), in cooperation with the German consultant for Waste Management IFAS (Ingenieurbüro für Abfallwirtschaft, Prof. R Stegmann und Partners) in Hamburg (D).

Royal Haskoning is the main contractor and carries the final responsibility for the management, the coordination and the (technical) deliverables of the feasibility study. IFAS operates as the subcontractor of Royal Haskoning. From a technical point of view the contribution of IFAS has been focussed to their knowledge and experience with the design and execution of technical measures to stimulate/enhance the natural biochemical and geochemical processes in the waste body (infiltration, recirculation, aeration, etc.).

The feasibility study comprises different activities and each activity requires specific competences. Therefore it was important to mobilize all relevant knowledge and experience available in the project group and the core team of the DFSL. For this reason the feasibility study has been supervised by members of both project group and core team, which played an active role in supporting the project team of Royal Haskoning/IFAS by contributing to specific activities each on their specific competences.

The composition of project team, core team and project group is presented in annex 2.

6 PROCESSES IN THE WASTE BODY

6.1 Basic mechanisms in the waste body

Organic matter (organic carbon) in the waste body plays a key role in the emission potential of a landfill. This organic matter, mainly present in disposed domestic waste and organic waste (vegetables, fruit, garden waste), will be degraded in time by various types of micro-organisms. The degradation of organic matter will only occur and proceed in the presence of sufficient moisture content and moisture transport. So the presence of water is a prerequisite for the degradation of present organic matter. Figure 6.1 schematically shows the basic mechanism of processes and emission potential (products), which is explained hereafter and in more detail in the next chapters.

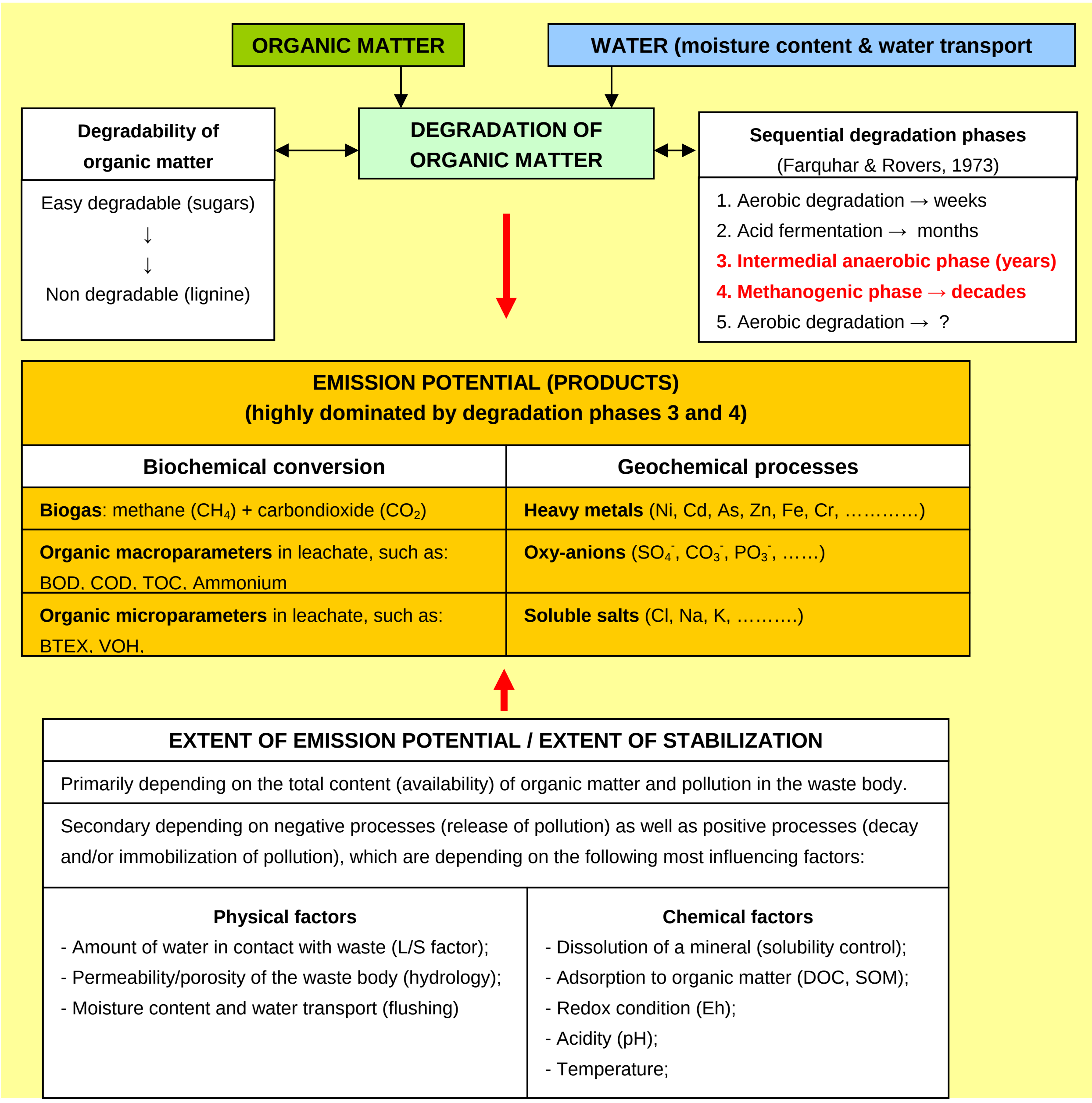

Figure 6.1 Basic mechanism of processes in the waste body and emission potential (products)

Sequential degradation of organic matter

The degradation of organic matter itself is the driving force behind the emission potential of organic dictated landfills. Degradation of organic matter by specific micro-organisms takes place according to certain sequential phases from the very start of disposed waste to decades after closing the landfill (figure 6.1, 5-phase model according to Farquhar & Rovers, 1973). Each stage has its own characteristics with respect to geochemical and biochemical conditions of the leachate in which all kinds of macro- and micro components can be:

- dissolved and/or precipitated,
- adsorbed to organic matter and/or clay particles
- converted into biogas,
- degraded into other (un)hazardous compounds

The first two phases of degradation process of organic matter (aerobic degradation and acid fermentation) are very short in time (several months) and therefore hardly contribute to the emission potential. So the most lasting methanogenic phase (decades) in particular is highly dominating the emission potential. It is also the phase in which the economically profitable collection of biogas takes place, due to anaerobic degradation of organic matter. It is obvious that the potential emission of a landfill, consisting of leachate and biogas, is determined by a complex of physical and chemical factors.

Degradability of organic matter

The presence, quantity and variety of organic matter in the waste body are depending on the type of landfilled waste. The present organic matter consists of a range of easy degradable components (sugars, proteins) up to slower and non degradable components (lignine, humic substances).
In ideal conditions only a part of the present organic matter is degradable and will be converted into biogas. This biochemical conversion process (methanogenic phase) is also responsible for the release of organic macro parameters in the leachate (BOD, COD, ammonium)

During decades the slowly and non degradable organic matter will be converted into stable components by means of a kind of “peat formation process”. Heavy metals and organic micro parameters (BTEX, VOH) will be immobilized by sorption to these stable organic components. Therefore the slowly and non degradable organic matter contribute to the sustainable emission reduction.

Emission potential (products)

The emission potential can be subdivided into different products, due to biochemical conversion processes and geochemical processes, which are:

Table 6.1 Emission potential in terms of products

PRODUCTS	
Biochemical conversion	**Geochemical processes**
▪ Biogas (methane and carbon dioxide) ▪ Organic macroparameters (BOD, COD, TOC, NH_4 ..) ▪ Organic microparameters (BTEX, VOH, ……)	▪ Heavy metals (Ni, Cd, Zn, Fe, Cr, …) ▪ Oxy-anions (SO_4^-, CO_3^-, PO_3^-, ……..) ▪ Soluble salts (Cl, Na, K, …….)

Once all present degradable organic matter is (an)aerobically converted, the emission will be reduced to the maximum extent and the maximum stabilization of the waste body has been reached. At that point the quality of the leachate should be compared to the relevant threshold values in order to determine whether sustainable emission reduction has been reached or not.

Extent of degradation

The extent of degradation of organic matter is depending on site-specific conditions with respect to the type and distribution of organic matter in the waste body as well as the presence and distribution of moisture in the waste body. For example easily degradable organic matter in combination with sufficient moisture will probably be fully degraded, while difficult degradable organic matter in combination with a lack of sufficient moisture will not or hardly be degraded.

Because the waste body is considered to be very heterogeneous with respect to the distribution of degradable organic matter as well as of moisture, the goal is to reach the most feasible extent of degradation, which can result in admissible emission levels of leachate and biogas.

As an example for the leachate emission, this main approach and goal has been visualized in figure 6.3, in which the degradation processes have been presented in four phases of the stabilization progress, being:

1. at the start of the exploitation of the landfill, highest contaminated leachate.
2. during autonomic processes a decrease of leachate concentrations takes place.
3. during enhanced degradation processes by applying technical measures[1], further decrease of leachate concentrations takes place.
4. most feasible extent of stabilization has been reached, which results in the most feasible reduction of leachate concentrations. It must be questioned whether these final concentrations meet the admissible emission levels.

If the finally achieved leachate concentrations (stage 4) are still exceeding the admissible emission levels with respect to groundwater, an environmental risk assessment (source-path-receptor approach) with respect to groundwater will determine the necessity of mitigating measures in case leachate migrates into the groundwater due to leakage of the bottom liner. Depending on the local situation, also Natural Attenuation processes (NA-processes) [2] might be able to reduce the concentrations in the groundwater plume to admissible concentration levels with respect to environmental and human risks. However, these NA-processes outside the waste body are not part of the feasibility study in this stage.

---

[1] The autonomic degradation process can be enhanced by applying technical measures such as infiltration/recirculation of leachate into the waste body and aeration of the waste body (see chapter 7 and 8 for more details)

[2] Natural Attenuation (NA) represents all natural processes in the waste body as well as in the downstream groundwater plume, influenced by emitted leachate, which are able to reduce/neutralize concentrations of contaminating compounds to admissible concentration levels with respect to environmental and human risks. These NA-processes are dominated by microbiological decay, chemical precipitation and sorption to organic matter and/or silt particles.

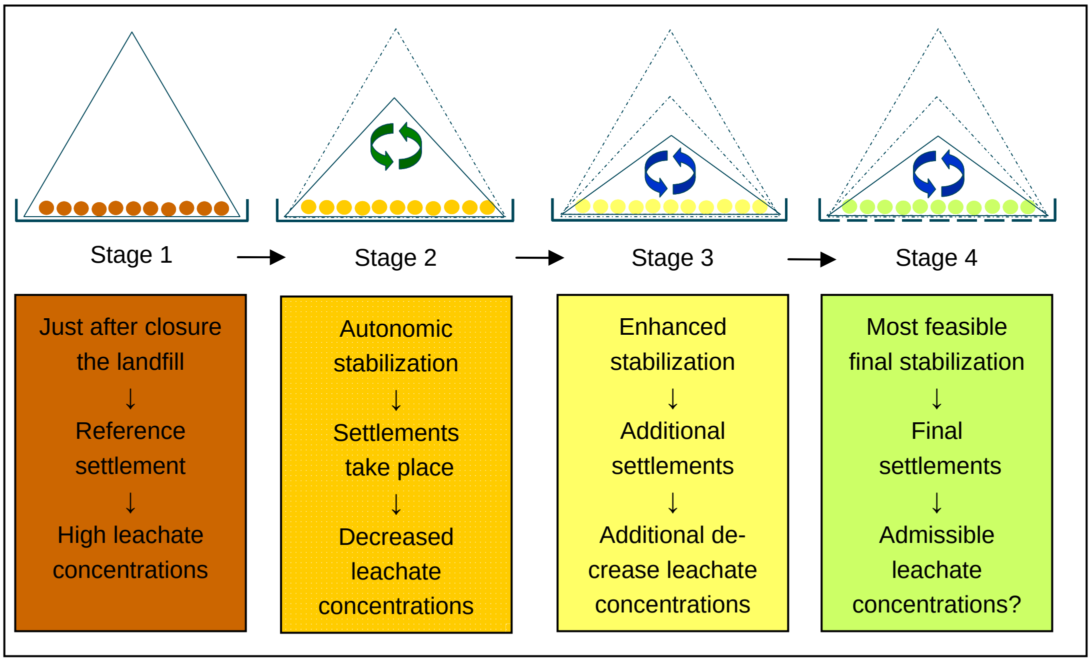

Figure 6.3 Progress of stabilization of organic matter and impact on leachate and settlements

6.2 Biochemical processes

6.2.1 Degradation of organic matter

As stated in the previous chapter, degradation of organic matter by specific micro-organisms takes place according to certain sequential phases from the very start of disposed waste to decades after closing the landfill. The most important and most lasting stage is the methanogenic phase (the green shaded phase 4 in table 6.1), in which the economically profitable collection of biogas takes place. The following phases are distinguished, according to the common applied 5-phase model of Farquhar & Rovers (1973) as presented in table 6.1.

Table 6.1 5 phase model of degradation of organic matter (Farquhar & Rovers, 1973)

Phase	Name	Main characteristics	Time frame
1	Aerobic degradation	Short initial period, dominated by aerobic degradation, consuming the oxygen that ended up in the waste during deposition in the landfill. The amount of leachate generated in this phase is not substantial.	weeks
2	Acid fermen-tation	When oxygen is consumed, conditions turn anaerobic. As solid organic matter (SOM) can not be absorbed by micro-organisms, processes are hydrolysis of SOM into dissolved organic matter (DOC) and biological con-version of DOC to volatile fatty acids (VFA). A variety of fermentation pro-ducts end up in the liquid phase. VFA and ammonium (NH_4) predominate in the leachate and the content of nitrogen (N_2) in bio-gas diminishes as it is displaced by hydrogen (H_2) and carbon dioxide (CO_2).	months
3	Intermedial anaerobic phase	When conditions turn more and more anaerobic, methane-forming bacteria evolve, starting to convert small organic molecules (mainly VFA) to methane (phase 4). This process is considered as a transition phase from acid fermentation to the next phase of methanogenesis with a steady growth of methanogenic bacteria. As the growth of methanogenic bacteria is initially suppressed by the acidic environment, it usually takes some time for them to develop and dominate the system. Methane concentration (CH_4) increases slowly with a decrease in hydrogen (H_2) and carbon dioxide (CO_2). Ammonium (NH_4) is still produced in the leachate.	years
4	Methano-genic phase	The methanogenic bacteria have overcome the acidic environment and this phase is characterised by a steady methane (CH_4) production. Hydrolysis and acetogenesis still occur in this phase, but methanogenesis is fast and as a result concentrations of VFA in the leachate are kept low. The compo-sition of leachate is characterised by a close-to-neutral pH value, a low concentration of VFA, and a reduced amount of total dissolved solids. Thus, the high leachate concentrations from the preceding acid production are weakened by this methanogenic process. The ammonium concentration still remains significant, also due to the degradation of dead methanogenic biomass. Methane-forming bacteria are the key organisms in the anaerobic conversion process. They produce methane (CH_4), a gas that escapes spontaneously from the liquid phase. The methane concentra-tion will be around 50 to 60% by volume with the rest being mostly carbon dioxide. The extent of anaerobic degradation of organic matter can be in-creased by applying infiltration/recirculation of leachate in/through the waste body (see chapter 7).	decades
5	Long term aerobic degradation	At the end of the previous phase all reachable organic matter is anaerobi-cally degraded and a certain extent of stabilization has been achieved. Still aerobic degradable organic matter is present in the waste body, because phase 1 was too short for a 100% aerobic degradation rate. This means that an emission potential is left. Although there is a lack of long term scientific data related to this phase, it is generally assumed that only the outside borders of the waste body will evolve towards an aerobic condition by intrusion of outside oxygen. The depth at which such aeration may progress, or whether it will occur at all, depends on specific landfill conditions such as moisture content and final cover. Reduction of emission in the inner part of the waste body can be reached by applying aerobic in situ aeration (see chapter 8).	?

Besides the production of biogas in the methanogenic phase, also all kinds of macro- and microparameters release, disappear, increase and decrease during the different phases. In figure 6.4 the development of characteristic parameters during the five degradation phases are visualized for biogas and leachate macroparameters.

The biochemical and geochemical conditions in the waste body, due to the degradation process of organic matter, are also influencing the emission potential of present micro-contaminants, which have been disposed along with the waste and/or have been included in the disposed waste. It concerns heavy metals and organic compounds. Figure 6.4 indicates the degradation phases and NA-potential for these micro-contaminants in the waste body, that contributes to a sustainable emission reduction of micro-contaminants.

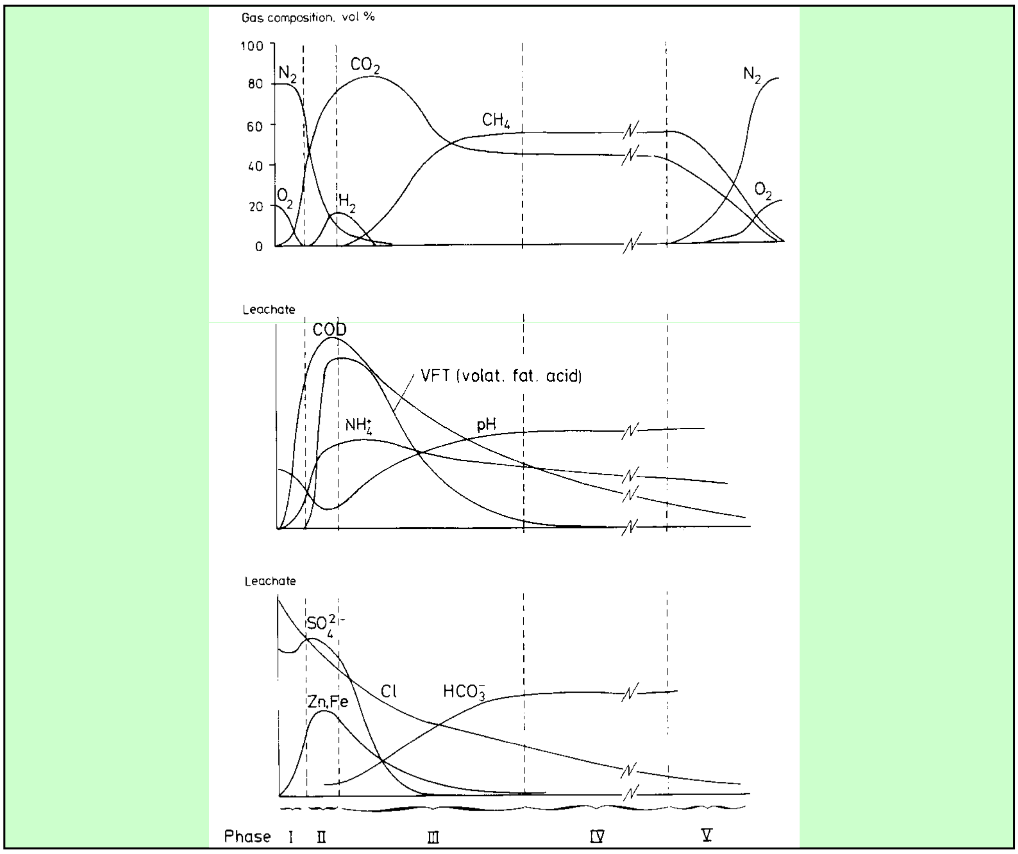

Figure 6.4 Degradation phases and developments in gas composition & macro parameters in leachate (Farquhar & Rovers, 1973)

	Phase 1 Aerobic	Phase 2 Acidification	Phase 3 Anaerobic transition	Phase 4 Methano-genic	Phase 5 Aerobic (borders) Anaerobic (inside)
Heavy metals	Partial leaching and emission		Chemical precipitation		Partial leaching (borders) Precipitation (inside)
	Sorption to solid non degradable organic matter (SOM) and silt particles → immobilization				
		Sorption to DOC → emission			
Aerobic degradable organic micro-parameters	Fast decay		Slow decay		Process of decay uncertain
	Sorption to solid non degradable organic matter (SOM) → immobilization				
Anaerobic degradable organic micro-parameters			Fast decay		Process of decay uncertain
	Sorption to solid non degradable organic matter (SOM) → immobilization				

Figure 6.5 Degradation phases and NA-potential for micro-contaminants in the waste body

A more specific and detailed scheme of the different degradation phases and the consequences of it for the emission products during the different phases, has been attached as annex 3.

6.2.2 Spatial distribution of organic matter.

It is generally accepted (lit. 1) that the waste body of existing landfills should be considered as very heterogeneous with respect to the distribution of organic matter. The organic matter consists of relatively easy degradable components to non degradable components on a sliding scale. In order to be able to come to a clear and understandable conceptual model of the processes in the waste body (see chapter 6.4), the degradability of organic matter has been simplified into three categories:

- easy degradable organic matter, like sugars and proteins.
- difficult degradable organic fraction, like (hemi)cellulose.
- non degradable organic fraction, like lignin.

Various types of waste have been disposed in various amounts over long periods. The result is a very heterogeneous spatial distribution of the three categories of organic matter within the waste body, without knowing the exact spatial positions. This has been modeled and visualized in figure 6.6. It has to be emphasized that the boxes in figure 6.6. are conceptual and are not reflecting the scaled model distribution of organic matter in the actual situation in the landfill.

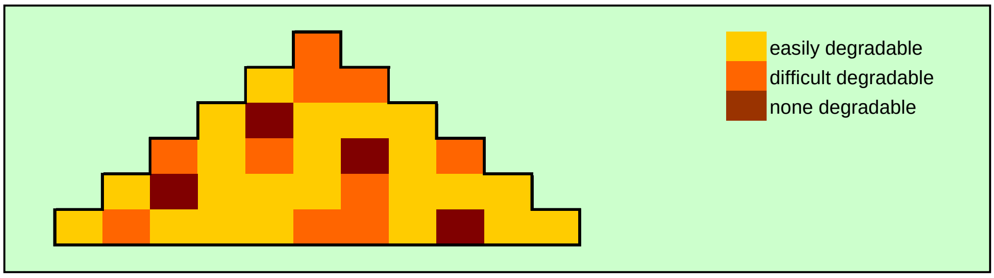

Figure 6.6 Conceptual model of heterogeneous spatial distribution of organic matter in the waste body (the showed boxes are not reflecting the scaled model distribution of organic matter in the actual situation in the landfill)

6.3 Geochemical processes

6.3.1 Basic chemical mechanisms

Three different chemical mechanisms control the release of contaminants (heavy metals, oxy-anions, salts) in the waste body:

1. the dissolution/precipitation of a mineral phase (**solubility control**):
2. the adsorption processes (**sorption control**):
3. the dissolution of soluble compounds in the waste material (**availability control)**:

Solubility control
Dissolution and/or precipitation processes of mineral phases control the acidity (pH) and the leaching of in particular major elements (e.g. Ca, Mg, Si) from waste materials. In addition, these processes may also control the leaching of minor elements (e.g. Cd, Mo, Pb, Zn) from waste materials (in addition to sorption controlled leaching, see below). The dissolved concentrations of contaminants in the leachate are then determined by the solubility of a specific mineral that governs the leaching behaviour. For example, the solubility of Zn might be determined by the solubility of the mineral phase zincite (ZnO), $Zn(OH)_2$ or $ZnSiO_3$. The leaching of contaminants that are controlled by mineral solubility is often strongly dependent on the pH of the leachate and the leached concentrations have no clear relationship with the total concentration in the waste material.

Sorption control
Heavy metals show affinity for adsorption to reactive surfaces such as organic matter (in the form of humic substances) and oxide surfaces (iron-oxides, aluminium-oxides). In case of organic matter a strong distinction must be made between solid organic matter (SOM) and dissolved organic matter (DOC). Sorption to SOM means that the heavy metals are immobilized in the solid phase, sorption to DOC means emission of heavy metals by means of water transport through the waste body.

Availability control
The total content of contaminants in the solid waste material has only a limited influence on the total leachable amount of the contaminants. This applies specifically to heavy metals and oxy-anions, because the release of these contaminants is primarily caused by geochemical mechanisms (e.g. sorption to DOC and pH) and physical factors (e.g. water transport).

Exceptions are soluble salts, of which the maximum leached amount over time is often similar to the total amount present in the waste material. Examples are the very soluble salts such as NaCl. Upon contact with water they will dissolve instantaneously and quantitatively. Those elements are availability controlled, as the total available concentration can be released from the solid waste material.

6.3.2 Acidity (pH) as the main influencing factor

The pH of the waste material and the pH of the leachate are crucial in determining the release of many contaminants. The pH value of the leachate determines the maximum water phase concentration at that pH value. Each constituent has its own pH-dependent release curve. Release curves are similar and systematic for different groups of elements. Figure 6.7 shows the general shape of the release curves of three groups of constituents, being salts, cations and anions. The strong influence of pH on the release is because the dissolution of most minerals as well as sorption processes (to oxides and organic matter) are pH dependent, which only applies to cations and anions (heavy metals and oxy-anions). It is clearly shown that the release of salts is pH-independent. Salts are availability controlled, as the total available concentration can be released from the solid waste material. The pH value of materials varies greatly. Cement-based materials (e.g. stabilized waste) superimpose a pH of around 12 (or higher) to its environment (leachate), whereas organic dictated landfills superimpose a predominating pH of around neutral (pH 6-8) during the most lasting methanogenic phase (decades).

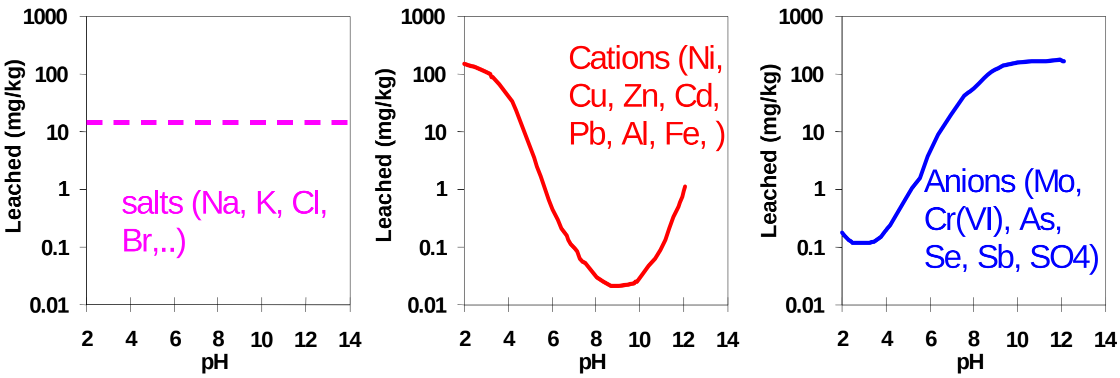

Figure 6.7 General leaching behaviour of three groups of constituents as a function of pH.

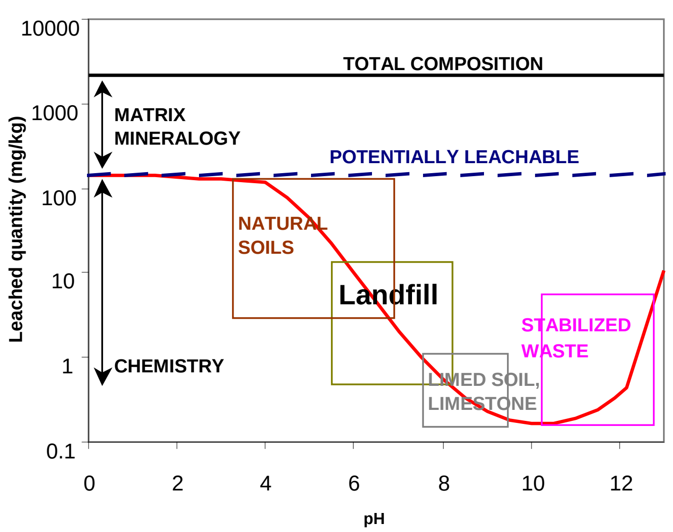

Figure 6.8 Standard presentation of leached quantity in mg/kg as a function of pH

Figure 6.8 shows a standard presentation and interpretation of results from a pH dependence leach test, expressed as released quantity from the waste material in mg/kg. The red curved line illustrates a release curve of a metal cat-ion. Note that there is a considerable difference between the total con-tent of the constituent in the waste material and the amount that is available for release (available = potentially leachable). The different pH values found in specific environments (soil, landfill, etc.) are indicated with boxes.

6.3.3 Geochemical speciation of contaminants

As stated in chapter 6.3.1, the potentially leachable amount of constituents from the waste material is significantly lower than the total amount in the waste material (exception are salts). The potentially leachable amount is used as an input parameter in geochemical model calculations (e.g. with the LeachXS database/expert system of ECN) to predict the leaching behaviour of waste materials. This is illustrated in figure 6.9 as an example of measured and predicted leaching behaviour as a function of pH versus total composition (in this example Ca).

The measured leaching data from a laboratory pH-static leaching test is represented as a function of pH by the red dotted data points. The black solid line represents the predicted total concentration of the considered element in solution (Ca in this example), which should ideally meet the red dotted measured data points. The upper line shows the total leachable concentration that can be released from the waste material. The red dashed box indicates the predominating pH-range in landfills.

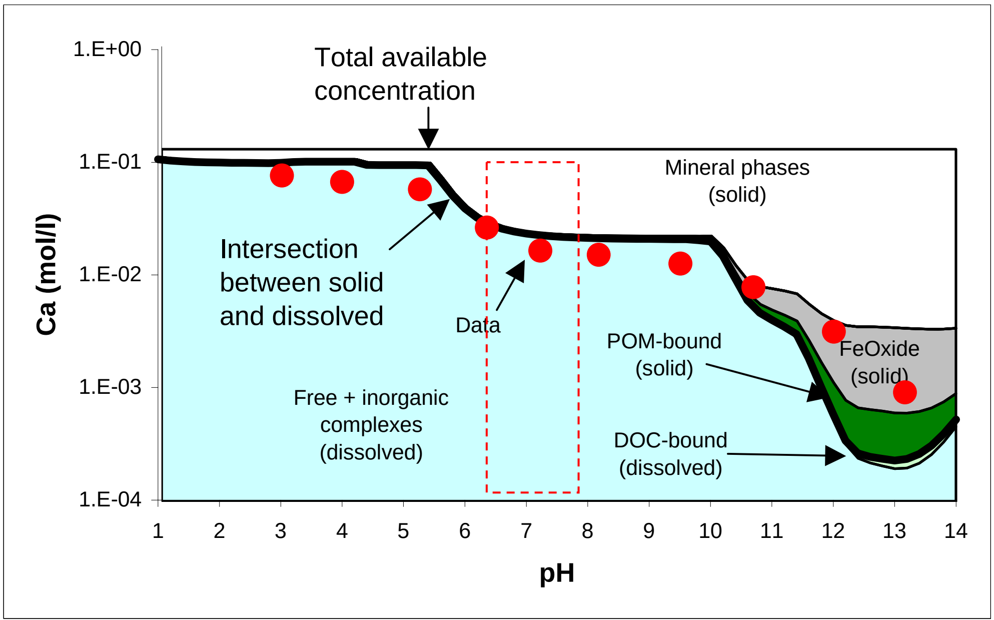

Figure 6.9 Leached concentration of Ca as a function of pH and (geo)chemical speciation of Ca in the solid matrix (above the black solid line) as well as in solution (below (below the solid black line).

Figure 6.9 also shows the calculated chemical speciation of the element in both the solid matrix and in the leachate. The general speciation of contaminants in the solid phase and in the leachate of waste materials is presented and specified in table 6.2.

Table 6.2 General speciation of contaminants in the solid phase and in the leachate of waste material. The major phases and species are specified according to figure 6.9.

SOLID PHASE	DISSOLVED (LEACHATE)
Mineral phases (e.g. CuO, $Pb(OH)_2$) White area in figure 6.9	**Free ion** (e.g. Cu^{2+}, Pb^{2+}) Light blue area in figure 6.9
Bound to solid organic matter Dark green area in figure 6.9 (complexation to solid organic matter (SOM)).	**Inorganic complexes** (e.g. $[Pb(OH)_4]^{2-}$) Light blue area in figure 6.9
Adsorbed to Fe/Al-(hydr-)oxides Grey area in figure 6.9 (Fe-oxide sorption)	**Complexed to DOC** Light green area in figure 6.9 (complexation to dissolved organic matter)

6.3.4 Crucial leaching parameters in the landfill situation

The main parameters by which leaching from waste material is dominated and might be influenced are:

- Acidity (pH)
- Redox condition (Eh)
- Dissolved organic carbon (DOC)
- Liquid/Solid ratio (L/S ratio)

Acidity and redox condition

pH and Eh in the waste body are more or less fixed parameters during the predominating methanogenic phase. This means a pH of around neutral (6-8) and methanogenic redoxconditons, which can be considered as favourable for the chemical precipitation of heavy metals. So during the anaerobic degradation of organic matter during the most lasting methanogenic phase, the pH and Eh will remain stable.

Dissolved organic carbon

The presence of DOC can enhance leaching of inorganic and organic contaminants by at least an order of magnitude. Heavy metals will bind to DOC (DOC-complexation) and more DOC causes increased leaching at neutral pH. In the presence of sufficient water transport in the waste body, DOC-bound heavy metals are contributing to the emission potential. During the methanogenic phase the DOC-concentration will decrease over time. At the end of the methanogenic phase all reachable anaerobic degradable organic matter has been stabilized, which means that DOC will not be formed anymore. As DOC is not easily flushed DOC can still mobilise metals and organic contaminants until this fraction is washed out. Then DOC has been dropped to levels at which metal (and organic pollutant) binding is still occurring, but at a level that is not critical from a regulatory perspective.

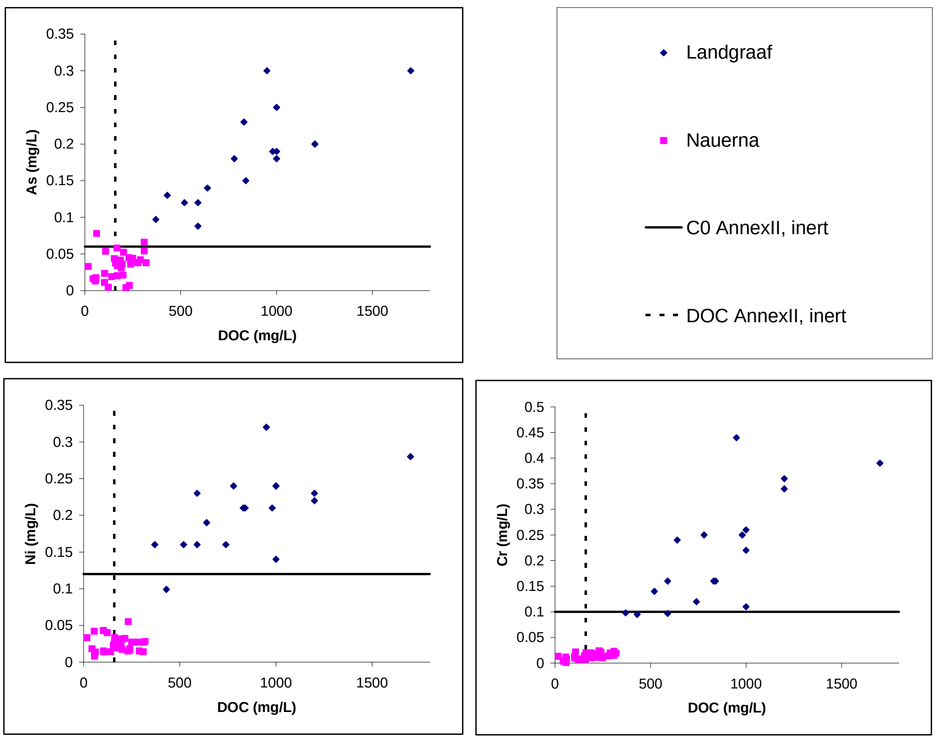

Figure 6.10 Metal concentrations (As, Cr and Ni) as a function of the DOC concentrations of the bioreactor pilot (Landgraaf) and the predominantly inorganic waste (Nauerna) pilot experiments.

This effect is demonstrated in figure 6.10 by plotting the metal concentrations (As, Cr and Ni) as a function of the DOC concentrations of the bioreactor pilot (Landgraaf, NL) and the predominantly inorganic waste (Nauerna, NL) pilot experiments.

The solid horizontal line represents the leaching limit value (C_0 concentration as the first eluate of percolation test at L/S = 0,1 l/kg) specified in the Annex II of the EU-landfill directive for acceptance of waste at an inert waste landfill. The dashed line represents the C_0 concentration for DOC. Figure 6.10 shows that the As, Cr and Ni concentrations in the bioreactor pilot are substantially correlated to the DOC concentrations. This observation was also made by Luning et al. (2006). The correlation is not so clear for the Nauerna data, suggesting that DOC plays a less important role in the leaching of these contaminants at the significantly lower DOC concentrations in this pilot experiment. Although these results are indicative, it might be concluded that the DOC concentrations in the landfill need to be lower than about 500 mg/l to reduce the metal concentrations to values below the C_0 concentration limit value in the Annex II for acceptance of waste at an inert landfill.

These observations will probably be also true for organic contaminants that show affinity for DOC adsorption, although there is less quantitative data available for these contaminants.

Liquid-solid ratio

The L/S ratio means the amount of water in contact with the waste material, expressed in L/kg. It will be clear that the higher the L/S ratio, the more constituents are released from the waste material up to the maximum leachable amount which is the potentially leachable amount of an element from the waste material at a given pH. This is illustrated in figure 6.11 for the anion fluoride and the soluble salt chloride from a MSWI bottom ash as a function of the L/S ratio at a the native pH of the material. For soluble salts, which readily wash out, concentrations decrease rapidly as a function of L/S ratio. For the anion fluoride a constant concentration is measured in each time interval (mg/l), which leads to a 1:1 slope in a cumulative leaching curve.

In an actual landfill with a height of 15m and an average infiltration of rainwater of 300 mm/yr during a time period of 25 years as an average time period for the methanogenic phase, the L/S ratio will be 0.5. The L/S ratio can be influenced by means of infiltration and or recirculation of leachate into the waste body.

Depending on the infiltration capacity and the permeability of the waste body, it has been demonstrated in various full scale pilot projects, that infiltration rates of 1000 - 1,500 mm/yr can be achieved. Based on the above mentioned landfill specifications, the L/S ratio will increase to 2.2 – 3.0 (including the natural rainfall of 300 mm/yr).

It can be concluded that also from a geochemical point of view, infiltration/recirculation of leachate into the waste body contributes to sustainable emission reduction, because:

- the enhanced L/S ratio results in a decrease of potentially leachable elements in the waste material.
- the DOC-concentrations in the leachate as a means of transport for DOC-bound heavy metals will decrease more rapidly to a minimum level at the end of the methanogenic phase.

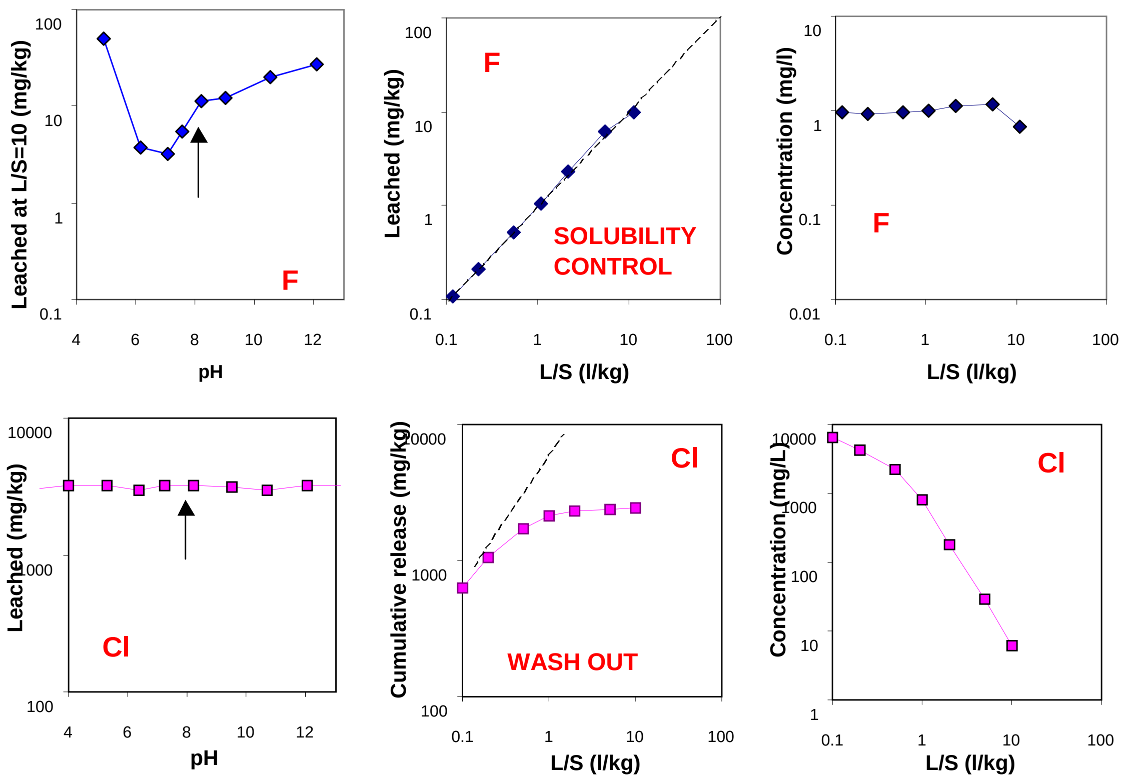

Figure 6.11 Data from a column leaching test on MSWI bottom ash at fixed pH

6.4 Hydrological processes

As long as an impermeable top liner is lacking, rain water infiltrates in the waste body and percolates through the waste body downwards to the leachate drainage system. Within the hydrological model it is generally accepted (lit. 1) that moisture content and transport of water to the drainage system take place according to the triple porosity model by distinguishing the following three zones:

1. Stagnant zones: negligible moisture content (only initial moisture content of the waste before disposal) and transport of water.
2. Mobile zones: slow transport of water.
3. Preferential channels: fast transport of water.

A certain percentage of the water transport (i.e. water-dissolved compounds) is covered by preferential channels. Exchange of water-dissolved compounds between the stagnant zones and mobile zones takes place by the process of diffusion. The moisture content in within the mobile zones and stagnant zones is not exceeding the field capacity of the waste, which means a non-saturated environment. The field capacity is the maximum moisture content at which all water, against the laws of gravitation, is retained by the waste.

Next to the described three zones, a small fully saturated zone is generally present at the bottom of the waste body, caused by accumulated rainwater to be discharged by the leachate drainage system.

Because of the various types of waste, which have been disposed over long periods, the hydrological conditions in the waste body are very heterogeneous. Besides, due to the disposal techniques (layer by layer) and by compaction these layers, the waste body is stratified. This is the reason that with respect to water (and also to biogas) the horizontal permeability is higher than the vertical permeability. As a consequence the water in the waste body is horizontally migrating until a location has been reached with a less vertical resistivity.

Last but not least it has to be mentioned that at high rates of landfill gas production, the pores in the waste are mainly filled with landfill gas. This means a decrease of pore volume that is available for water and as a consequence an increase of resistivity with respect to water flow. Conversely you can say that the flow of water will decrease the permeability for landfill gas. Landfill gas and water are each others opponents.

This all mean big differences of permeability at different locations in the waste body. The result is that stagnant zones (dry pockets) alternates with mobile zones (hydrophilic pockets), without knowing the exact spatial positions. This has been modeled in figure 6.12. It has to be emphasized that the boxes in figure 6.12 are conceptual and are not reflecting the scaled model distribution of hydrological zones in the actual situation in the landfill.

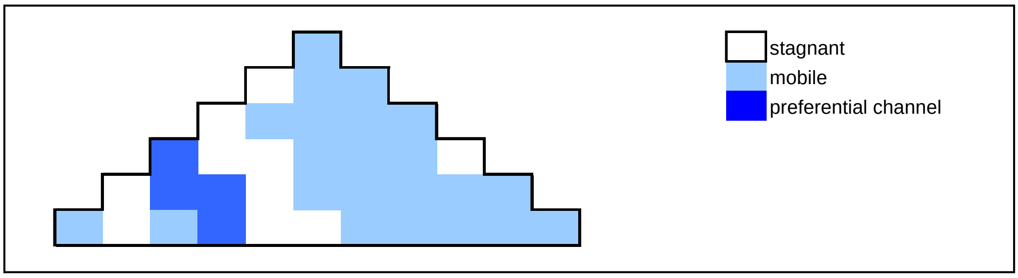

Figure 6.12 Conceptual model of heterogeneous spatial distribution hydrological zones in the waste body (the showed boxes are not reflecting the scaled model distribution of hydrological zones in the actual situation in the landfill).

6.5 Integrated conceptual model of processes in the waste body

6.5.1 Extent of degradation and stabilization of the landfill

All three categories of organic matter as well as all three hydrological categories of the triple porosity model are present in the waste body of the landfill, both at random and unknown positions.

Combining both categories as presented in table 6.3 results into the following five (5) categories of degradation extent of organic matter (the indicated percentages haven been chosen at random and may not be used as exact figures):

1. 100% degradation
2. 80% degradation
3. 60% degradation
4. 10% degradation
5. no degradation

The presence of water is a prerequisite for the degradation processes. For example in stagnant zones with only the initial moisture content in the waste before disposal and in spite of the presence of easily degradable organic matter, the extent of degradation of organic matter will be rather small (60%). At the other hand easily degradable organic matter in preferential channels will be fully degraded (100%).

Table 6.3 Categories of the extent of degradation of organic matter

Hydrological zones ↓	**Categories of degradability of organic fraction**		
	Easily Degradable	Difficult degradable	Non degradable
Preferential channel	**100%**	**80%**	**0%**
Mobile	**80%**	**60%**	**0%**
Stagnant	**60%**	**10%**	**0%**

The above mentioned hypothesis has been modelled by combining the biochemical model (figure 6.6) and the hydrological model (figure 6.12) into a conceptual model of landfill stabilization (figure 6.13).

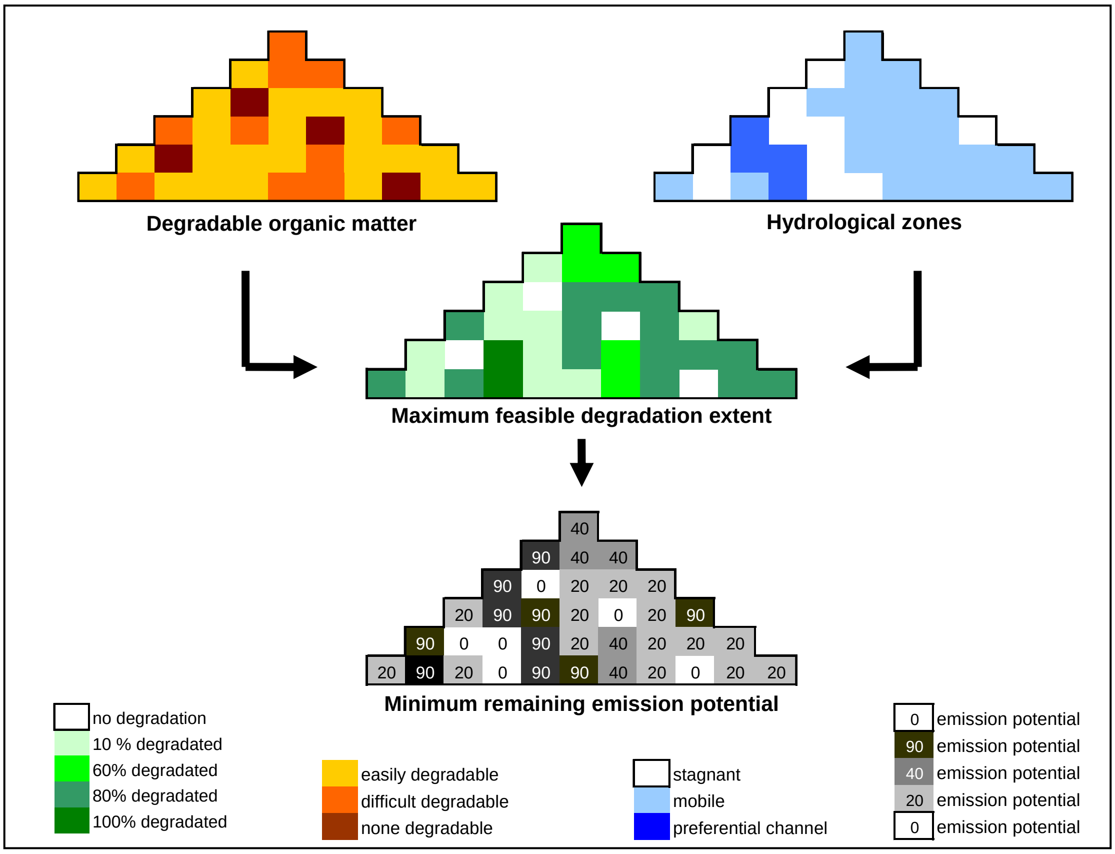

Figure 6.13 Conceptual model of the process of landfill stabilization (the showed boxes are not reflecting the scaled model distribution of degradation extent/remaining emission potential in the actual situation in the landfill).

6.5.2 Place and time of degradation processes in the landfill

From the previous chapters it is entirely clear that the waste body of existing landfills should be considered as very heterogeneous with respect to the type and spatial distribution of organic matter and moisture content in the waste body. This is the main reason that the (interaction of) biochemical, geochemical and physical processes do not work out equally smooth and complete all over the waste body.
By considering the waste body as a collection of very small waste pockets (lit 8), this means that the extent of degradation will not be the same in every pocket at the same time. In other words, at the same time one waste pocket is still in the acid-fermentation phase, a second one in the intermedial anaerobic phase and a third one is already in an advanced stage of the methanogenic phase, etc. This is visualized in figure 6.14 by presenting different degradation phases in different waste pockets at point in time 1, point in time 2, etc.. This will continue until the maximum feasible degradation extent c.q. minimum remaining emission potential in every waste pocket in the waste body will be achieved.

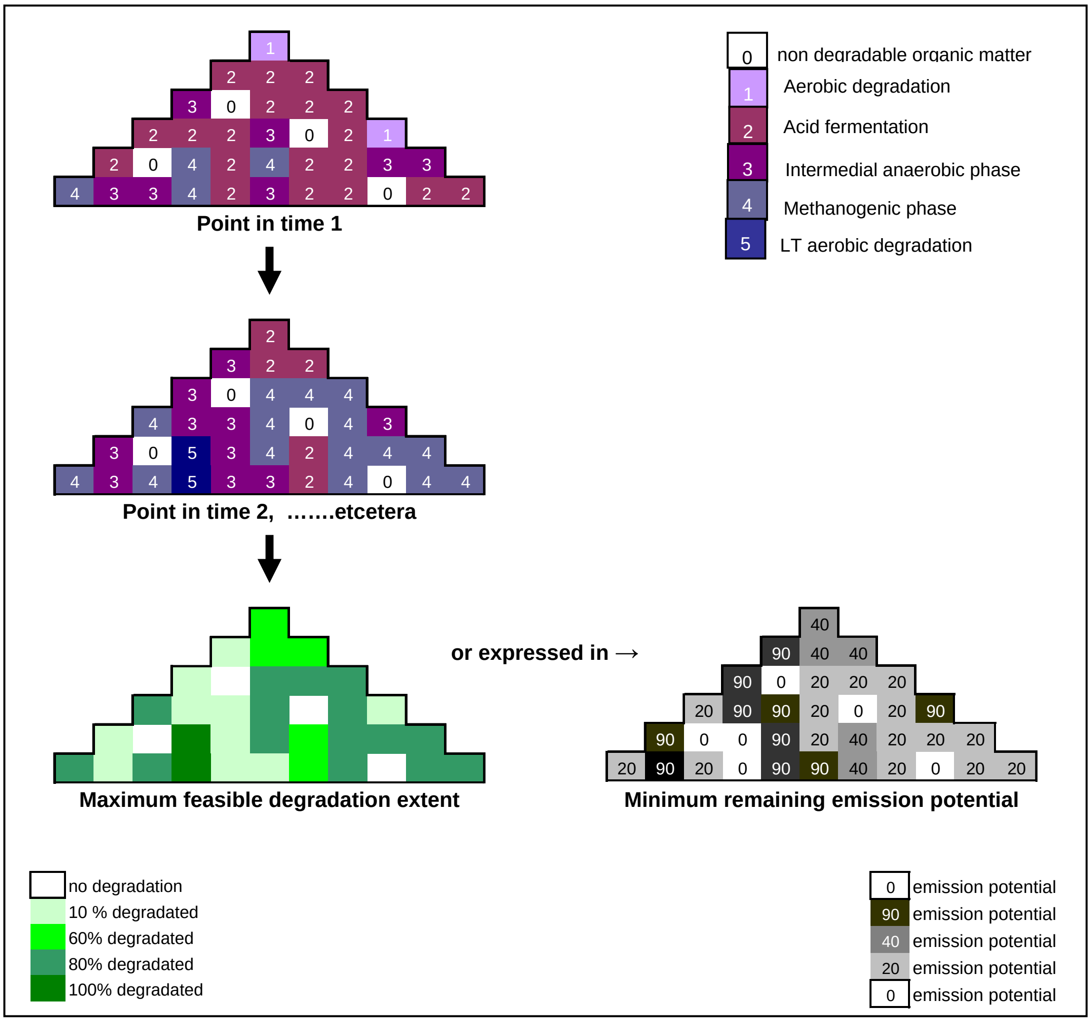

Figure 6.14 Conceptual model of the sequential degradation phases in place and time

6.5.3 Conceptual process design

In figure 6.13 and 6.14 various notions are used. It is essential to understand what is meant by these notions. In table 6.4 these notions are defined and explained and also positioned as sequential steps in a global process design (figure 6.15) in order to achieve the admissible emission levels as the final goal. The admissible emission levels can be achieved by means of a sufficient extent of sustainable emission reduction as the results of sufficient extent of degradation of degradable organic matter.

From a point of view of environmental cost-effectiveness, it is by definition not necessary to aim for the maximum feasible sustainable emission reduction in advance. It might be possible that the admissible emission levels are achieved in an earlier stage. Maybe as a result of autonomic degradation processes only or as a result of operational enhanced technical measures. In that case the landfill stabilization process can be stopped and the achieved sustainable emission reduction so far will be sufficient. The fact that the admissible emission levels can be achieved by means of sufficient sustainable emission reduction anyway, makes less stringent aftercare or discharge from aftercare possible.

At the other hand it should not be excluded that at the end the maximum feasible sustainable emission reduction do not meet the required limit values to be applied with respect to admissible emission levels.

In that case traditional mitigating aftercare measures must be applied in order to avoid unacceptable emissions due to the landfill. From a point of view of environmental cost-effectiveness it is recommended to predict this scenario in the earliest possible stage of the stabilization project and/or process in order to avoid needless expenditures.

Of course this process design consists of a number of and "go/no go" situations and decision-moments, which have to be founded on solid arguments and figures. For that reason knowledge of key performance indicators (KPI) and how to interpret them is crucial for the process design as well as for the technical design of a landfill stabilization project. These KPI's are presented in the next chapter.

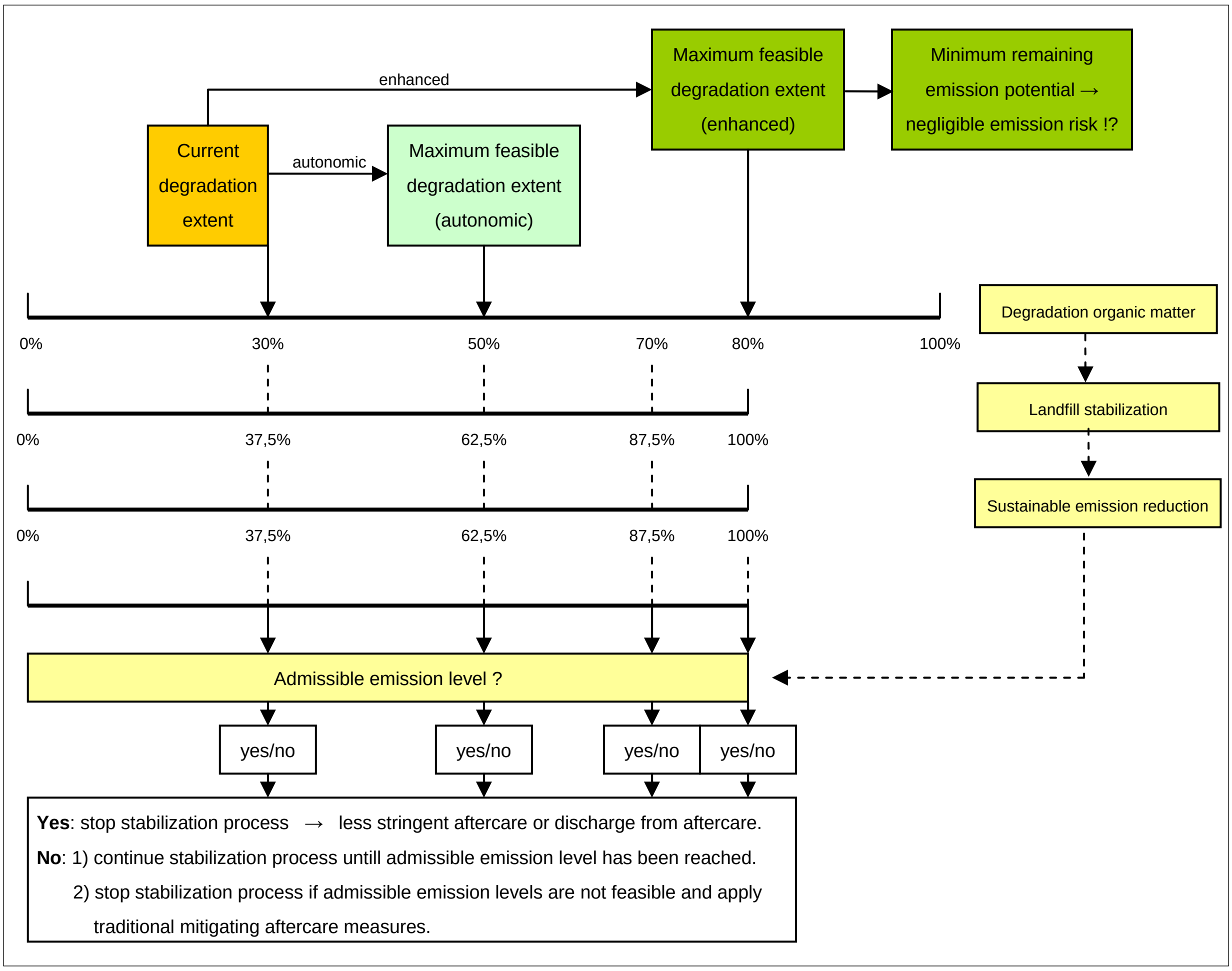

Figure 6.15 Conceptual process design

Table 6.4 Process design based upon the conceptual model of landfill stabilization

Notions/steps	Definition and explanation
Degradation extent of waste ↓	Degradation of organic matter takes place on the scale of very small waste pockets in the landfill in the order of magnitude of decimeters. The goal is to achieve the maximum feasible degradation extent of degradable organic matter in the waste in the given circumstances. This can be the result of autonomic degradation processes or enhanced degradation measures such as infiltration/recirculation of leachate and/or aeration of the waste. Because of the heterogeneous spatial distribution of degradable organic matter and water in the landfill, it is not realistic to expect at the end a 100% degradation of all degradable organic matter.
Stabilization extent of the landfill ↓	Stabilization is considered on the scale of the total waste body of the landfill. Theoretically a 100% stabilized landfill is equal to 100% degradation of all degradable organic matter in the waste body. In practice a 100% stabilized landfill can put on a par with the maximum feasible extent of degradation of degradable organic matter by having applied all possible measures and efforts. This means for example that the maximum feasible degradation of organic matter due to only autonomic degradation processes, results for example in a 60% stabilization extent of the landfill. The remaining 40% can be achieved by applying enhancing technical measures (infiltration/recirculation of leachate and/or aeration of the waste).
Sustainable emission reduction ↓	Sustainable emission reduction is defined as a stable and not reversible reduction of emission of constituents from the landfill for both biogas and leachate. The maximum sustainable emission reduction will be achieved if the 100% stabilization of the landfill, as defined above, has been realized.
Admissible emission level	It should not be excluded that the maximum sustainable emission reduction, as defined above, do not meet the required limit values to be applied with respect to admissible emission levels. In that case mitigating aftercare measures must be applied in order to avoid unacceptable emissions due to the landfill. At the other hand it is realistic to expect that the required limit values have been achieved. In that case less stringent aftercare or discharge from aftercare would be possible. It also might be possible that the required limit values with respect to admissible emission levels are achieved in an earlier stage. In that case and from a point of cost-effectiveness the operation to achieve the maximum sustainable emission reduction can be stopped and the partial achieved sustainable emission reduction will be sufficient.

6.6 Key performance indicators

Key performance indicators (KPI's) enable the determination of the current extent and future developments of degradation of organic matter and consequently allows the determination of the maximum feasible extent of stabilization of the landfill c.q. the maximum feasible sustainable emission reduction. The KPI's are used to be able to answer the following main questions (see also figure 6.15):

- Has the waste body (or parts of it) already reached the lasting methanogenic phase or not?
- If so, is it still at the beginning, at the end or somewhere in the middle of the methanogenic phase?

- Has the maximum feasible extent of stabilization been reached and if not, how long will it still last in autonomic circumstances and how profitable and cost-effective is the installation of technical measures to enhance the on-going stabilization process.
- Will the maximum feasible sustainable emission reduction lead to admissible emission levels?

The main indicators to monitor the development of the stabilization process of the landfill are:

- leachate composition.
- methane production.
- landfill settlement.
- in situ waste temperature.

Interpretation of data can be confusing because of the heterogeneous nature of the waste body, expressed in:

- the significant spatial variation of type of waste;
- the spatial variation of presence of organic matter;
- the spatial variation of degradability of organic matter;
- the distribution of moisture content and moisture transport;
- the simultaneous presence of the different phases of the degradation processes at different places in the waste body.

The interpretation of data can be further complicated because of leakages in gas extraction wells, which causes air ingress and lowers/cease/retard the methane production (methanogenic bacteria are very sensitive for oxygen).

So, profound knowledge and expertise of KPI's and how to interpret them, is crucial for the process design as well as for the technical design of the demonstration project and measurement / monitoring program.

Annex 4 shows a complete list of KPI's, which have been scientifically accepted and/or have showed to be workable in already executed large scale projects. In the list the KPI's are defined and explained and it is indicated how to be measured. The list has been subdivided in the following categories:

- General KPI's
- Leachate KPI's
- Gas KPI's

Besides the list can be subdivided into:

- primary KPI's, which can be directly related to the effects of the main process of degradation of organic waste and the overall stabilization process of the landfill.
- secondary KPI's, which are related to the performance of the necessary and required conditions for a successful degradation process.

In table 6.5 the KPI's have been summarized, in which the primary KPI's are listed bold.

Table 6.5 Primary and secondary key performance indicators (primary KPI's is listed bold)

General	Leachate	Gas
Temperature	**Redox (Eh)**	**Measured/calculated gas production**
Settlements	**Ammonia (NH_4)**	**CH_4/CO_2 ratio**
Waste composition	**Conductivity (Ec)**	**Gas extraction rate**
Moisture content	**Acidity (pH)**	Oxygen (O_2)
Moisture transport	**Biochemical oxygen demand (BOD)**	Inhibitors
Water balance	**Chemical oxygen demand (COD)**	
Time capsule	**COD-BOD**	
	BOD/COD ratio	
	Total organic carbon (TOC)	
	Dissolved organic carbon (DOC)	
	Benchmarking (o.a. LeachXS)	
	Chloride (Cl^-)	
	Total Volatile Fatty Acids (VFA)	
	Alkalinity	
	Nutrients (including NA-parameters)	
	Sulphate (SO_4) and Sulphide (SO_2)	
	Nitrate (NO_3) and Nitrite (NO_2)	

6.7 Risk assessment

6.7.1 Environmental risk assessment

Environmental risk assessment method is based on the principle of the "source-path-receptor approach. With respect to landfills, four risk factors can be distinguished:

1. Emission of landfill gas
2. Emission of leachate into groundwater
3. Emission of leachate towards surface water
4. Contact with waste (coverage layer)

This feasibility study has been limited to the risks of emission of leachate and landfill gas from the source (i.e. the waste body). The first part of the risk assessment should consist of a comparison between:

1. at one hand the present and forecasted (autonomic developments and enhanced developments by means of technical measures) emission levels of macro- and micro-contaminants in the leachate of the waste body;
2. at the other hand the admissible emission levels related to human and ecological risks, which are based upon generally accepted standards.

The standards that can be used are:

- The Dutch 'Circular on target values and intervention values for soil remediation (2008)';
- The Dutch 'Soil Quality Decree' , 22 November 2007 (Besluit Bodemkwaliteit);
- European Groundwater directive (Kaderrichtlijn Grondwater);

- EU-landfill directive annex II of 19 December 2002, concerning the limit-values of inert waste.

In annex 5 the limit values of the above mentioned standards have been listed for various parameters. The four standards are explained below.

Dutch 'Circular on target values and intervention values for soil remediation (2008)'
The Dutch Circular on target values and intervention values for soil remediation relates to cases of contamination of soil, groundwater and aquatic sediment assessed as part of the remediation regulations in the Dutch Soil Protection Act (Wbb).
The soil remediation intervention values indicate when the functional properties of the soil for humans, plant and animal life, is seriously impaired or threatened. They are representative of the level of contamination above which there is a serious case of soil contamination. The target values indicate the level at which there is a sustainable soil quality. In terms of curative policy this means that the target values indicate the level that has to be achieved to fully recover the functional properties of the soil for humans and plant and animal life. From the intervention value and target values the intermediate value is calculated ((intervention + target value)/2). This value sets the limit concentrations above which further research is necessary according to the Dutch Law.

Dutch 'Soil Quality Decree' (22 November 2007)
The Soil Quality Decree guarantees an unequivocal policy on sustainable soil management. The new Decree endeavours to achieve a balance between man and the environment and to allow scope for social developments. To balance a healthy living environment with the use of the soil for various purposes: for housing, work, leisure and to grow crops and more. For the use of excavated soil and dredged material as a building material, threshold values have been formulated. Depending on the type of use, the following five threshold values are specified:

- Natural background values;
- Maximum values soil quality categories for housing (generic);
- Maximum values soil quality categories for industry (generic);
- Maximum emission values (large scale soil works);
- Local maximum values (area specific).

European Groundwater directive
In the European Groundwater directive each member country is asked to formulate threshold values for their water bodies. The water body in the Netherlands is divided into four catchments: the Eems, Maas, Rijn en Schelde. At this moment the directive is still a concept and the threshold values are intentioned to guard the overall quality of the catchments. In the KRW threshold values for 6 parameters are formulated. *(Chloride, Nickel, Arsenic, Cadmium, Plumb, en Phosphate).* The landfill Wieringermeer is located in the Rhine (west) catchment and the landfill Kragge is located in the Schelde catchment. Depending on the type of water different threshold values are formulated.

EU-landfill directive annex II of 19 December 2002 concerning inert waste
The objective of the EU landfill Directive is to prevent or reduce as far as possible negative effects on the environment from the landfilling of waste, by introducing stringent technical requirements for waste and landfills.

The Directive is intended to prevent or reduce the adverse effects of the landfill of waste on the environment, in particular on surface water, groundwater, soil, air and human health. It specifies acceptance criteria for waste. These criteria have been developed by means of modeling a source-path-threatened object, such as a drinking water well.

A second part of the risk assessment should consist of drawing an overall picture of criteria, by which the effectiveness of enhancing technical measures with respect to the extent of stabilization of the landfill can be demonstrated and by which the consequences of a less stringent aftercare or release from aftercare can be assessed. The development and elaboration of a sound process design with sufficient go/no go situations and decision moments, based on solid criteria, is a prerequisite to be able to assess in a reliable manner (see figure 6.15):

1. the extent of the achieved sustainable emission reduction and the corresponding remaining emission potential;
2. whether the admissible emission levels have been reached accordingly to the selected risk-based limit values.

The process design as well as the criteria should be developed in good cooperation and consultation with the competent authorities during the execution period of the demonstration projects. In this way the results of the demonstration projects might contribute to the creation of an accepted risk assessment method that includes both environmental and geotechnical (see next chapter) aspects. An example of this approach can be found in the German Landfill Ordinance of 2002 (lit 2 and 3).

6.7.2 Geotechnical risk assessment

In this study the geotechnical risk assessment will be limited to settlements in the waste body due to:

- the degradation of organic matter: rule of thumb: decay of 1% carbon results in a reduction of volume (at a specific gravity of 1 t/m^3) of 1.5 -2%.
- water squeezing out of the pores in the waste body (reduction in waste volume);
- settling by infiltration/recirculation of water and/or leachate.
- settling by aerobic in situ stabilisation.

These settlements can be a risk to the overall stability and slope stability of the landfill as well as to the present infrastructure at the top of the landfill and can cause damage to top-liners, bottom-liners, and drainage-systems for leachate and biogas.

During the demonstration projects settlements of waste will periodically be measured by means of settlement beacons, installed at critical positions. An attempt will be made to determine what settlements are caused by which factors as indicated above.

7 MEASURES ENHANCING ANAEROBIC STABILIZATION (INFILTRATION)

7.1 Site and boundary conditions for anaerobic in situ stabilization

Infiltration and/or recirculation of leachate as a technical measure to enhance anaerobic stabilization at existing landfills can only be applied successfully if the selected landfill meets some site-specific requirements. The minimum requirements which have been formulated for the demonstration projects are:

- the landfill should be closed.
- knowledge on amounts and composition of waste disposed over time in order to estimate the quantity of degradable organic matter.
- the presence of a qualified bottom liner.
- by preference the absence of an impermeable top liner.
- a working leachate drainage system, by preference consisting of compartmentalized leachate drainage systems.
- by preference the presence of a leachate treatment plant.
- static stability of the landfill body in case infiltration takes place within the area close to the slope.
- by preference the availability of data time series concerning leachate quantity and quality, the amount and quality of landfill gas produced and development of settlements.
- The presence of a gas drainage system to be able to collect gas during increased gas production.
- by preference the availability of infrastructure and or the possibility to install relevant infrastructure in order to measure and sample individual leachate drains, gas wells and settlements.

7.2 Infiltration media

The following infiltration media can be applied, depending on the local conditions and the chosen infiltration system:

- surface water.
- untreated (raw) landfill leachate.
- pre-treated/purified landfill leachate.
- liquid leachate purification residues (e.g. concentrate).
- process water from waste treatment plants (e.g. from anaerobic digestion of bio waste).

For the selection of the infiltration method, the quality and quantity of the infiltration medium are important. The essential parameters which determine the infiltration capacity and behaviour are the following:

- components of the infiltration medium (organic contamination, nitrogen and salt content, etc.).
- dry matter content and particle size distribution of the dry matter.
- blockage, incrustation and corrosion behaviour, which must be taken into consideration particularly when selecting the material for the infiltration system.

The infiltration of uncontaminated process or surface water, but also of purified leachate, offers the advantage that no partial recirculation of soluble leachate components into the landfill body occurs as well as the fact that negative effects of the infiltration medium on the infiltration system are unlikely.

As for the pre-treated leachate from a leachate treatment plant (e.g. permeate from a reverse osmosis device), it must be checked whether or not the former is sufficiently available in order to guarantee optimization of the waste moisture by means of infiltration. This also applies to raw leachate and liquid leachate purification residues. In cases where the available quantity of corresponding infiltration media is too small, different media may be used "in parallel". This means different media within the period of the infiltration measures may be used.

7.3 Technical methods for infiltration of water

7.3.1 Overview of applied methods

The overview has been based on experiences and results of a great number of full scale infiltration projects at landfills worldwide. A list of these projects is presented in annex 6

Technical methods for water infiltration must be planned in such a way that controlled and even moisture penetration of the landfill body is achieved. Likewise, short circuit currents and preferred seepage paths must be avoided as much as possible using suitable measures.

There are different technical methods available with regard to the infiltration into the landfill body. The choice of infiltration system is determined by the planned or existing surface cover, the quality of the infiltration medium and the quantity to be infiltrated. With regard to the landfill boundary conditions and the targets of infiltration, the following (combination of) infiltration methods can be used:

- horizontal infiltration systems (below the surface of the landfill):
  - two-dimensional infiltration methods
  - linear-shaped infiltration methods (trenches)
  - infiltration fields (gravel fields) with well shafts
  - surface cover with high permeability
- vertical infiltration systems:
  - utilization of existing vertical gas collection systems
  - vertical wells / infiltration columns
  - infiltration lances in short screen distances

A survey of Rettenberger et al. (2005) resulted in about 50 infiltrations projects in Germany. The used infiltration methods were summarized as follows:

- 25% trenches
- 22% drainage systems
- 18% no detailed information (partly still in the planning phase)
- 15% lances
- 9% vertical infiltration wells
- 7% miscellaneous
- 4% by existing gas wells

As a tendency the development led from small-scale infiltration tests to large-scale establishment and operation of infiltration equipment with a growing number of horizontal systems.

7.3.2 Two dimensional infiltration

In the landfill sections for infiltration horizontal pipes can be installed in the equalizing and gas drainage layer below the surface cover (figure 7.1). This can be done in combination with the installation of the surface cover or later. Pipes are installed with a little slope or at equal altitude. Infiltration may occur over the whole infiltration area and therefore, depending on the horizontal and vertical permeability of the waste body, reach the whole volume of the landfill body that should be influenced.

For the installation of the perforated pipes, trenches can be excavated within the equalizing and gas drainage layer, so the drainage layer acts as a filter for improved and even water distribution. If the pipes had to be dismantled after the termination of infiltration, e.g. for the installation of a final surface cap, an additional technical and financial demand should be considered (a.o. Dutch landfills Landgraaf, Wijster and Vlagheide).

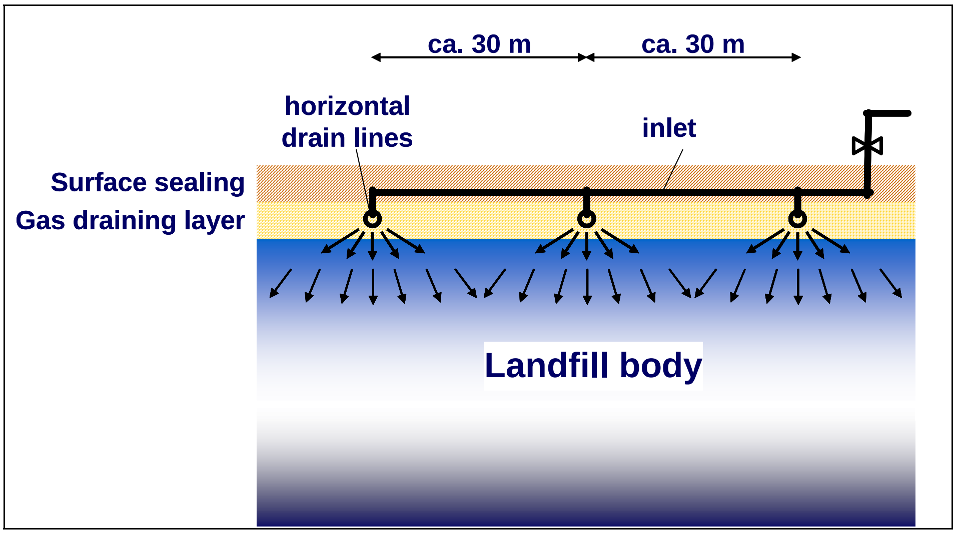

Figure 7.1 Example of a two-dimensional infiltration method (Hupe et al., 2003)

7.3.3 Linear-shaped infiltration (trenches)

The design and installation of linear-shaped infiltration methods (trenches) is comparable to the above mentioned method. The trenches are often excavated in the upper layer of the waste body so a water distributing drainage layer is missing.

The trenches can be charged via one point or in order to improve the equal water distribution by a perforated pipe.

The minimum width of the trenches depends on the diameter of the perforated pipes and is often in the range of 0.5 to 1.0 m.

The height of the trench might be about 1.0 m, often covered by the temporary surface cover. The distance between the trenches can be 15 – 30 m.

Figure 7.2: Example of six trenches for the infiltration of a landfill section (derived from IFAS planning, 2006)

7.3.4 Infiltration fields with well shafts

Based on the experience gained on different landfill sites, a combination of two-dimensional infiltration fields that are supplied by vertical infiltration systems (well shafts) was developed (Hupe et al., 2003). This infiltration system is designed as follows:

- Well shafts are installed at the landfill surface for a controlled water addition.
- Below the well shafts, infiltration fields (gravel fields) are laid out in order to distribute the infiltration medium over the area (figure 7.3).
- The charging of the well shafts / infiltration fields may be implemented using tank trucks or a largely automated water distribution system, consisting of distribution buildings and piping. For long-term infiltration measures, the elaborated piping and distribution system should be employed.
- In cases where the installation of the corresponding infiltration system results in a raise of the landfill body, a raising of the existing well shafts may also be required. Further infiltration units may be installed on the raised landfill area subsequent to the completion of filling (figure 7.4).

The determination of the dimensions for the well shafts and infiltration fields (diameter and height), as well as the distance between the individual well shaft / infiltration field units must be realized taking into consideration the local conditions.

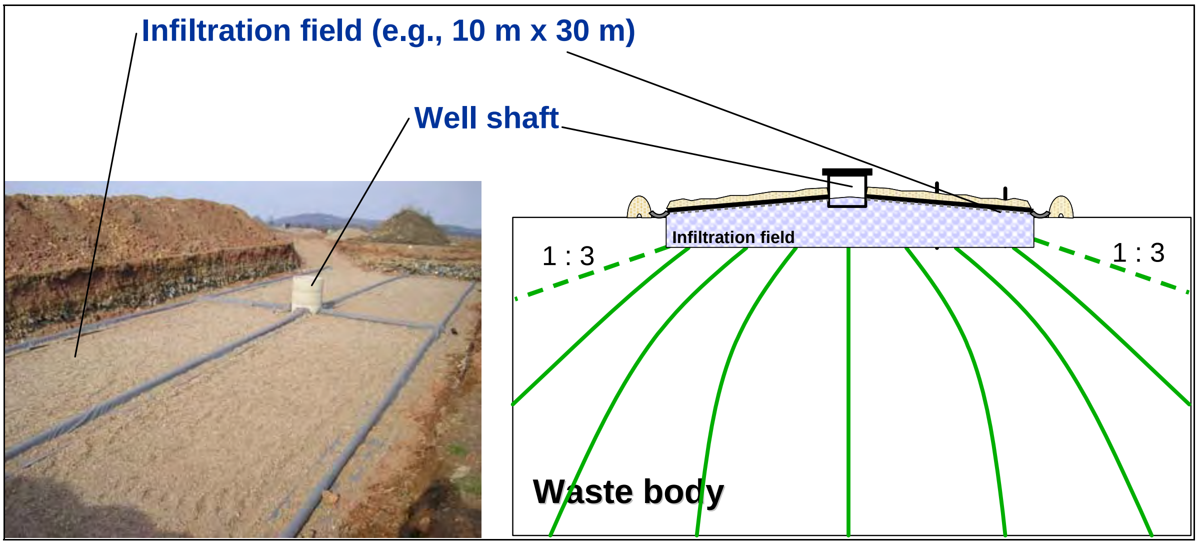

Figure 7.3 Example of an infiltration field integrated in a temporary cover with a well shaft for charging and the sphere of action below the infiltration field (HUPE et al., 2003)

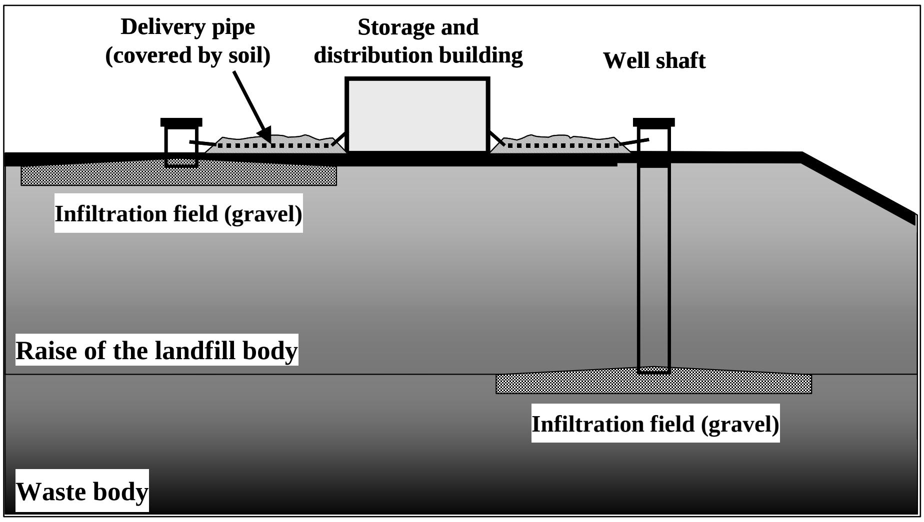

Figure 7.4 Raise of an existing well shaft and installation of a new well shaft / infiltration field system with water distribution system (integrated into a surface sealing, if required) (HUPE et al., 2003)

In order to avoid uncontrolled gas emissions with regard to this system, the area of the infiltration field may be equipped with a gastight covering/sealing. The well shaft is water and gastight. For even moisture penetration throughout the waste body, an accumulation of leachate within the infiltration field is useful in the fill up period in order to achieve distribution of the infiltration medium over the entire surface of the infiltration field. The option for leachate accumulation must be taken into consideration during the planning phase and may be realized in a process-related and structural manner.

In order to reduce respectively avoid plugging, incrustation or precipitation, uncontaminated or pre-treated waters can be used.

Infiltration fields with an automatic water distribution system were installed at the landfill Leppe and the landfill Mechernich in Germany.

7.3.5 Lances in short screen distances

In the infiltration section vertical lances can be installed through the temporary cover in shorter distances. Via the lances the medium can be infiltrated with a controlled pressure and volume by valves, stop cock, water meters etc. (figure 7.5). Several lances can be supplied via one pipe or hose with distribution devices.

The lances can be made from steel-pipes with a length of about 2-3 m that are perforated in the lower section and pressed into the landfill body. When short distances of 5 – 15 m between the lances are applied, a rather even distribution over the area and the volume of the landfill question can be achieved. After the termination of the infiltration the lances can be pulled out of the waste body.

Infiltration by lances was already applied at the German landfills Erbenschwang and Dreieich and the Dutch landfills in Wijster and Elspeet.

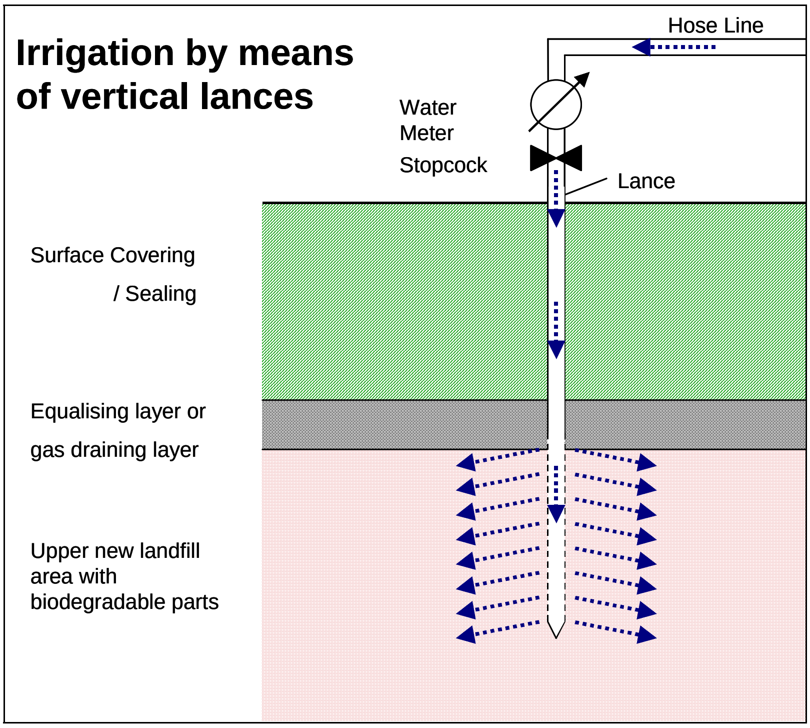

Figure 7.5 Example of lances as a vertical infiltration system (Hupe et al., 2003)

7.3.6 Infiltration in vertical wells / infiltration columns

Vertical infiltration can be applied by infiltration columns that are drilled or digged into the landfill body. They may have a height of 5 – 15 m and a diameter of 1 – 2 m and might be filled with coarse gravel or processed construction and demolition materials (figure 7.6). The columns can be supplied by pipes that are installed in the surface cover or the upper waste layer. Compared to lances that can be fed with a higher volume per infiltration cycle as they offer a high pore volume in the column.

Columns as described were installed at the German landfill Halle-Lochau.

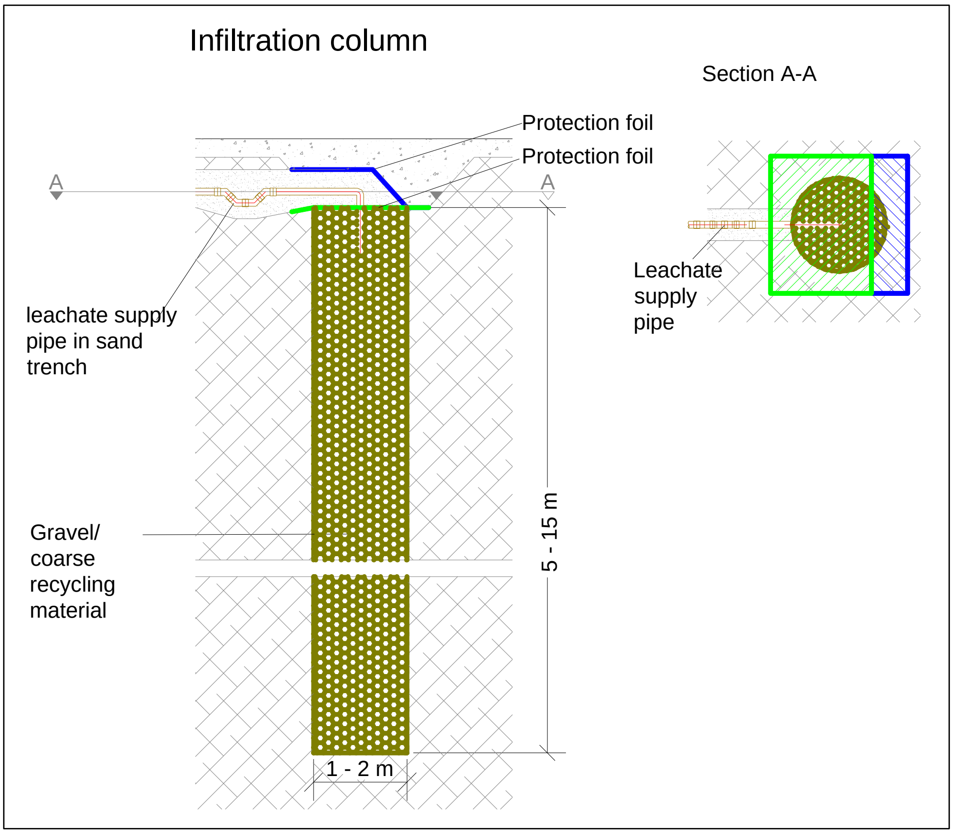

Figure 7.6 Example of a vertical infiltration column (derived from IFAS planning, 2006)

7.3.7 Temporary surface cover with high permeability

A further option of infiltration with reduced opportunities to control and regulation is the application of surface cover with a high permeability, for example an earth layer of about 1.0 – 1.5 m. Depending on the climatic situation at the landfill site and the materials used for the cover, it allows a certain infiltration of rain water entering the landfill body.

8 MEASURES ENHANCING AEROBIC STABILIZATION (AERATION)

8.1 Site and boundary conditions for aerobic in situ stabilization

The aerobic in situ stabilization may be employed where the following site and boundary conditions are met:

- low landfill gas production (collection and treatment is still required but economic utilization of methane as an energy source is no longer possible), avoidance of a long-term and cost-intensive poor gas treatment.

- prior to the installation of a surface sealing in order to enable the anticipation of the main settlements and at low landfill gas production in order to avoid concentration and gas migration.
- landfills with bottom liner and decreasing leachate contamination which, in the long term, still exceeds the legal requirements for direct discharge.
- landfills without bottom sealing with increased risk potential of emission of contaminated leachate to groundwater and/or surface water.
- old deposits without any protection measured such as top liner and bottom liners, where remediation and or containment measures (surface sealing, vertical slurry walls, geohydrological isolation, etc.) would be too cost-intensive or technically impracticable.

8.2 Technical methods for aeration

8.2.1 Overview of applied methods

The overview has been based on experiences and results of a significant number of full scale aeration projects at landfills worldwide. A list of these projects is presented in annex 6.

Several methods for the aerobic in situ stabilization of landfill are applied:

- High pressure aeration (e.g. BioPuster®, Austria)
- Low pressure aeration (e.g. Aero-Flott®, Germany)
- Pressure aeration and suction (e.g. Smell-Well®, Austria)
- Oversuction (e.g. DepoPlus®, Germany)
- Active air injection without active extraction

8.2.2 High pressure aeration

The high pressure aeration was initially designed for methane and odour elimination before excavation activities in landfills and landfill mining.

With the BioPuster® system, ambient air is enriched with technical oxygen and is pressed into the landfill body by pressure impulses up to 6 bars. Lances of 2 – 4 m are used for the supply with oxygen. For this reason, many results and experience refer only to the upper waste layer of about 4 – 6 m.

The 'Bio-Puster Method' has been used in Austria since 1991, for example for the landfill Vienna-Donaupark, for the Berger landfill and the Fischer landfill (in situ preliminary aeration 2002 – 2006) before excavation.

A full scale aerobic landfill system has been in operation at the Donlands Landfill (Toronto, Ontario) for more than 18 years.

8.2.3 Low pressure aeration

The basic technical concept of the low pressure aeration of the landfill body consists of a system of gas wells, through which atmospheric oxygen is led into the landfill body via active aeration in such a way that an accelerated aerobic stabilization of the waste is realized.

Simultaneously, the low-contaminated waste gas is collected and treated in a controlled manner by means of adjacent gas wells (figure 8.1). Aeration is effected using low pressures and is continuously adjusted to meet the oxygen demand so that energy consumption is low and constantly optimized.

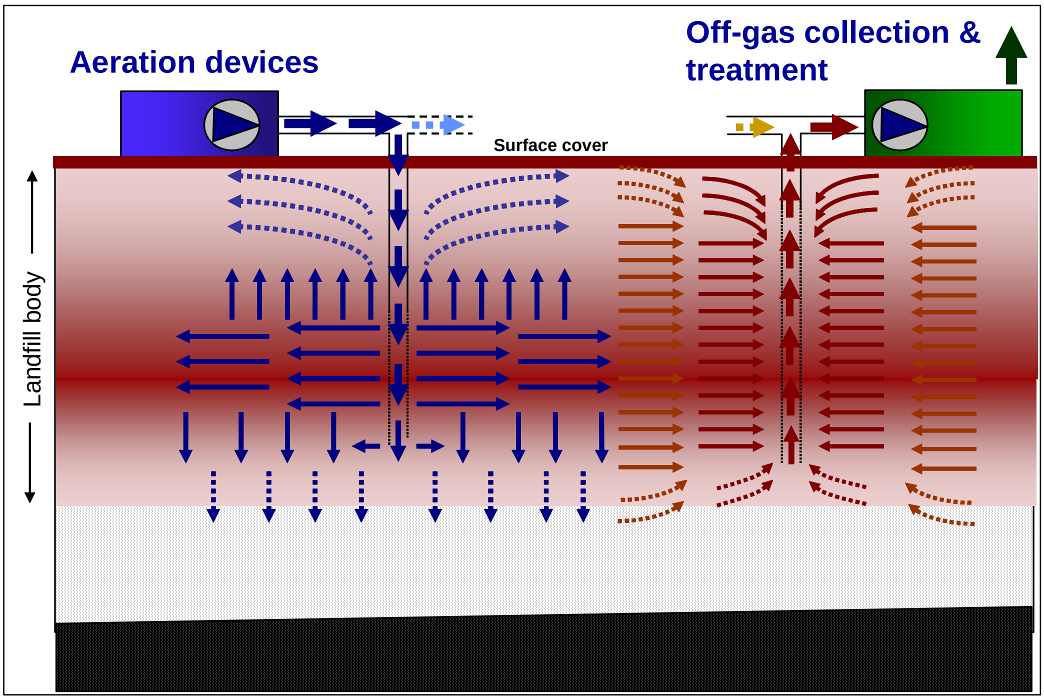

Figure 8.1 Concept of the aerobic in situ stabilization by low pressure aeration

Low pressure aeration in Germany
The essential technical equipment comprises (Heyer et al., 2005):

- gas wells for aeration purposes and for the collection of waste air, where existing gas wells can be used.
- gas mains system for aeration purposes and for the collection of waste air, where existing gas wells can be used.
- gas distribution system for the adjustment of the aeration rates and of the overpressure, or of waste air collection rates and of the negative pressure per gas well.
- aeration and gas extraction aggregates in the gas booster station.
- waste air treatment stages: e.g. autothermic methods (RTO) or biofilters

The low pressure aeration was developed by the Hamburg University of Technology and has been constantly improved in the last ten years. The treatment period is often between 4 and 6 years. Experience for biological stabilization of the landfill body up to the height of 25 m was gained. On several landfills a final storage quality of the stabilized waste could be witnessed by extensive scientific monitoring programs (Stegmann et al., 2008).

As regards the stabilization operation using low pressure aeration Aero-Flott®, experience could already be gained at several municipal waste landfills and old deposits that were successfully completed 2006 and 2007:

- Kuhstedt landfill, district of Rotenburg (Wuemme) – Lower Saxony, Germany, BMBF project (Ministry of Education and Research) (with test fields for the examination of alternative surface sealings), 2001 - 2007
- Old Amberg-Neumühle landfill – Bavaria, 2001 - 2006
- Milmersdorf landfill, district of Uckermark – Brandenburg, 2002 - 2006

The largest project that is currently operated is the aerobic in situ stabilization of the Doerentrup landfill, ABG Lippe, district of Lippe, Northrhine-Westphalia, that started 2007.

In addition, aeration tests were carried out on several German landfills and old deposits, in order to dimension a site-specific low pressure aeration and adjust operation to the local conditions.

Low pressure aeration in the USA

In the USA in situ aeration is often applied at younger bioreactor landfills (Hudgins, 2005). The main aim is to reduce the waste mass and to gain new landfill capacity because of reduction of waste volume. The strategy is rather comparable to the biological pre-treatment that has been carried out in Europe in the last 15 years. The aeration is carried out by lances in a distance of 10 – 15 m. Sometimes water infiltration or leachate recirculation is combined with aeration. In several projects the exhausts of the aeration process were not collected and treated. This caused significant odour emissions and a negative impact on the climate (greenhouse gas emissions). For this reason this kind of aeration was not applied in Germany.

8.2.4 Pressure aeration and suction (Smell-Well)

Pressure aeration and suction methods can be used with low or high pressure (e.g. Smell-Well®, Austria). It was developed for conversion from anaerobic to aerobic conditions before landfill mining. Air is forced into and out of the landfill body. Therefore gas lances were applied in the upper layer of about 4 – 6 m of the waste body to be excavated. The aeration process is carried out over several days or a few weeks mainly to reduce odour emissions.

The Smell-Well system was first applied for a landfill mining project at Deponie Burghof in Ludwigsburg (Germany) between 1993 and 1994 (Rettenberger, 1998). Since then various big projects of aeration before excavation were carried out in Austria, Italy, Korea, Japan United Arabian Emirates (Sharjah).

Since 2007, a landfill mining project in Quebec, Canada is carried out where each year about 300,000 m^3 are aerated for a short time before excavation and transferred to a new landfill section. This method was mainly used for aeration over a short period before excavation but not for complete biological stabilization to a final storage quality like the low pressure aeration. For this reason experience and influence of aeration are restricted to the upper layer of a landfill body.

NV Afvalzorg owns and operates a Smell-Well system since 2000. It has been successfully applied to mitigate emission problems at Braambergen landfill (Scharff, 2001) and Zeeasterweg (Jacobs and Scharff, 2003).

8.2.5 Oversuction methods

With over suction methods the effect of aeration is achieved via suction operation including drawing-in of the atmospheric oxygen over the surface of the landfill and/or via passive aeration wells. According to the author's experience, this is implementable effectively only at sites with emission-relevant deposition thicknesses of ≤ 10 m as otherwise, the oxygen supply and thus aeration may not be guaranteed or takes a long time.

Over suction can be carried out with:

- gas wells for the collection of waste air (existing gas wells can be used)
- as far as necessary: gas wells or comparable devices for passive aeration
- gas mains system for the collection of waste air (where existing gas wells can be used)
- gas collection station
- gas extraction aggregates in the blower station
- waste air treatment stages: e.g. autothermic methods (RTO) or biofilters

This procedure, enabling stabilisation and gas-related decontamination, is applied in, amongst others, the following old waste disposal sites:

- Old Schenefeld landfill, district of Pinneberg - Schleswig-Holstein, Germany
- Old Kiel-Drachensee landfill, city of Kiel – Schleswig-Holstein, Germany

The situation of these sites was characterised by following boundary conditions:

- Endangering of redevelopment constructions by migrating landfill gas.
- Missing technical barriers
- The essential precondition for the application of passive aeration via over-suction was a relatively insignificant thickness of the waste body and a low demand of oxygen, so that a sufficient amount of oxygen could be supplied over the depth of the waste body (Hupe et al., 2004).

Another oversuction method is known as the DepoPlus®-method that has been applied on several landfills and old sites. It works with multi-level gas wells and higher suction pressures.

8.2.6 Active injection of air without active extraction

A further option of aerobic in situ stabilization could be the aeration of gas wells without a controlled collection of the exhausts. In this case it is expected that the exhausts leave the landfill body due to the overpressure by migration via the landfill surface. The surface of the landfill, maybe covered with a temporary cover (soil layer), shall act as a biofilter for odour elimination and methane oxidation.

In Europe this option is applied in the Landgraaf full-scale aerated bioreactor project. Due to the good environmental conditions in the top-layer (temperature, moisture, oxygen content) and the presence of a distribution layer below the oxidation layer no methane emissions could be measured (FID measurement). The CH_4 load in the oxidation layer is approximately 2.5 $l/m^2/hr$. In the presence of sufficient temperature (above 20 degree Celsius) and sufficient oxygen (>5% O_2) and a homogeneous top layer, the oxidation will be sufficient. In practice the homogeneous distribution in the top layer will be the weakest link. Start-up with active extraction and treatment is recommended. The oxidation process will be monitored by off-gas measurements (before treatment) as temperature, methane and oxygen content. After stabilization of the oxidation process a test programme can be started to establish the need for active extraction and treatment by FID emission control.

9 ASSESSMENT OF MEASURES ENHANCING STABILIZATION

9.1 Assessment criteria and assessment method

The feasibility study is aiming to demonstrate sustainable emission reduction at the existing landfills by means of the application of technical measures, which are able to enhance the natural stabilization processes in the waste body. It is not the intention to demonstrate the functioning of experimental and/or promising technical measures themselves. So it has been decided to apply only the technical measures, which have been often used at full scale landfills sites and have proven themselves with respect to reliable results. By applying this main criterion, the demonstration projects will be concentrated as much as possible on the effects of the technical measures on the emission reduction (stabilization processes).

This main criterion will be used as a first step of selection of the technical measures. The remaining technical measures will be assessed by means of a number of second level criteria as mentioned in table 9.1.

The technical measures will be scored for each criterion on a five point scale, consisting of the following scores:

- ++ very good/ favourable
- + good / favourable
- 0 neutral
- - bad / unfavourable
- -- very bad / unfavourable

The assessment is qualitative and the assignation of the scores has been based upon expert judgement and ready knowledge present with the experts of IFAS and Royal Haskoning as well as with all members of the supervising team, which are the project group and the experts of core team of the Dutch Foundation for sustainable landfilling. The expert judgement and ready knowledge has been acquired by own experiences at demonstration projects as well as by studying the experiences and results of a great number of full scale infiltration and aeration projects at landfills worldwide. A list of these projects is presented in annex 6.

In the next two chapters the results of the assessment of measures for both anaerobic and aerobic stabilization are presented.

Table 9.1 Criteria to assess technical measures to enhance stabilization of waste bodies

Criterion	Infiltration	Aeration
First step of assessment (all technical measures)		
Often used and proven measures/methods at large scale landfills with reliable results	X	X
Second step of assessment (remaining technical measures)		
Equal and controlled distribution of infiltration medium	X	X
Aeration in waste height of 10-20 m	-	X
Required operation time	X	X
Operation demand (costs)	X	X
Energy demand	-	X
Emission control (collection and purification of exhausts)	-	X
Technical demand (costs)	X	X
Impact on existing surface cover	X	X
Demand dismantling	X	X
Criterion	**Infiltration**	**Aeration**
Opportunities future applications	X	X
Impact on gas collection	X	-
Durability	X	-

9.2 Assessment of measures for anaerobic stabilization (infiltration)

In the matrix of Table 9.2, the different infiltration methods are compiled with the mentioned criteria of assessment.

The evaluation shows that the infiltration using linear-shaped infiltration (trenches) or the infiltration with well shafts and infiltrations fields will be the most appropriate methods. These infiltration measures in the green shade columns meet best the main criterion of often used and proven measures/methods at large scale landfills. Besides, these two infiltration measures are also scoring the best on the other criteria.

Compared to these two methods the two-dimensional infiltration, that covers the whole landfill surface, lances in short distances and existing vertical gas wells show some disadvantages. Infiltration via a permeable temporary surface cover has a special position in this assessment as it is a rather “natural” infiltration method that should be obeyed as an additional effect on the water budget in parallel to one of the other methods.

Table 9.2 Assessment infiltration measures

Assessment criteria	Horizontal systems				Vertical systems		
	Two dimen-sional infiltration	Linear-shaped infiltration (trenches)	Infiltration fields with well shafts	Surface cover with high per-meability	Lances in short screen distances	Vertical wells & infiltration columns	Existing vertical gas wells
First step							
Often used and proven	**0**	**+**	**+**	**-**	**0**	**0**	**-**
Second step							
Equal water distribution	++	+	+	-	+	-	-
Required operation time	+	+	+	-	0	0	0
Operation demand (costs)	0	0	0	+	-	0	0
Technical demand (costs)	-	+	+	+	-	+	+
Impact surface cover	--	0	0	+	+	0	+
Demand dismantling	0	0	0	+	+	+	+
Future applications	0	+	+	0	-	0	--
Impact on gas collection	0	+	+	+	+	+	--
Durability	+	+	++	+	-	+	-
Sum of scores	**1+**	**7+**	**8+**	**3+**	**0**	**3+**	**4-**

9.3 Assessment of measures for aerobic stabilization (aeration)

In the matrix of Table 9.3, the different aeration methods are compiled with the mentioned criteria of assessment.

Table 9.3 Assessment aeration measures

Assessment criteria	High pressure aeration	Low pressure aeration	Pressure aeration and suction (Smell-Well)	Oversuction method	Active air injection without active extraction
First step					
Often used and proven	**0**	**++**	**0**	**0**	**-**
Second step					
Equal air distribution	+	+	+	0	0
Aerobization 10-20m	-	+	-	0	+
Required operation time	+	0	0	-	0
Operation demand (costs)	-	+	0	+	+
Energy demand	-	+	0	0	+
Emission control	0	+	0	0	-
Technical demand (costs)	-	+	0	+	+
Impact surface cover	0	0	0	+	0
Demand dismantling	0	0	+	+	0
Future applications	-	+	0	0	0
Sum of scores	**3-**	**8+**	**1+**	**3+**	**2+**

The evaluation shows that the low-pressure aeration (green shaded column) will be the most appropriate method as it is cost-effective, scientifically investigated and shows a positive impact on the landfill behaviour respectively the required reduction of the emissions. Moreover the aeration equipment can be used for an oversuction operation if for example in the final period of the aeration process only a low amount of oxygen is required.

For these reasons the low pressure aeration measure meets best the main criterion of often used and proven measures/methods at large scale landfills with reliable results. Besides, this aeration measure is also scoring the best on the other criteria.

Over-suction methods can be used effectively with landfill bodies of restricted heights and/or a very low oxygen demand.

High-pressure aeration and pressure aeration and suction (like the “Smell-Well”-System) are mainly used for short-term aeration of the upper layer of 2 – 6 m of the landfill body for odour elimination before landfill excavation works. Therefore their applicability for the long-term aeration of the whole landfill body over several years is restricted. It is however possible to convert existing equipment into low pressure aeration equipment.

The air injection without active gas extraction is not well monitored and investigated. Although it might have some economic advantages, the fact that the gaseous emissions are not collected and treated in a controlled manner is regarded as negative. For this reason this method is not recommended for a demonstration project (using a proven method). However this option of operation can be applied with the low pressure aeration system, when the oxygen demand is very low in the final period of the stabilization process and the exhausts show almost no remaining methane concentrations. In this case a well working methane oxidizing cover layer is of great importance. Moreover uncontrolled gas migration into the leachate collection system because of the overpressure has to be avoided.

10 SUMMARY AND CONCLUSIONS

10.1 Backgrounds, initiative and main goal

When solid waste is landfilled, a number of biochemical and geochemical processes occur in the waste body, which can lead to undesirable and unacceptable emissions of landfill gas (odor nuisance and global warming due to methane). So landfills can threaten the environment.

The current Dutch policy concerning modern landfills in the Netherlands is based on isolation of the waste from its environment after the operational period. Infiltration of rain water into the waste body is limited by means of an impermeable top liner and measures to capture and process landfill gas have to be installed. This approach however is not a sustainable solution. The pollution potential stays in place and will become imminent, whenever the isolation measures fails. Therefore the isolation requires eternal aftercare. funding for isolation measures and to buy off the eternal aftercare.

A group of Dutch landfill owners, combined in the Dutch Sustainable Landfill Foundation (DSLF) consider isolation and eternal aftercare not a real and sustainable solution for the mitigation of unacceptable emissions due to landfills. They initiated a project 'Sustainable Landfilling' (lit. 1) to develop ways to reduce the emission potential of the waste. Main conclusion of this research was that when biochemical and physical processes are allowed to complete, emission potential is reduced significantly. The project 'Sustainable Landfilling' however aimed at landfills, yet to be constructed.

The success of the project 'Sustainable Landfilling' led to the main question whether it is also possible to retrofit existing landfills to in such a way that they become more sustainable. If this question can be answered positively, questioning the level and period of aftercare or discharge from aftercare would be possible. The DSLF is convinced that the EU Landfill Directive provides the possibility for aftercare that is tailor-made to the real risk of emissions from the waste body.

So the DFSL took the initiative to evaluate the possibilities and effects of sustainable landfill-methodologies at existing landfills. The main goal of this initiative can be formulated as follows:

The full scale demonstration of sustainable emission reduction at one or more existing landfills in the Netherlands

An independent risk analysis is essential for the assessment of the achieved extent of the sustainable emission reduction and the corresponding remaining emission potential. So the results of the demonstration project have to contribute to the creation of an accepted risk assessment method that includes both environmental and geotechnical aspects.

Within that framework the DFSL requested the Dutch landfill owners to submit landfills, which meet the requirements for a suitable landfill site as described in the Terms of Reference (annex 1). Finally two landfills could be selected:

- the landfill “Wieringermeer” in the province of North-Holland (NL) and owned by the landfill operator Afvalzorg;
- the landfill “Kragge” in the province of North-Brabant (NL) and owned by the landfill operator Essent Environment South.

The first step of the initiative is the execution of a feasibility study with respect to the suitability of the two selected landfills. The present report is a part of this feasibility study.

10.2 Processes in the waste body

The main process responsible for the emission of contaminated leachate and gasses is the degradation of organic matter. Organic matter constitutes a large part of the waste in a landfill and is degraded in time by microorganisms.
The degradation of organic matter only occurs and proceeds in the presence of sufficient moisture and moisture transport. As a result of the heterogeneity of a landfill in terms of organic matter distribution and moisture content, the degradation phase varies in space and time in the waste body. At some locations moisture deficient pockets will exist, where degradation is zero. While at other locations degradation takes place because of sufficient moisture.

The natural degradation processes are proceeding in five degradation phases. Each phase can be identified using Key Performance Indicators (KPI). The most important and most lasting stage with respect to emission potential is the methanogenic phase (decades), in which the economically profitable collection of biogas takes place.

The processes in the waste body have been modelled by means of a “conceptual model of landfill stabilization” by integrating the biochemical, geochemical and hydrological processes.

100% degradation of all degradable organic matter in the entire waste body will be difficult to achieve. However the autonomic stabilization processes can be enhanced by infiltration of water and aeration in order to reach the most feasible extent of stabilization and consequently the most feasible sustainable reduction of emission of leachate and gas.

10.3 Process design

From a point of view of environmental cost-effectiveness, it is by definition not necessary to aim for the maximum feasible sustainable emission reduction in advance. It might be possible that the admissible emission levels are achieved in an earlier stage. Maybe as a result of autonomic degradation processes only or as a result of operational enhanced technical measures. In that case the landfill stabilization process can be stopped and the achieved sustainable emission reduction so far will be sufficient. The fact that the admissible emission levels can be achieved by means of sufficient sustainable emission reduction anyway, makes less stringent aftercare or even discharge from aftercare possible.

At the other hand it should not be excluded that at the end the maximum feasible sustainable emission reduction do not meet the required limit values to be applied with respect to admissible emission levels. In that case traditional mitigating aftercare measures must be applied in order to avoid unacceptable emissions due to the landfill. From a point of view of environmental cost-effectiveness it is recommended to predict this scenario in the earliest possible stage of the stabilization project and/or process in order to avoid needless expenditures.

The above mentioned approach has been modelled in a "conceptual process design" as presented below.

Of course this process design consists of a number of and "go/no go" situations and decision-moments, which have to be founded on solid arguments and figures. For that reason knowledge of key performance indicators (KPI) and how to interpret them is crucial for the process design as well as for the technical design of a landfill stabilization project.

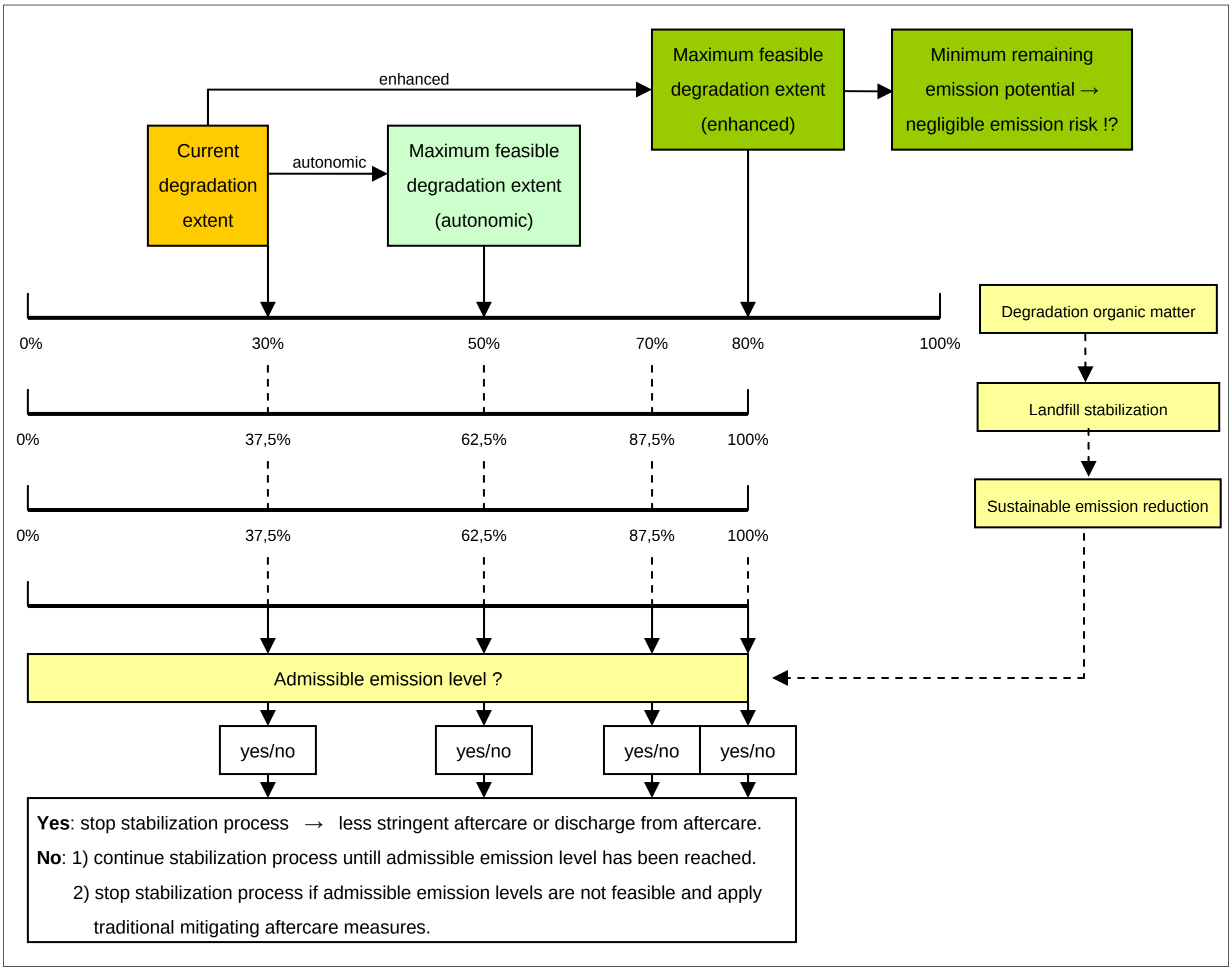

Figure 10.1 Conceptual process design

10.4 Key performance indicators

Key performance indicators (KPI's) enable the determination of the current extent and future developments of degradation of organic matter and consequently allows the determination of the maximum feasible extent of stabilization of the landfill c.q. the maximum feasible sustainable emission reduction.

So, profound knowledge and expertise of KPI's and how to interpret them, is crucial for the process design as well as for the technical design of the demonstration project and measurement / monitoring program.

The main indicators to monitor the development of the stabilization process of the landfill are leachate composition, methane production, landfill settlement and in situ waste temperature.

Annex 4 shows a complete list of KPI's, which have been scientifically accepted and/or have showed to be workable in already executed large scale projects. In the list the KPI's are defined and explained and it is indicated how to be measured.

The KPI's has been subdivided into:

- primary KPI's, which can be directly related to the main process of degradation of organic waste and the overall stabilization process of the landfill.
- secondary KPI's, which are related to the performance of the necessary and required conditions for a successful degradation process.

The KPI's allow answering the yes/no questions as indicated in the conceptual process design of figure 10.1.

10.5 Risk assessment

Environmental risk assessment method is based on the principle of the "source-path-receptor approach. With respect to landfills, four risk factors can be distinguished:

- Emission of landfill gas
- Emission of leachate into groundwater
- Emission of leachate towards surface water
- Contact with waste (coverage layer)

This feasibility study has been limited to the risks of emission of leachate and landfill gas from the source (i.e. the waste body).

The first part of the risk assessment should consist of a comparison between the measured and admissible emission levels. Standards that can be used are:

- The Dutch 'Circular on target values and intervention values for soil remediation (2008)';
- The Dutch 'Soil Quality Decree' , 22 November 2007 (Besluit Bodemkwaliteit);
- European Groundwater directive (Kaderrichtlijn Grondwater;
- EU-landfill directive annex II of 19 December 2002, concerning the limit-values of inert waste.

In annex 5 the relevant limit values of the above mentioned standards have been listed for various parameters.

A second part of the risk assessment should consist of drawing an overall picture of criteria, by which the effectiveness of enhancing technical measures with respect to the extent of stabilization of the landfill can be demonstrated and by which the consequences of a less stringent aftercare or release from aftercare can be assessed.

The development and elaboration of a sound process design with sufficient go/no go situations and decision moments, based on solid criteria, is a prerequisite to be able to assess in a reliable manner (see figure 6.15):

1. the extent of the achieved sustainable emission reduction and the corresponding remaining emission potential;
2. whether the admissible emission levels have been reached accordingly to the selected risk-based limit values.

The process design as well as the criteria should be developed in good cooperation and consultation with the competent authorities during the execution period of the demonstration projects. In this way the results of the demonstration projects might contribute to the creation of an accepted risk assessment method that includes both environmental and geotechnical aspects (see below).

The geotechnical risk assessment will be limited to settlements in the waste body due to the autonomic and enhanced degradation processes in the waste and hydrological effects. These settlements can be a risk to the overall stability and slope stability of the landfill as well as to the present infrastructure at the top of the landfill and can cause damage to top-liners, bottom-liners, drainage-systems for leachate and biogas.
During the demonstration projects settlements of waste will periodically be measured by means of settlement beacons, installed at critical positions.

10.6 Technical measures for enhanced stabilization of landfills

The feasibility study is aiming to demonstrate sustainable emission reduction at the existing landfills by means of the application of technical measures, which are able to enhance the natural stabilization processes in the waste body. It is not the intention to demonstrate the functioning of experimental and/or promising technical measures themselves. So it has been decided to apply only the technical measures, which have been often used at full scale landfills sites and have proven themselves with respect to reliable results. In this way the demonstration projects are concentrated as much as possible on the effects of the technical measures on the emission reduction (stabilization processes).

Due to this dominant assessment criterion, only the technical measures as showed in table 10.1 are eligible for application at the two existing landfills Kragge and Wieringermeer.

The assessment has been based on experiences and results of a great number of full scale infiltration and aeration projects at landfills worldwide. A list of these projects is presented in annex 6.

Table 10.1 Eligible technical measures for the demonstration projects

Infiltration/recirculation measures (anaerobic stabilization)	**Aeration measures** (aerobic stabilization)
▪ Linear shaped infiltration (trenches) ▪ Infiltration fields with well shafts	▪ Low pressure aeration ▪ Oversuction methods ▪ Active air injection without active extraction, but with a methane-oxidizing cover layer[3]

The final selection of technical measures to be designed at the two landfills Kragge and Wieringermeer is depending on the site-specific circumstances as well as on the current status of the landfills with respect to the degree of stabilization. These aspects are addressed in the two site-specific reports.

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[3] This option can be applied when the oxygen demand is very low in the final period of the stabilization process and when the exhaust shows almost no remaining methane concentrations. In this case a well working methane oxidyzing cover layer is of great importance.

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Annex 1
Terms of Reference

Title: Terms of reference feasibility study pilot project sustainable emission reduction at existing landfills

Client: Stichting Duurzaam Storten

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1. Introduction

This document describes the terms of reference for a feasibility study for a pilot project for sustainable emission reduction on existing landfills. In addition the required activities to be carried out are described. The feasibility study is a first step in order to execute a full-scale pilot. Theoretically it is possible that more than one landfill is suitable for a pilot project. For each landfill a number of specific aspects of the feasibility study need to be elaborated. This mainly concerns an analysis of existing data, prediction of the achievable level of emission reduction and the design of technical and procedural aspects of the pilot project (including permits etc.). The feasibility study will be executed for the landfills Kragge and Wieringermeer. It has to be emphasised that this choice does not necessarily mean a project will be carried out at both landfills. These terms of reference will contribute to a fair and uniform comparison of sites. In this document the framework, hypothesis and goal of the entire project are described. These lead to the specific goals and activities to be carried out for the feasibility study. In a concise form the most important criteria are described for the selection of one or more sites. Then the activities to be carried out for the feasibility study are described in more detail. After the proposal for project execution the deliverables of the feasibility study are described. The activities can be subdivided in generic aspects of importance to all sites and site specific aspects. In this proposal an attempt the distinction is clarified as much as possible.

2. Framework and hypothesis of the pilot project

2.1. Framework

The current policy concerning modern landfills in the Netherlands is base don the assumption that after the operational period landfills are isolated in order that water flow through the waste is limited to such an extent that emissions to ground and surface water are reduced to acceptable levels. In addition measures to capture and process landfill gas have to be installed. This approach requires eternal aftercare. The isolation measures on top of the landfill have to be kept in good condition and must be periodically replaced. The landfill operator is required to accumulate the necessary funding for isolation measures and buying off the eternal aftercare. Results of the Sustainable Landfill research show that in a landfill a huge number of processes occur that result in an emission reduction. It is technically and economically feasible to construct landfills in such a way that after an active aftercare phase a situation is created in which the potential emission of the landfill is low enough to discharge it from aftercare. The question at hand is whether stimulation of these processes on existing landfills can also lead to a significant reduction of the potential emission as a result of which less stringent aftercare or discharge from aftercare would be possible. An important basic assumption is that discharge from aftercare is preferred above eternal aftercare. The foundation is convinced that the EU Landfill Directive provides the possibility for aftercare that is tailor-made to the real risk of emissions from the waste body. This has resulted in the initiative to plan two pilot projects to demonstrate sustainable reduction of emission and to execute a feasibility study. It is a requirement that the pilot projects are carried out at full-scale. This means pilot projects will be carried out at existing landfills, that are recently closed, that have a bottom liner and where a surface sealing has not yet been installed. The pilot will occur in a complete landfill cell with a surface of several hectares and a height of the waste of 10 to 15 meters. The pilot projects will consider both anaerobic and aerobic stabilisation of the waste body by means of stimulation of degradation processes. This could be done with infiltration and recirculation of (pre-treated) leachate, enhanced gas extraction and/or active aeration. The basic assumption is that the bio- and geochemical conditions in the waste body are mainly determined by the presence and speciation of organic matter in the waste. Accelerated degradation and stabilisation of this organic mater results in conditions in which almost all critical compounds have a minimal solubility or are largely degraded. I addition there is a large number of processes, called ‘natural attenuation’ (NA), that can mitigate any possible emission outside the landfill. These NA processes are however not part of the pilot project at hand.

2.2. Terms of reference

It is important to emphasise that the pilot ‘Sustainable emission reduction on existing landfills’ is a demonstration project. This means that the following aspects are of great importance:

- Open communication with competent authority and policy makers.
- Open and extensive communication with national and international scientists.
- Achieving the results has to clearly demonstrated with measurements and data. This does at least apply to mass balances of compounds important in regulations with respect to emission control.
- The applied technology and process control has to be clearly substantiated and documented including costs and benefits.
- The result of the project and measures should be visible at a relatively short notice (3 to 5 years). This means that a measurement protocol and the necessary infrastructure should be based on that target.
- The project aims for reduction of the potential emission. It should be stated that 100% reduction down to acceptable emissions may not (always) be achievable. In that case it is acceptable to rely on NA processes in the groundwater plume influenced by leachate. This is however not part of the demonstration project. It means that both for the short term and the long term predictions will made concerning the potential emission. The models used for these predictions have to be properly substantiated. In addition these models have to be widely accepted by relevant experts.
- An independent risk analysis is essential for the assessment of the result of the pilot project. To that end it is important to have a well substantiated measurement and description of the situation before the start of the pilot. The results of the pilot project have to contribute to the creation of an accepted risk assessment method that includes both environmental and geotechnical aspects. The intention is that this method plays a role in a procedure for the discharge from aftercare.

2.3. Hypothesis

The potential emission of a landfill is determined by a complex of factors. The organic material present in the waste body and the extent to which it has been converted is of major importance for the potential emission of a waste body. Organic material determines to a large extent, but not exclusively, the geochemical conditions in the waste body and consequently the speciation of dissolved organic carbon (DOC), heavy metals and other compounds such as ammonium, nitrate, sulphate and methane. In particular the role of mineral phases, clay, Al -, Mn- and Fe-oxides should not be underestimated. Stabilisation of organic matter occurs because degradation by micro-organisms leads to conditions in which the potential emission of a huge number of compounds is substantially reduced. This is partly due to arising conditions with minimal solubility of a huge number of compounds (heavy metals, sulphides, ..) and partly because compounds themselves are degraded or converted (organic micro pollutants). The conditions for optimal growth of micro-organisms is determined by a number of factors such as moisture, pH, temperature, presence of nutrients and inhibitors. The hypothesis that forms the basic assumption of this project is that in all landfills degradation by micro-organisms is present (methane is produced). This degradation is far from optimal because the conditions in the landfill spatially differ very much. The main causes for this spatial variability in degradation conditions are related to variability in the presence of water. In addition to completely dry zones there are also hydrophobic zones. When there is insufficient moisture micro-organisms can not grow, small amounts of moisture are accompanied by high dissolved salt concentrations etc. On the other hand stagnant water is also not beneficial because a low degree of percolation and exchange could result in high salt concentrations, low pH values etc. Optimal conditions include sufficient and moving moisture everywhere in the waste body. An aim of the pilot project is to demonstrate that technical measures based on infiltration (remove dry areas), recirculation and perforation of impermeable layers (enlarge mobility, remove stagnant zones) result in a sustainable reduction of potential emission in the long term. The challenge for the pilot projects is to demonstrate this reduction of potential emission at short term (3 to 5 years), especially in comparison with the time scale of the emission process (decades to centuries).

3. Goals of the pilot project

- To implement and demonstrate the effectiveness of (technological) measures to substantially reduce the long term potential emission existing landfills.
- To achieve this by reducing the variability in hydrological conditions in the waste body resulting in an optimisation of conditions for biological conversion.
- The effectiveness of measures to reduce the potential emission has to be predictable. The results of the pilot shall contribute to the development of a prediction tool that is substantiated with models already developed. Among others clear changes in trends in measured and modelled gas emissions, variability in hydrological and degradation conditions can be used.
- To develop and apply a methodology to demonstrate that the potential emission has been reduced. This methodology forms an important element of the environmental and geotechnical risk assessment instrument. The methodology is substantiated with measurements, data time series and changes in variability of conditions in the waste body (before and during the process). Among others geophysical methods, conservative ions, speciation of organic matter, data time series of specific measurement points (gas potential, DOC), etc. will be used.
- The results of the pilot project contribute to the development of specific aftercare that is suitable for an existing landfill with a reduced potential emission.

4. Goals of the feasibility study

The primary goal of the feasibility study is to draft a well substantiated project proposal for two pilot projects. The substantiation concerns generic aspects comprising more than just the pilot projects and specific aspects relating to projects and the proposed landfill sites.

4.1. Generic goals:

- Describe the scientific framework of processes occurring in the waste body, especially concerning microbiological requirements for degradation in waste bodies.
- Present an overview of often applied methods and technologies to infiltrate and/or recirculate water and/or leachate by using experience of other projects in the Netherlands, Europe and the rest of the world.

- Describe general criteria for the selection of a suitable pilot site.
- Develop and execute data analysis methodology to analyse available data time series of potentially suitable landfill sites.
- Establish which environmental and geotechnical risk assessment methods are suitable for evaluation of potential emission. Establish what type of results is required to substantiate such a risk assessment method. This is crucial, because it determines successful demonstration of effectiveness of measures.

4.2. Pilot specific goals:
- Select and/or confirm the sites for pilot projects.
- Execute the site specific data analysis to concretise the goals of the pilot projects.
- Concretise the execution of the pilot projects. Elaborate the experiments and the accompanying measurement protocol in such a way that the results of measures to be implemented can be shown in with statistical significance considering the available information.
- Draft a substantiated project budget to support an investment decision by the operator.
- Guarantee active involvement of the competent authority with the execution of the pilot project.
- Draft a basic project plan.

5. Requirements for the selection of suitable sites
Not all landfill sites are suitable for the execution of a pilot project. The minimum requirements are:
- Closed landfill.
- Knowledge on amounts and composition of the waste disposed over time.
- Presence of a bottom liner.
- Surface sealing not yet installed.
- Maximum height of the waste not more than approximately 15 meters.
- Presence of compartments in the bottom liner, including the possibility to separately measure and control the gas and water management.
- Presence of a leachate treatment plant.
- Availability of data time series concerning the development of leachate quality and quantity, the amount of landfill gas produced, the quality of landfill gas and possibly additional measurements and analyses to complement the available data.
- Availability of infrastructure to measure and sample individual leachate drains, gas wells, piezometers, etc.
- Willingness of the landfill operator to invest in the pilot project.
- Consent and approval of the competent authority with respect to the pilot project.

These requirements will be concretised in the feasibility study.

6. Activities of the feasibility study
The activities for the feasibility study can be subdivided in four main activities:
1. Collect and compile available information with respect to infiltration, extraction and recirculation. Perform a scan for requirements for biological degradation in landfills. Concretise the requirements of chapter 5 concerning the selection of pilot project sites.
2. Develop a generic analysis method of available data time series and additional information aiming at a best possible prediction of the result to be realised with the pilot project. The method is applied to assess data sets made available of possible sites in order to substantiate the selection of the pilot and to draft a specific project plan for the pilot. Possibly some additional measurements will be included.
3. Financial substantiation of the pilot project, creation of acceptance by the competent authority and other stake holders. The method of cost estimation is laid down in a generic budget for a pilot project.
4. Draft a basic project plan that serves as template for detailed elaboration of the site specific project plans after selection of suitable sites. The site specific project plan includes a draft design of the pilot project, an elaboration of the management of the measures and an elaboration of the research, measurement and monitoring protocol.

6.1. Collection and compilation of information

During a preparatory workshop (Appendix B) on 17 December 2007 techniques to reduce emission that could be implemented on landfills were discussed. The focus was on measures that influence or control the gas and water phases. It is clear that different methods can be applied. They each have their advantages and disadvantages. In the feasibility study the information in the tables (see Appendix A) is used to obtain an overview of national and international experience. In addition it is important to obtain an overview of which conditions are important for biological degradation of organic matter. This information is important to determine the measurement and monitoring protocol to convincingly show that the potential emission is sustainably reduced. The following aspects have to be taken into consideration:

- Scan experience in The Netherlands, Europe and world-wide. The starting point for this activity is in the previous investigations and reports carried out by TNO and the experience available with landfill operators and consultants involved in DS2.
- Compare different techniques (technical solutions, management regime, ..) applied for infiltration, recirculation of leachate and clean water and injection of air.
- Evaluate the method of monitoring (performance indicators) and the results that were achieved.
- Compare goals of the different projects with the results achieved. As much as possible project managers and scientists involved are interviewed to obtain background information. The goal is to obtain understanding of what works and what does not work and if possible why it does (not) work.
- Identify options to degrade organic matter and to reduce the resulting potential emission, such as stimulation of moisture transport, perforation of impermeable layers (e.g. application of Mebradrains), pre-treatment or heating of leachate before infiltration, etc.
- In addition to anaerobic methods also aerobic methods are to be considered. This concerns methods of aeration etc.
- Evaluate possible control strategies, e.g. combine techniques (e.g. start with leachate infiltration and follow-up with air injection; combine geophysical investigation and goal oriented measures, nutrient dosage etc.)
- Compile experience concerning limiting conditions for biological degradation of organic matter and organic pollutants (at least in terms of order of magnitude). It is expected to be possible to indicate which measurements could be carried out to verify what limiting conditions occur in the pilot projects. In selecting sites it is useful to verify the expectations with actual measurements.
- Assess which methods and techniques are available to verify whether the goal of the pilot (sustainable reduction of emission) has been achieved. Available experience, the way in which techniques have been applied to show the target was achieved, the problems and opportunities, the performance indicators are to be considered. It is extremely important to execute a proper set of measurement to establish the situation before starting the stabilisation project in order to unambiguously determine the reduction in potential emission.

The results of this study are generic and relevant for the complete sustainable landfill research. They will be reported in English. In the report the findings are elaborated in such a way that they enable a substantiated choice concerning application within the boundary conditions of the pilot project. It is important to have detailed understanding of design parameters, costs and expected results to be obtained with techniques for infiltration, extraction, recirculation and aeration. The results are to be elaborated so that it is clear how the techniques will be applied. The accompanying measurement and monitoring design is to be described, including the performance indicators with which the effect of the different measures to be implemented will be shown. In addition the knowledge and understanding obtained during the study is to be applied to supplement and specify the requirements for pilot project sites as described in chapter 5.

6.2. Data analysis and prediction of results

The operators of the Wieringermeer and Kragge sites, after establishment of compliance with the requirements described in chapter 5 and concretised in activities in paragraph 6.1, will make data time series available of amounts of gas formed, gas composition, amounts of leachate formed and leachate composition. In case these data are insufficient for this feasibility study the operator will arrange for additional sampling and analysis at short notice. In recent years enormous progress has been made in the development of models and concepts that can predict the future behaviour of landfills. It is extremely important for the pilot projects to state which result is desired with the methods to be implemented and what the uncertainty of the prediction is in order to draw solid conclusions afterwards. In order to achieve this it important to carry out the following steps:

- A statistical interpretation of existing data time series to indicate trends and to obtain understanding of temporal and possibly of spatial variability of the selected sites.
- With existing information from the DS1 pilots execute scenario analyses fed with information measured at different sites in order to obtain understanding of the current status of the pilot project sites and the achievable results. Apart from LeachXS also a number of different suitable models are used to explain the landfill gas production and to make predictions about the future. Based on these results understanding is obtained of the achievable ‘band width’ and statistically significant conclusions on the extent of emission reduction.
- Based on realised gas extraction and an evaluation of the level of degradation of the waste (possibly as an element of the measurement prior to starting the project) an indication is given of the amount of organic material that can still be converted and the amount of landfill gas to be produced. Also an indication is given on the amount of oxygen required for aerobic conversion.

With these activities a generic method is substantiated to determine the current status of sites. This has consequences for the establishment of what we want to achieve and which measurements are required to verify this. The statistical interpretation provides understanding of the statistic significance of the results to be achieved. In other words, how big should the effect on the measured performance indicator be before a solid conclusion can be drawn? Based on these statements conclusions can be drawn concerning the goals of the pilot projects and the results realised in previous projects (USA, France, Germany, United Kingdom). Special attention will be given to the extent in which hard conclusions are drawn based on measurement results. It is expected that with respect to drawing conclusions a recommendation will be done to adjust measurement frequencies and parameter sets prior to the start of the pilot projects.
The method of data analysis is generic and relevant for the complete sustainable landfill research. They will be reported in English. The results of the data analysis are specific for the selected pilot project site, but will (due to the new situation of organisations involved) also be reported in English. The results of the data analysis serve to substantiate the proposed measurement and monitoring protocol. This concerns sampling and measurement methods, number of observations, etc. This is to be done based on the activities described in paragraph 6.1. For each pilot project a number of recommendations are given for establishing the situation prior to the start of the project and the expected changes in certain parameters that are indicators for the relevant processes and for verifying the intended result.

6.3. Financial substantiation

The execution of a pilot project is very expensive. An estimation of the required budget for the different activities is very important. As a first activity in the feasibility study the generic costs of the different techniques possibly applicable in a pilot project are determined. The generic costs are translated to the specific pilot project. To this end a detailed planning of the implementation of different techniques is required. The cost estimation will be carried out in general terms and in a number of exercises. The cost estimation template will be based on the conditions and suitability for the Wieringermeer and Kragge landfill sites. As much aspects as possible will be elaborated concretely.

It is emphasised a final cost estimation can only be made after a decision by the foundation. Only then detailed offers can be requested from suitable contractors. The financial feasibility depends on a large number of external factors. Sustainable reduction of emission intends to achieve an end to aftercare or at least a less intensive form of aftercare. The costs to realise this have to be balanced by potential cost reductions the landfill operator or other future benefits. Future benefits can be revenues for the operator as well as general societal long term benefits. It is therefore of eminent importance that all stakeholders are involved in the valuation of benefits and weighing the investments and revenues to establish the feasibility of sustainable reduction of emissions. An important assumption is that cost savings related to delay in the construction of a surface sealing will have an important contribution in financing the immediate costs of a pilot project. This assumption has to substantiated and verified. To this end the approach in the realisation of the Vlagheide pilot project will be adopted.

6.4. Social acceptance
An important element of the feasibility is in the social acceptance of sustainable reduction of emission, most of all with the competent authority. This means that defining sustainable reduction of emission, defining the methodology to assess the risk of potential emission, defining the acceptable level of aftercare at different levels of reduced emission has to be done in close cooperation with the competent authority. The result of this activity should lead to a positive and constructive contribution of the competent authorities to the execution of the pilot projects. It will not be possible to fully elaborate an environmental and geotechnical risk assessment methodology. It will also not be possible to fully elaborate the acceptable levels of aftercare at different levels of reduced emission. The results of the pilot project will contribute to the future development of such methodology. Commitment and an active contribution of the competent authorities with the pilot projects will enlarge the success rate. It is required to obtain permission to delay the construction of the surface sealing in order to have a sufficiently long period of monitoring supplying meaningful results. It is therefore important to pay attention to current permits, potential limitations and activities, measures or equipment for which permission is required.

6.5. Basic project plan
With the results of the feasibility study a basic project plan for the pilot project to reduce emission will be drafted. The basic project plan is a template for the final project plan on the selected sites. The basic project plan will be drafted with the Wieringemeer and Kragge sites in mind. It will be drafted in consultation with all parties involved in the feasibility study. The basic project plan needs to include the following aspects:

- Design of the pilot (drawing that indicates infrastructure for leachate infiltration, air injection and required measurements).
- Schematic representation of the required management of the different measures applied during the pilot project.
- Representation of the experimental programme.
- Detailed description of the measurement and monitoring protocol.
- Draft a model for cost estimation of the entire pilot project.
- Scheme for the exploitation of the pilot project.
- Scheme for planning of activities of the pilot project.

7. Project execution and management

7.1. Allocation of tasks
In Figure 1 the different tasks and responsibilities of parties involved in the sustainable landfill research are represented. Understanding the different tasks and responsibilities is important for an efficient execution of the feasibility study and the pilot projects.

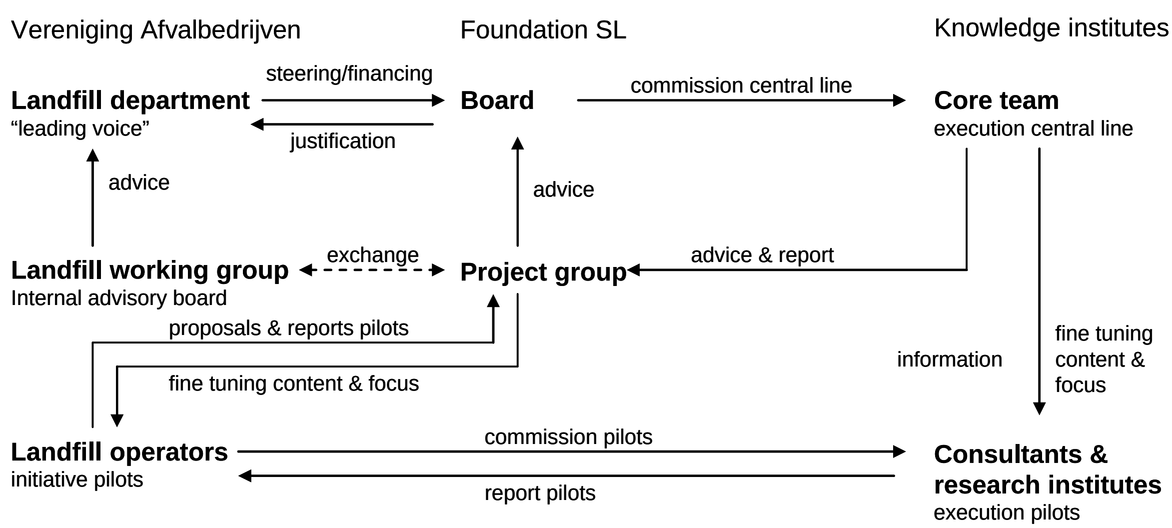

Figure 1. Tasks and responsibilities.

Based on these terms of reference and considering Figure 1 the following steps will be undertaken:
1. Landfill operators take the initiative to propose a site for a pilot project.
2. The foundation requests an offer and commissions the feasibility study to a (group of) consultant(s).
3. Findings of the feasibility study are reported to the project group.
4. Landfill operators initiate final design and cost estimate and submit a proposal for construction and execution of a pilot project to the project group.
5. The project group submits an advice to the board of the foundation.
6. The board decides about the pilot and the financial contribution from the foundation.
7. Landfill operators and board sign an agreement on the pilot project.
8. Landfill operators commission the construction and execution of the pilot projects, this includes measurements and monitoring and supervision by the consultants involved in the research programme.

It is important to assign different activities to different persons (and organisations) since each activity requires specific competences. Collection and compilation of generic information is best carried out be someone with an excellent understanding of processes occurring in landfills, experience with working on landfills and knowledge of civil engineering methods and techniques. It is important that this activity, especially in its initial stages, is controlled by Hans Oonk en Hans Woelders. They have a good overview of projects that have been carried out in The Netherlands, Europe and world-wide. Data analysis and prediction of results is best carried out by an ECN employee, since experience with LeachXS is important Drafting cost estimates and realisation of social acceptance is best carried out in close cooperation with a landfill operator. The basic project plan is drafted in cooperation with all parties involved. The core team will have an important role to test and check achievements. Progress of the work will be guarded by both the core team and the project group. The coordination of the work should be in the hands of one of the involved parties. Preferably this is the party that is responsible for providing the basic project plan.
This terms of reference document is intended to support the process of commissioning the feasibility study and the design of pilot projects.

7.2. Project planning

The feasibility study is preferably started in September and will be finalised before the end of November 2008. This will enable an investment decision by the landfill operators in budget formulation process for 2009 at the end of this year. The time schedule of the feasibility study will be determined by the time required for planning and organising of consultation. Before a budget for a pilot project can be drafted it is important to have sufficient technical information and the way in which the reduction of emission is to be realised.

8. Deliverables

The most important product of the feasibility study is a report to the foundation. Based on this report the foundation and the landfill operators can make a decision on execution of the pilot projects. The report consists of at least five parts: a generic part, two site specific assessments and two basic project plans (for Kragge and Wieringermeer)

- The generic part provides an overview of techniques that can be applied to sustainably reduce landfill emission and a method to interpret data time series of landfill sites in the framework of a landfill stabilisation project.
- The two site specific assessment reports contain the results of the data analysis and are the final check for suitability of the site. They should also provide the description of the current status of the site necessary for drawing statistically significant conclusions later on.
- The two basic project plans describe the technical measures, the expected results, the measurement and monitoring protocol and the required permits. In addition the basic project plans contain a budget estimate and a section dedicated to potential benefits.

Appendix A: Aspects relevant for influencing processes with the water and gas phase.

	General	**Degradation OM**	**Nitrogen**	**Heavy metals**	**Oxy-anions**	**Major elements**	**salts**	**Stability/settlement**	**Infrastructure**	**Heterogeneity/preferential flow**	**Physical properties**	**Water content / distribution**	**Organische micro's**
Characterization													
sample analysis	Quality of leachate can be determined from samples taken at different locations. Analysis package and sample quality should ensure complete geochemical analysis. Define minimum requirement for analysis	analysis of samples, BOD/COD ratio's but perhaps also some biological tests? Assessment of ratio organic and inorganic carbon? Organic matter fractions HY, FA, HA. Voor aansluiting op nieuwe regelgeving wellicht ook TOC/DOC meten. Totaal C, opgelost vs gesuspendeerd? Boorprofiel, afvalmonsters (ingevroren en bewaren).	analysis of samples, distinction in ammonium etc.	idem	idem	idem, crucial for modelling chemical speciation (not same frequency as other parameters). Carbonaat, Na, K, Mg, Si, Fe, Mn, Ca, Al, SO4, Cl	idem, monitoring of EC in time in leachate but also within landfill		How to collect samples. Incidental and fixed sampling points. Trenches, drains, vertical wells?	samples from drains, monitoring-wells etc.	tracer tests voor porositeit … diffusie.		niet alleen BTEX, PAKs maar ook endocriene disruptors, weekmakers (ftalaten). Deze componenten zijn tegenwoordig een hype. Discussie zelf niet opstarten, maar afwachten tot overheden met de vraag komen. We hebben dan mogelijk al informatie. Checken met de EPRTR-lijst (ook voor gas), vastgesteld door VA.
water flow	landfill is an unsaturated/saturated system with a significant amount of preferential flow - Magnitude can be estimated (safety factor may be applied to take future channelling changes into account). Perhaps we need to resort to more stochastic approaches of modelling water flow (resident solute lifetimes).Alleen stortpercolaat of ook in de grondwaterpluim? Alleen pilot op een stortplaats met bodemafdichting (anders is de massabalans moeilijk sluitend te krijgen)? Dat laatste is waarschijnlijk een voorwaarde om een pilot te mogen uitvoeren (toestemming bevoegd gezag). Mogelijk wel een grondwatermonitoring toch noodzakelijk, we kunnen dan de NA monitoring uitvoeren.	Degradation may change permeability due to clogging	ammonium en nitraat				May be used to quantify preferential flow (e.g. Nauerna) when information is available on the total salt content.				water retention characteristic, porosity, density etc. etc.	Hydraulic pressure, matrix potential, water content measurements (preferably realtime), geophysical methods. Op meerdere momenten. CH4/CO2-ratio's. vochtsensoren in het afval.	
Historical data	Pilots from DS 1. Kolomonderzoek van Roberto. Eventueel andere kolommen?	Status of degradation in pilots fromDS1	Data generated in pilots from DS1	Data generated in pilots from DS1	Data generated in pilots from DS1	Data generated in pilots from DS1	Data generated in pilots from DS1						
Manipulation													
infiltration / irrigation	A wide range of options is available. Ranging from surface ponds , infiltration beds/blankets, trenches, drains to different kinds of vertical wells. What criteria are important to make choices on how to proceed? Flooding?	Water content is important for degradation. Dry landfills are more or less mummified. Degradation of organic matter consumes water so for some systems additional water is required. Question is how much water should we add? How can we assess if it is enough? Are there tools to identify dry spots and with injection ensure wetting of material at appropriate places (I suppose not so much water needed for degradation. A lot more needed for flushing).	Infiltration is a means of adding (traces) of oxygen in to the landfill. This oxygen will oxidise some of the nitrogen available as ammonium. How much denitrification will then occur. How much acidification due to sulfide oxidation?	?	?		Salts behave more or less conservatively. The only way to get rid of them is by leaching them with the water. In principle this is a dilution proces. Can we calculate how much water we require to reach the defined regulatory values. Best to limit salt load in acceptance.	Addition of water will compromise the stability of a landfill. We must have an idea how this happens if we want to proceed safely.	As remarked in the general section, choice of infrastructure will be very important	Heterogeneous flow is known to be an important factor in landfills. We need to quantify this effect. Using infiltration experiments and tracers gives us a unique opportunity to attempt to quantify the aspects of heterogeneous flow.	Hydraulic conductivity (changes) of the landfill is important. Especially the heterogeneous distribution. This requires a 3D conceptual approach.	This will be very heterogeneous. How much dry spots are acceptable. What can we do to make dry spots wet? Can we quantify the distribution in water content in a for a landfill sensible way?	

recirculation	We need means to extract and re-infiltrate the leachate. We must be aware of clogging etc. due to enhance biological activity and perhaps even the formation of mineral precipitates.	Recirculation is known to enhance the degradation. Different hypotheses are given on what causes this enhancement. On the one hand water content, on the other hand transport. Can we carry out an experiment to quantify the different effects? Scale will be important? Aim for degradation is "easier" to achieve than flushing salt. Wetting may be sufficient for degradation to occur. "Surgical injection of water"	Recirculation can also be a means of adding oxygen to the landfill in order to stimulate nitrification and denitrification. Traces of nitrite are important for the anamox proces. How can we optimize our recirculation proces in order to have an optimal nitrogen removal.	DOC levels need to be decreased. Largely inorganic - low release	Solubility limitations are likely. Fe III oxide may be an active control under oxidisung conditions		Can we remove salts during recirculation. Probably very expensive...	Enhanced degradation will increase the settlement speed? Can we control the process.	Again a challenge, especially when leachate from different sections of the landfill will get mixed because clogging will be difficult to prevent. What should the scale of the manipulation be? It may be that a number of small(er) scale systems are easier to control than one large scale system?	see above, perhaps we can figure out a tracer experiment. Another important question is the scale of the manipulation. Do we have a large number of small scale local recirculation systems or one large scale system for the whole compartment?	geophysical monitoring tools.		
leaching	Leaching occurs when water is not recirculated back in to the landfill. This requires a significant amount of waste water treatment. What should we do about the salts? Is it necessary at all, how much water needs to be treated?						Leaching only starts to be significant as soon as 2 to 4 pore volumes have been flushed. How much water is required to reach this?						
treatment	Treatment of the leachate can be carried out during recirculation (i.e. the biorotor at Landgraaf) but also at the end.		We moeten er ' iets' mee om tot duurzame niveaus te komen. Kunnen we wat leren van oude stortplaatsen. Kijken of we het kunnen inpassen in de pilots.										
Proces monitoring													
In-situ in the landfill body	This should be done with sensors. Water content and conductivity are the most easy sensors to apply. Non invasive geophysical approaches can also be used. Which choice should we make. Develop a tool to inject water locally and after one day extract this water or a part of it again for analysis. "Omgekeerde porous cup"	The water content in the landfill is an important measure to estimate the possibility for biodegradation processes?					pH geleidbaarheid redox	Measurement beacons, water tension measurement, volumetric watercontent		tracer experiments			sensors, geo-elektrische metingen?
In the recirculating leachate	sensors for pH, E.C., T and Eh. Flowmeter	Biodegradability testing. DOC analysis	Analysis of nitrogen species	Chemical analysis	Chemical analysis	Chemical analysis			Sensors and data loggers for general data (pH etc.)				
On waste samples taken in time	Obtaining samples from a relevant number (to be defined) borings and preparing a composite sample for testing a well as an evaluation of the variation of the individual samples against the characterisation of the composite may prove very useful as reference base for the monitoring of the modifications to the cell or compartment . Randvoorwaarde: infrastructuur voor watermonstername zo aanleggen dat per compartiment gestuurd en gemonitord kan worden. Hoe compartimenten scheiden? Keuze grootte pilot op basis van te verwachten randeffecten. Eventueel omliggende compartimenten ook monitoren. In praktijk zijn compartimenten niet fysiek gescheiden met verticale folie-afdichtingen!	Analysis of OM content, biodegradability testing.	Leaching test and analysis of nitrogen species	Leaching test	Leaching test	Leaching test		Core drilling devices. There is a substantial risk of heterogeneity in sampling	Heterogeneity is substantial when separate samples are taken. Proper composite samples need to be tested in conjunction with the subsamples.				

Proces prediction													
Empirical data drive models (state space)	Using correlations over time in the measurement data set has proven to be good way to make predictions on future behaviour. (Is this true?? Hans) This approach is a way of using the data to find clues on important proces relationships.												
Mechanistic models	A wide range of models has been published. However, very little models have been developed to be applicable for our situation. Full mechanistic model of Nauerna and Landgraaf do a pretty good job. This can be easily adjuted to take preferential flow under conditions as observed in the full scale cells into account.The real question is if complex hydrology will tell us so much more	It is important to have an overview of the different approaches to OM degradation modelling in landfills. In this we can use our approach from DS1 as a benchmark and reference point. Do we need additional processes included in our models? Expand the DS 1 model with full chemistry in LeachXS as a scenario	Important processes to consider are denitrification and the anamox process.	LeachXS in combination with orchestra is very much the state of art. Coupling to transport and physical structure might be interesting.	LeachXS in combination with orchestra is very much the state of art. Coupling to transport and physical structure might be interesting.	LeachXS in combination with orchestra is very much the state of art. Coupling to transport and physical structure might be interesting.	LeachXS in combination with orchestra is very much the state of art. Coupling to transport and physical structure might be interesting.	Geomechanical behaviour of landfill bodies has been the subject of much modelling efforts (McDougal, Beaven and White) We need to start a collaboration in order to make use of their ideas...					
Combinations?	Haarstrick pointed towards a hybrid modelling approach for tackling heterogeneity etc. Mechanistic models are combined with neural network and fuzzy-logic modelling approaches. We need to collaborate with him on these issues.Annette Johnson studied infiltration and rain events in landfills , may be worthwhile to have a look at that and build a LeachXs scenario that allows intermittent wetting simulating rain events.			aangenomen DOC - zware metaalrelaties robuust? Wat gebeurt er bij mineralisatie?									

	General	**Degradation OM**	**Nitrogen**	**Heavy metals**	**Oxy-anions**	**Major elements**	**salts**	**Stability/settle-ment**	**Infrastructure**	**Heterogeneity/preferential flow**	**Physical properties**	**Water content / distribution**	**Temperaturen**
Characterization													
sample analysis	Air samples can be taken from sample points within the landfill and from the gas extraction . Voor compartimenten/delen van het afvalpakket moeilijker dan voor een integrale stortplaats. Eventueel monstername en bepaling gasvormingspotentieel … wel een lastige meting.	Measurements of produced amounts of gas en composition (CH4, CO2) provide insight in the degradation of biomass. The most mass disappears from the landfill in the form of gas. "Haal produced amounts er maar uit. Niet per bron." Vlagheide wel … CH4, CO2, O2, onderdrukken, onderdrukverschillen. Sommige stortplaatsen periodiek geheel palet aan componenten. Deel van balans, want diffuus emitterend deel wordt niet gemeten. Vergelijken met stortgasmodel in combinatie met een emissiemeting. Emissiemetingen duur, dus in combinatie met emissiemodellering. Temperaturen zijn belangijkre indicatoren!!	It will be nearly impossible to quantify the amount of nitrogen removed from the landfill as N2. NH3 emissions can be measured. Stable isotopes may provide a tool. Eventueel te meten in anoxische zones. Twijfel aan toegevoegde waarde. evt. NH3-monsters bij bronnen bij beluchtingsproeven.	Hg in stortgas mogelijk een probleem. Amerikaanse publicatie via Heijo.	n.r.	n.r.	n.r.	Klink wordt vaak geregistreerd en is mogelijk ook van belang en niet direct te relateren aan biologische activiteit. Eventueel USA-ervaringen.	Zou aanwezig moeten zijn op de locatie van pilot: bronnen, meestal niet voorzien voorzien van debietmetingsvoorziening. Zou mobiel eventueel wel aan te brengen moeten zijn. Eventueel bronnen geschikt maken voor waterinfiltratie. Vraag is of dit wel te combinatie is.	Alpha-factor 13C/12C mogelijk indicatie van voorkeurskanalen, informatie van Heijo. Eventueel luchttracertests bij luchtinjectieproeven (informatie USA, Oostenrijk, Hans, Heijo). Uhrmann heeft een push-pull methode voor bepaling methaanoxidatie. CH4/CO2-ratio is mogelijk een maat. Rapport ESF eind januari	n.r.	Waterbalans compleet? Water is een randvoorwaarde. In geval van aerobe stortplaatsen waken voor uitdroging.	Bronnen volgen. Sondes in stortlichaam plaatsen?
water flow	water impedes gas flow and vice-versa												
Historical data	Gas production and composition is a very dynamic process. Long term data-sets provide a means for quantification initial amount of reactive organic carbon available in the landfill. Zie sample analysis.												

Manipulation												
infiltration / irrigation	The idea is that increased watercontent results in increased reactivity and as such increased gas production. Misschien is dit alleen maar een idee … Kijken naar voormalige stortplaatsen? Valt mogelijk veel uit te leren voor wat betreft water en gas.	Effect waterkwaliteit op effectiviteit percolaatwaterkwaliteit. Hoe hoeveelheid water die je inbrengt te optimaliseren … moet je stoppen bij veldcapaciteit of kun je verder gaan. Ontwerp is belangrijk, rekening hoeden met schijnwaterspiegels. Beinvloeding water en gasonttrekking.. zo ontwerpen dat ze elkaar niet in in de wielen rijden. Schoon water of percolaatwater gebruiken voor recirculatie?							Semi-permeabele afdichting? Grond afdichting? Oxiderende laag? Hoe minimaliseren we de resterende emissies. Chemische additieven?			
recirculation	recirculation increases degradation rates and as a result gas production											
leaching												
treatment	produced gas is generally burned											
aeration	Oxygen can be supplied to the landfill body by forced aeration. Landfill gas production should decrease, ratio of CH4/CO2 should decrease significantly. What stop criteria should we use when applying forced aeration. Je kunt de vraag misschien beter andersom stellen: Wanneer ga je beginnen? Als je te vroeg begint --> energieverlies, broei? HAns W. Enzymen? Debieten volgen en vergelijken met het gasproductiemodel. Water en gas combineren. Via het gasmodel bepalen op welk moment er belucht moet gaan worden.		Nitrification should be stimulated, as a result NH3 emissions should decrease. N2 emissions should increase (stable isotopes?)	Oxidation of reduced species may result in increased mobility. Reduced iron species will oxidize thus increasing adsorptive surface area.				Increased aeration will result in increased biodegradation and as a result we expect an increased settlement.	Oxygen in an aerobic environment is highly toxic for a large part of the microbial population. Dissolved reduced species will oxidize, generally resulting in precipitates. As a result clogging is expected. Hoe uit te voeren? Koppelen aan het gasproductiemodel om te bepalen wanneer er belucht moet gaan worden. Welke brondichtheden, debieten? Leidraad Huub Glas voor percolaatinfiltratie.	Flow of air caused by forced aeration will take place via preferential flow paths. Transfer rates to the landfill bulk will be controlled by a diffusive proces. It will be important to quantify this diffusion rate in order to estimate the length of time aeration will be required. Another important question is if the aerobic conditions will persist after aeration has ceased.		
Proces monitoring												
In-situ in the landfill body	Gas pressures, in-situ oxygen levels, in-situ redox condition are important parameters for monitoring the effects. Measurement of the gasproduction in-situ.											
In the recirculating leachate	pH and redox											
On waste samples taken in time	Organic matter composition. Goed nadenken over hoe wat en waar ivm heterogeniteit. Karakterisering in termen van stabiel en reactief organische stof.											
In the gas stream												
Proces prediction												
Empirical data drive models (state space)	Many landfill gas production models are available. Some are even integrated with organic matter degradation and geochemistry. LeachXS has this capability. These range from fully empirical (exponential models) to more mechanistic descriptions.											
Mechanistic models												
Combinations?												

Appendix B: Memo in preparation of the workshop of 17 December 2007.

Workshop Pilot: improving the sustainability of current landfills

Timo Heimovaara
November 14, 2007

1 Introduction

1.1 Goal of the whole project

The goal of the second sustainable landfill project in the Netherlands (DS2) is to provide knowledge and data on improving the sustainability by significantly reducing the potential emissions of existing Dutch landfills so that policy makers and regulators are willing to accept the reduced emission concept and that they will start to stimulate its application. In addition, we aim to increase acceptance by landfill operators in such a way that they will start to implement reduced emission concepts in the day to day practice of land-filling. The main reason for accepting the concepts is that it is better for our environment while being intrinsically safe and therefore a long-term solution.
In order to achieve this goal we need to develop an instrument for long-term sustainable management of landfills. This instrument should assist landfill operators to collect relevant data and make (economic sound) decisions based on the collected data. In addition the instrument will assist landfill operators to explain the rationale behind certain measures because different scenarios will be implemented so that (future) consequences of certain measures may be compared. The instrument should enable us to select optimal measures for stabilizing the landfill as well as providing criteria (accepted by the authorities) which will have to be fulfilled for reducing the aftercare efforts based on the reduced potential emission or even releasing the landfill from aftercare.
In principle we want to aim for an isolation and aftercare regime that is proportional to the potential emission, and any measure that can be implemented in order to reduce the potential emission will result in benefits during after-care.
This goal is very ambitious and due to the small budget only a very limited part of such an instrument can be achieved. In the end of 2009 we will have developed a simple version (version 0.1) which will give an indication of the possibilities of such an instrument. This version will have limited functionality but it will provide a reference point for future development and the feasibility of the approach should have been demonstrated.

1.2 Building blocks

In the previous project (DS1) three pilot projects were started and carried out. Initially each project was considered to be a separate approach that was able to stand on it's own. However, in the course of the project we realized that landfills (although using different land-filling concepts) behave in similar fashion. Using a conceptual modelling approach, we were able to come up with an approach in which we could link the three pilot concepts with each other. For the current project the monitoring of two the previous three projects is to be continued and we have included the Vlagheide pilot because of an overlap in goals. The reason to include these pilots in this project is because the knowledge developed in these pilots, the available data and the possibility to (easily) carry out additional experiments provides important building blocks for the overall goal of the project.
Another very important building block is LeachXS. In the former project, data has been added to the database of LeachXS and expert modules have been added making LeachXS in to a very versatile expert system. With this system we can compare the chemical development of a landfill with many other landfills, simulate the development over time and thus make predictions about future behaviour. In order to facilitate data interpretation, results can immediately be compared with different types of regulatory levels. As such LeachXS is a very important expert tool in this project for interpreting and integrating the data that has been and will be collected.

1.3 Goal of the workshop

The goal of this workshop is to define the setup of the new pilot(s) which is(are) to be started in the DS2 project. A pilot is to be carried out on a landfill that is currently in operation or has recently been closed. In addition the pilot should be considered to be an extra building block for achieving the final end goal of DS2. In the workshop we want to make an inventory of possible experiments we can carry out while at the same time checking the feasibility with the landfill operators present at the meeting. In addition we want to achieve a common understanding on the goals and ambitions for this project.

2 Approach

A number of important issues, of which we need to pay more attention to, have been defined in the first project (DS1). The most important issues were identified to be:

- Regulatory values need to be reached for all parameters. If the reduced emission concept is able to realize the limit values for all parameters except one, regulators will probably still require stringent precautionary measures which will certainly be expensive.
- Important possible problematic parameters have been identified to be nitrogen, salts and perhaps some of the oxy-anions. Conditions in the surrounding environment of the landfill may provide a means to overcome these problems.
- The heterogeneity of water flow in the landfill and the consequences this has for the flushing of salts, the bio-degradation, etc. We realize that heterogeneity is a fact of life - the question is if it is possible for us to identify parameters and safety factors for predicting the long term behaviour in preferential flow paths.
- The behaviour of nitrogen is highly related to the behaviour of the living biomass within the landfill. Nitrogen processes are extremely complex and are very much dependent of the redox condition. Aeration may result in removal of nitrogen from the landfill while stimulating the stabilization of the waste. However, we must take the effects of oxidation on other parameters (such as a possible remobilization of heavy metals) in to account as well.
- Irrigation, recirculation, aeration etc. require significant amounts of infrastructure in the landfill body. What is technically possible when installing infra-structure in already existing landfill bodies? What are the costs? What are the benefits? Which type of infrastructure is best?
- Manipulation of processes in the landfill is most easily done by manipulating water and gas flows. What effects does this manipulation have on the stability of the landfill body? What precautionary measures should be taken?

2.1 Defining the research questions for the pilot

As stated above our only real option to manipulate the processes in an existing landfill body is to play around with the aqueous phase (including additives) or with the gas phase. In addition we have defined the most important issues we need to investigate in the previous paragraph. In order to organise the results from the different building blocks we identify a number of generic activities in the project(s):

- characterization of the current (and former) state;
- identification and quantification of the most important processes;
- manipulation of important processes to achieve our goals;
- monitoring of the processes and changes in the state;
- prediction of the future state as a result of different manipulation scenario’s;

In general identification and quantification of the most important processes can best be done by performing experiments in which we manipulate the processes, so we will combine experimentation and quantification. In order to provide an overview of the different options we combine all information in two tables (see accompanying spreadsheet), one for the water phase and one for the gas phase. In each table we have the important issues along the horizontal and the generic activities along the vertical. In the resulting fields of the table we can identify the questions and issues which we need to address in the project. Our ambition is to define and prioritize the most important questions in the workshop. In the workshop we will also try to point out the direction the activities must take in order to answer the important questions. In addition we will also try to define the important criteria which must be fulfilled beforehand in order to achieve a successful project

2.2 After the workshop: Filling in the projects

After having identified all important questions we can define the activities we have to carry out in order to obtain the answers. We can expect the activities to be a combination of experiments both in the field and lysimeters as well as in the laboratory, theoretical literature study and modelling based on the experimental results. In order to carry out this activity, the tables will be completed in order to get an overview of all questions. Then Hans van der Sloot, Hans Oonk and Timo Heimovaara will try to fill in the activities for each question and finally all results will be compiled in to a proposal for the Project Group.

Annex 2
Members of project team, core team and project group

Contractors

The feasibility study is executed by the Dutch consultant Haskoning Nederland B.V., a company of Royal Haskoning in Nijmegen (NL), in cooperation with the German consultant for waste management IFAS (Ingenieurbüro für Abfallwirtschaft) in Hamburg (GE). Royal Haskoning is the main contractor and carries the final responsibility for the management, the coordination and the (technical) deliverables of the feasibility study. IFAS operates as the subcontractor of Royal Haskoning. The project team is composed as follows:

Project team	Organisation	Position and competence
Willem van Vossen	Royal Haskoning	Project manager and senior landfill expert
Dennis Zegers	Royal Haskoning	Civil engineer (engineering methods and techniques)
Maartje van Meeteren	Royal Haskoning	Geochemist/biochemist
Kai-Uwe Heyer	IFAS	Senior civil engineer (engineering methods and techniques)
To be nominated	IFAS	Civil engineer

The project team is supported by specialists of Royal Haskoning with specific competences. This specialist team is composed of:

Specialist team	Organisation	Competence
Ton Schomaker	Royal Haskoning	Senior microbiologist/biochemist
Fred Olie	Royal Haskoning	Senior hydrogeologist (contamination transport)
René Boerboom	Royal Haskoning	Senior civil engineer (engineering methods and techniques)

Projectgroup and core team of the Dutch Foundation for Sustainable Landfilling

The feasibility comprises different activities and each activity requires specific competences. So it is important to mobilise all relevant knowledge and experience, which is available in the project group and the core team of the DFSL. For this reason the progress of the feasibility study is supervised by both project group and core team. The project group and core team are composed of the following members:

Projectgroup Name	Membership	Organisation
Hans Woelders	Project group	Essent Environment
Heijo Scharff	Project group	Afvalzorg
Hans van der Sloot	Core team	ECN
André van Zomeren	Core team	ECN
Hans Oonk	Core team	OonKAY
Timo Heimovaara	Core team	Technical University Delft

Annex 3
A specific and detailed scheme of the different degradation phases and the consequences of it for the emission potential and reduction

Degradation processes in the waste body	**Products**								
	Biochemical conversion						Physical-chemical speciation		
	Biomass					Organic micro-parameters	Heavy metals	Oxy anions	Salts
	Carbon	Nitrogen	Sul-phur	Phos-phorus	Organic ma-croparameters				
Phase 0: Initial phase Initial waste disposal, oxydation and moisture accumulation	First easily de-gradable car-bon (C) must be oxidized, before nitrifica-tion can/will start	Minerali-sation to NH3/NH4 -> NO2 -> NO3				Rapid decay of volatile organic hydrocarbons and vaporisa-tion or decay of lower VOH's.	May act as inhibitor of biological stabilization process. Concentation is controlled by carbonate, chloride and phosphate.		Salts are washed out, but preferential flow/ mobile zones determines how much. Quick initial release and low release based on diffusion from stagnant zone.
Phase 1: Hydrolysis Transition leachate is formed, redoxcondi-tions shift from oxygen to nitrate to sulphates.	Hydrolysis is called the liquefaction and release of solid organic matter (SOM)I into dissolved organic matter (DOC). Micro-organisms are only able to convert DOC.				Dissolved organic carbon (DOC)	Biological deacy of organic compounds	Emission of heavy metals by sorption to DOC and POC. Con-centration is control-led by carbonate, chloride and phos-phate. Sorption on iron-oxide and AL-oxide. Clay nteraction		
Phase 2: Acidification This phase can be sub-divided in acidogenesis and acetogenesis. Low pH is characteristic.	Volatile Fatty Acids (VFA) predominate in leachate, a.o. acetate.	NH_4 pre-dominates in leacha-te (ammo-nification).					Idem as phase 2 and in addition emission of heavy metals due to low pH.		
Phase 3 and 4: Methanogenesis	Part of VFA are transfor-med into CH_4	NH4 still remains significant	H_2S and S^{2-}				Chemical precipitation of heavy metals.		
Phase 5: Stabilization and oxidation	$CH_4 + O_2 \rightarrow CO_2 + H_2O$)	$NH_4/NH_3 \rightarrow NO_2 \rightarrow NO_3$					Remobilization of heavy metals ?		

Annex 4
List of Key Performance Indicators (KPI's)

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	GENERAL	
KPI	**What / Why**	**How**
Temperature	Increase of temperature in the waste body corresponds with increase of the activity of micro-organisms (bio-activity). In the methanogenic stage: - Psychrophilic bacteria: < 20°C - Thermophilic bacteria: > 44°C - Mesophilic bacteria: 20 to 44°C (relevant for landfill methanogenesis). Production of methane increase significantly (up to 3 times) with a temperature raise from 20 to 40°C. Infiltration/recirculation measures can over-cool the system if moisture is added to rapidly. This causes a decrease of temperature and consequently a decrease of methane production. Aeration will significantly increase the temperature as aerobic degradation processes release more energy as heat.	- Sensors in the waste body (small reach). - gas emission temperature - leachate temperature - infrared measurements
Settlements	Degradation of organic matter results into settlement of the waste. Time-settlement diagrams give an indication whether stabilisation has been achieved (zero settlement) or not. Additional settlements after installation of infiltration/recirculation systems indicates additional degradation of remained degradable organic matter.	- Installation of settlement beacons. - Optional: remote radar methods provide very accurate height measurements, perhaps an option to see if lapse data are available for the two landfills.

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Waste composition	Type of waste is related to the amount of carbon to be degraded. Domestic waste possesses more carbon than demolition waste. So knowledge of the waste composition as detailed as possible will help to determine the total amount of degradable organic matter as an input for the calculation model of gas production prognoses. Diffrerence between the amount of degradable organice matter in waste samples at the start and at the and of the stabilization process is an good indicator of the extent of degradation of organic matter.	- Solid waste sampling and analysis. 1st order model (TNO). Multiphase model (Afvalzorg). - Analysis organic fractionation (ECN) before and after demonstration project.
Moisture content	More moisture can increase the gas production. Optimum of 60%, a higher moisture content does not enhance nor decrease the gas production. Methane production reduces at decreasing moisture content and will cease completely below a 10% moisture level. - Moisture content < 25% → inhibits significantly biodegradation processes - Moisture content > 35% → optimum biodegradation processes	- Waste sampling. - Geo-electrical survey. - Sensors
Moisture transport	Moisture transport facilitates: - exchange of substrates and nutrients - dilution of inhibitors (a.o. VFA) - distribution of bacteria The rate of methane production with free moisture movement increases significantly as compared with stagnant zones.	- Geo-electrical survey. - Monitoring of leachate concentration change in time (Ec, etc.) in diffe-rent sections of drains. - Tracer tests, chloride ratio analysis.
Water balance	From the 100% rainfall, a certain percentage will evaporate (30-50%), a certain percentage will reach the base (20-40%) and a certain percentage will absorb in the wast body (10-50%). For example, at the German landfill Erbenschwang: 17% of infiltrated leachate reached the base by preferential channels and 83% was absorbed in the waste body and really contributed to the increase of moisture content in the waste. Note: pay attention to the required accuracy, also in realtion to the spatial distribution.	- Calculations based up-on field measurements of rainfall (weather sta-tion), water storage in waste, discharge of leachate drainage system. - Tracer tests, chloride ratio's

Time capsule	Comprising common used and degradable things like newspaper, banana, etc. Indicates the occurrence of bio-degradation and is useful for communication purposes only. Put several time capsules in the waste at different places to visualize the difference in extent of degradation processes in different degradation circumstances (good communication means to third parties).	Bury before and ex-cavate after demon-stration project
Bulk electrical conductivity, induced potential and self potential.	Indirect measure of leachate conductivity, water content distribution and temperature in the landfill. Highly dependent on the water content in the waste. Time lapse monitoring provides us with an excellent insight in the spatial effect of treatment approaches. The induced potential is a measure of the chargeability of the solid phase present (when doing a Geoelectrical measurement, a time varying charge is injected in an electrode and subsequently a range of potentials are measured. The rate in which the measured potential stabilizes is a measure of the chargeability of the solid phase) The chargeability is different for mineral phases and organic matter. We expect the chargeability to change during landfill stabilization. Self potential is the electrical potential that results from natural geoelectric phenomena: flow of ions with water, presence of redox gradients etc. Papers have been presented illustrating the application of SP for measuring the redoxconditons down gradient of a landfill.	- In-situ probes (TDR (coated and non-coated) probes provide information on water content and bulk electrical conducitivy. - Geo-electrical methods (ERT, IP and SP) are highly dependent on water content, water flow and electrical conductivity.
Density distribution	The hypothesis is that landfills consist of horizontal layers, this means a strong anisotropy in water flow (horizontal conductivity will be larger than vertical conductivity). This can result is persistant dry pockets even under conditions of high infiltration.	High resolution seismic measurements provide insight in the strength distribution within the landfill body. This strength is related to the density. Images of density provide info on the anisotropy within a landfill.

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	LEACHATE	
KPI	**What / Why**	**How**
Redox condition (Eh)	Methanogenic bacteria prefer an optimum Eh between -100mV and -300mV. Besides the degradation processes (Natural Attenuation) in the waste body are related to different sequential redox conditions (from aerobic up to methanogenic), which are able to neutralize micro-contaminants. Note: - redox measurements are notoriously difficult in mixed redox conditions. Interpretation is difficult. - Geochmical models based on redox active species provide good indications; this needs measuring the redox species (NA-parameters). - pay attention to spatial distribution to obtain e sufficient accurate picture; micro-organisms groe in bio-films in which very sharp redox gradients are present.	- Field measurements. - Chemical analysis on NA-parameters.
Ammonia (NH_4)	NH4 is largely produced by hydrolysis and fermentation of the biodegradable nitrogen-containing organic compounds. Its concentration stays high, as it is not converted in the anaerobic processes. Its concentration can be reduced significantly by aerobic in situ stabilization. Indication of decaying organic matter. Possibly anaerobic ammonium oxidation by the anammox bacteria. These bacteria have the unique metabolic ability to combine ammonium and nitrite or nitrate to form nitrogen gas. Presence of the anammox-bacterium and nitrite leads to anaerobic denitrification of ammonium.	Chemical analysis (field kits)
Conductivity (Ec)	Indication of dissolution of salts. High conductivity means hig salt concentrations.	Sensors/divers and/or field measurements.
Acidity (pH)	pH increases from acidogenic phase (4,5-7,0) to methanogenic phase (7,0-8,2). Methanogenic bacteria only tolerate a pH between6 and 8. If pH drops due to e.g. ingress of oxygen, the methanogenic bacteria are suppressed and the conversion of hydrogen (H), carbon dioxide (CO_2) and acetic acid to methane will not proceed as a result of accumulation of VFA.	Sensors and/or field measurements.

Biochemical oxygen demand (BOD)	BOD reflects the biodegradability of the easily degradable organic matter in a sample. It measures the quantity of O_2 needed by bacteria to degrade organic matter in 5 days at a temperature of 20°C. Bacteria are demanding O_2 for the degradation of easily degradable organic matter. High BOD → high demand of O_2 → high amount of aerobic easily degradable organic matter.	Chemical analysis
Chemical oxygen demand (COD)	COD is a measure of the oxygen equivalent of the organic matter content that is susceptible to oxidation by a strong chemical oxidant. All organic matter is oxidized into CO_2. COD does not make a distinction between biological active (degradable) organic matter and biological inactive (none degradable) organic matter. COD is the rate of degradation of the total quantity of organic matter, easily as well as difficult degradable organic matter. This means that COD is always higher than BOD (COD/BOD > 1).	- Chemical analysis
COD - BOD	Indicates the amount of the sum of difficult + none degradable organic matter.	
BOD/COD ratio	This ratio is commonly used as an indicator to distinguish acidogenic and methano-genic leachate. As leachate develops from acidogenic to methanogenic, the BOD/COD ratio is expected to drop to reflect the reduction in its biodegradability. Ratio of 0,7 for a raw young leachate to 0,1 for a well-stabilised methanogenic lea-chate. According to Kruse (1994) three characteristic periods can be distinguished: - acid phase: BOD/COD > 0,4 - intermediate phase: 0,4 > BOD/COD > 0,2 - methanogenic phase: BOD/COD < 0,2	
Dissolved organic car-bon (DOC)	Heavy metals will adsorb to DOC, in particular to humic substances. So DOC is the means of transport for the emission of metals. If stabilization has been achieved, emission of heavy metals is no problem any more because of the absence of DOC.	- Chemical analysis - Fractionation method described in van Zome-ren & Comans, ES&T, 2007, 41, 6788-6761
Fractionation of DOM	DOM can be fractionated in hydrophilic acid (Hyl), Humic acid (HA) and Fulvic acid (FA). During the aging of the landfill the composition of the DOM shifts from Hyl to HA to FA.	- Chemical analysis- - Fractionation method described in van Zome-ren & Comans, ES&T, 2007, 41, 6788-6761

Bench marking	Comparison of measured chemical parameters in a landfill with average chemical composition of a number of other investigated landfills. Kruse (1994) investigated 33 landfills in Germany from which a table has been established of chemical composition of the leachate versus categories of landfill age. By using the LeachXS dBase (ECN) the COD/DOC information will be placed in perspective to degradation data for lysimeter studies and pilot studies to assess the present extent of degradation / stabilization of the waste body.	- Consultation and use of databases such as: LeachXS dBase (ECN); Krümpelbeck and Ehrig (1999); Ehrig, 1989; Kruse 1994. - Different types of reactive models
Total organic carbon (TOC)	Unlike BOD and COD, TOC measurement is independent of the oxydation state of organic matter, and does not measure other originally bound elements such as nitrogen and hydrogen. Also it does not include inorganics that can be measured by BOD and COD.	Chemical analysis
Chloride(Cl^-)	Indication of dissolution of salts. As a conservative parameter it can be used as tracer, will only decrease as a result of flushing the waste body.	Chemical analysis
Total VFA	Is the majority of the organic matter in acidogenic leachate (50% of COD load). VFA's are the most easily biodegradable organic acids to be converted to methane. VFA inhibits the methanogenic processes.	Chemical analysis
Alkalinity	Alkalinity is a measure of all bases present in the leachate and is a measure of how much acid is required to achieve a pH of 4-5. It is generally expressed as a concentration of calciumcarbonate ($CaCO_3$). It acts like a pH buffer, which may significantly improve the efficiency of methanogenic degradation by maintaining a close to neutral pH-range. Its major source comes from soil and demolition waste. To start methane production an acetic acid to alkalinity ratio < 0,8 is essential. For a good methane production: alkalinity > 2000 mg/l and volatile acids < 3000 mg/l For the best results alkalinity should be measured in the field (titration method), because the measurement is strongly influenced by degassing of CO_2	- Chemical analysis - field measurement by tirtration method.

Nutrients (incl. NA parameters)	Landfill micro-organisms require nutrients for their anaerobic activities referring to nitrogen, phosphorus, and other micro-nutrients including sulphur, calcium, magnesium, potassium, iron, zinc, copper and cobalt. Anaerobic assimilation requires much less nutrients than aerobic conversion processes. In most landfills there are generally adequate supplies of these nutrients.	Chemical analysis
Sulphate (SO_4) Sulphide (SO_2)	Methane production reduces if sulphate is present. This suppression of methane production is not related to toxic effects, but due to substrate competition; the sulphate reducing bacteria also consume hydrogen and acetic acid during sulphate reduction. Transition from acidogenic to methanogenic shows a drop of sulphate concentration, caused by the reduction of sulphate to sulphide. Such a drop indictates the presence of sulphate-reducing bacteria	Chemical analysis
Nitrate (NO_3) and Nitrite (NO_2)	Concentrations are expected to be low under negative redox anaerobic conditions. Nitrate (NO_3) can occur in the leachate during aeration because of nitrification processes in the waste body. A landfill also contains a large volume of of unsaturated waste; if oxygen can freely enter the landfill, parts of the waste body will be oxidyzed and nitrate will be formed	Chemical analysis
Metals & other macro parameters	Macroparameters, heavy metals etc. are essential for understanding the geochemical evolution of the landfill body. Minimal parameter set to be monitored: Ca, Mg, Na, K, NH4, pH, Cl, SO4-2, NO3-, HCO3-, Fe+2, (Mn+2), DOC etc...	Chemical analysis

	G A S	
KPI	**What / Why**	**How**
Comparison measured and calculated gas production	Indicates roughly the extent of stabilisation of organic matter: Calculated > measured roughly indicates still a low extent of stabilisation. Keep in mind a deviation of calculated gasproduction in comparison with measured gas production of at least ± 20%). So, be very carefull with the interpretation of this ratio!	Model gas production prognosis and field measurements
Ratio of methane (CH_4) and Carbon dioxide (CO_2)	Ratio of CH_4 and CO_2 of 50/50 to 60/40 indicates that the stage of methanogenesis has been reached. A ratio of 60/40 (or 1,5) is the expected ratio as an indicator for a full development of methanogenesis.	Field measurements at the gas wells and/or gas collection pits
Gas extraction rate	Very important under anaerobic and aerobic conditions, constant measurement necessary to assess intensity of biological conversion processes and carbon release via the gas path. Moreover the efficiency of the gas collection system can be assessed and optimized.	Field measurements
Oxygen (O_2)	Presence of O_2 inhibits the activities of anaerobic bacteria. Anaerobic bacteria are very sensitive to the presence of oxygen.	Field measurements at the gas wells and/or gas collection pits
Nitrogen	Nitrogen is present in the atmosphere in high concentrations, in order to close the gas balance and to maintain equilibrium in pressures, knowledge of N2 can be important.	Gas analysis

<table>
<tr>
<td>Inhibitors</td>
<td>Besides oxygen, hydrogen, pH and sulphate, also cations concentrations, heavy me-tals and organic compounds have inhibitory effects on the methanogenic bacteria.

<u>Cations </u>(sodium, potassium, calcium, magnesium and ammonium):
- In low concentrations: essential as micro-nutrient
- In high concentrations: significantly inhibit methane production (see table below for for moderate inhibitory levels of main cations). In most landfills concentrations are below these levels.

<table>
<tr><td>Sodium</td><td>3500 – 5500</td></tr>
<tr><td>Potassium</td><td>2500 – 4500</td></tr>
<tr><td>Calcium</td><td>2500 – 4500</td></tr>
<tr><td>Magnesium</td><td>1000 – 1500</td></tr>
<tr><td>Ammonium</td><td>1500 – 3000</td></tr>
</table>
<u>Heavy metals</u>:
Present concentrations in landfill not high enough to influence the sensitive methanogenic bacteria.

<u>Organic micro compounds</u>
High concentrations of these toxic organic compounds are required to impose significant inhibitory effect on a methanogenic system. In MSW-landfills concentration too low to have an inhibitory effect.</td>
<td>Chemical analysis</td>
</tr>
</table>

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Annex 5
List of limit values of macro- and micro parameters

LIMIT VALUES WATER								
Component	**Unit**	**Values Wbb* >10 m-mv**	**Values Wbb***	**Values Wbb***	**Values Wbb***	**EU-directive****	**KRW Rijndelta**	**KRW Schelde-delta**
		Target value	**Target value**	**Intermediate value**	**Intervention value**	**Inert waste**	**Wieringer-meer*****	**Kragge*******
N-Kj	µg/l							
As	µg/l	7,2	10	35	60	60	15	15
Al	µg/l							
BOD	µg/l							
Ba	µg/l	200	50	337,5	625	4000		
Be	µg/l	0,05		7,5	15			
Cd	µg/l	0,06	0,4	3,2	6	20	0,5	0,5
COD	µg/l							
Cr (total)	µg/l	2,5	1	15,5	30	100		
Cr III	µg/l							
Cr VI	µg/l							
Cu	µg/l	1,3	15	45	75	600		
Hg	µg/l	0,01	0,05	0,175	0,3	2		
Mn	µg/l							
Mo	µg/l					200		
Ni	µg/l	2,1	15	45	75	120	30	30
Pb	µg/l	1,7	45	60	75	150	11	11
Sb	µg/l	0,15		10	20	100		
Se	µg/l	0,07		80	160	40		
Sn	µg/l	2,2		25	50			
Tl	µg/l	2		3,5	7			
V	µg/l	1,2		35	70			
Zn	µg/l	24	65	432,5	800	1200		
Br	µg/l							
Cl	mg/l		100	50		460	140	140
CN	µg/l		5.0 (vrij) 10.0 (complex)		1500			
F	µg/l					2500		
PO4	µg/l							
nH4	µg/l							
NO3	mg/l						50	50
NO2	µg/l							
SO4	µg/l					1500000		
DOC	µg/l							
Phenol	µg/l		0,2	1000,1	2000	300		
PAK	µg/l							
nafthalene	µg/l		0,01	35	70			
phenanthrene	µg/l		0,003	2,5	5			
fluoranthene	µg/l		0,003	0,5	1			

Component	Unit	Values Wbb* >10 m-mv	Values Wbb*	Values Wbb*	Values Wbb*	EU-directive**	KRW Rijndelta	KRW Schelde-delta
		Target value	Target value	Intermediate value	Intervention value	Inert waste	Wieringer-meer***	Kragge****
b(a)anthracene	µg/l		0,0001	0,25	0,5			
chrysene	µg/l		0,003	0,10	0,2			
b(k)fluoranthene	µg/l		0,0004	0,03	0,05			
b(a)pyrene	µg/l		0,0005	0,03	0,05			
b(g,h,i)perylene	µg/l		0,0003	0,03	0,05			
i(1,2,3-cd)pyrene	µg/l		0,0004	0,03	0,05			
benzene	µg/l		0,2	15	30			
ethyl benzene	µg/l		4	77	150			
toluene	µg/l		7	504	1000			
dichloromethane	µg/l		0,01	500	1000			
vinylchloride	µg/l		0,01	2,5	5			
aldrin	µg/l		0.009 ng/l					
dieldrin	µg/l		0.10 ng/l					
mineral oil	µg/l		50	325	600			
PCB (total of 7)	µg/l		0,01	0,01	0,01			
H3	mBq/l							
U238	mBq/l							
Pb 210	mBq/l							
Po 210	mBq/l							
Th	mBq/l							
DOC	µg/l					160000		

* Dutch circular for soil remediation 2008

** EU landfill directive Annex II 19 dec 2002 : Concentration in the first eluate of the columntest at L/S = 0,1 l/kg.

***Stroomgebiedbeheerplan Rijndelta hoofdrapport, 22 december 2008

****Stroomgebiedbeheerplan Schelde hoofdrapport, 22 december 2008

LIMIT VALUES MATERIAL						
Component	**Unit**	EU-directive*		Dutch Soil Quality Decree**		
		Inert waste	Non hazardous	Non isolated	Isolated	Large scale
			waste	materials	materials	soil works
Leaching test at L/S = 10						
As	mg/kg	0,5	2	0,9	2	0,61
Ba	mg/kg	20	100	22	100	4,1
Cd	mg/kg	0,04	1	0,04	0,06	0,051
Cr (tot)	mg/kg	0,05	10	0,63	7	0,17
Co	mg/kg			0,54	2,4	0,24
Cu	mg/kg	2	50	0,9	10	1
Hg	mg/kg	0,01	0,2	0,02	0,08	0,49
Mo	mg/kg	0,5	10	1	8,3	0,48
Ni	mg/kg	0,4	10	0,44	15	0,21
Pb	mg/kg	0,5	10	2,3	2,1	15
Sb	mg/kg	0,06	0,7	0,16	0,7	0,07
Se	mg/kg	0,1	0,5	0,15		
Sn	mg/kg				2,3	0,093
V	mg/kg			1,8	20	1,9
Zn	mg/kg	4	50	4,5	14	2,1
Cl^-	mg/kg	800	15000	616	8800	50
F^-	mg/kg	10	150	55	1500	
SO_4	mg/kg	1000	20000	1730	20000	
DOC	mg/kg	500	800			
TDS	mg/kg	4000	60000			
Composition						
	mg/kg					
Fenol	mg/kg	1		1,25		1,25
TOC	mg/kg	30000	50000			
BTEX	mg/kg	6		4,75	4,75	4,75
PCB	mg/kg	1		0,5	0,5	0,5
PAH	mg/kg	40		50	40	40
Mineral Oil	mg/kg	500		500	500	500
* EU landfill directive Annex II 19 dec 2002						
** Dutch Soil Quality Decree, 22 december 2007						

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Annex 6
Overview of international projects with respect to infiltration/recirculation and aeration

Country	Name/place	Time period	Description	References
Australia	BFI – Lyndhurst	1994	Leachate recirculation with recharge wells/infiltration trenches	Yuen, 1995
	New South Wales	1995/1996	Horizontal infiltration pipes	Van den Broek, 1995
Netherlands	Vlagheide, Schijndel	2005/2009	Leachate recirculation with horizontal infiltration trenches	Van Vossen et al, 2009
	Vam, Wijster	1997	Leachate recirculation with horizontal infiltration trenches	Oonk et al , 1996
	De Kril, Elspeet	2002	Vertical infiltration wells and clean water	Oonk et al, 2004
	Test cell, Landgraaf	2001/2009	Leachate recirculation with horizontal infiltration trenches	Woelders et al, 2005,
	VAM, Wijster	2002	Vertical infiltration wells and clean water	Oonk et al, 2004
	Braambergen	2001	Aeration by Smell-Well system for mitigating emission problems	Scharff et al, 2001
	Zeeasterweg	2002	Aeration by Smell-Well system for mitigating emission problems	Jacobs & Scharff, 2003
	Landgraaf	2006	Air injection with methane-oxidyzing cover layer	Woelders, 2009
	Landgraaf	2005	Methane oxidyzing cover layer	Woelders et al, 2005
UK	Brogborough	1986	Intermittent injection of leachate	Blakey et al 1995
	Landfill 2000	1993/1994	Horizontal leachate infiltration system	Campbell et al, 1995
	Seamer Carr	1990		De Rome & Gronow, 1995
				Knox & Gronow, 1993
USA	Alachua, Florida	1991	Horizontal leach trenches	Yuen et al, 1995
	SSWMC, Delaware	1982/1985	Leachate recharge wells	Vasuki, 1988 & Maier et al, 1995
	SSWMC, Delaware	1995	HIRES horizontal leach fields	Maier et al, 1995
	Monroe County, New York	1995	Bioreactor	Carson, 1995
	Mountain View, California	since 1982	Stimulating gasproduction	Pacey, 1989
	Seneca Meadows, New York	since 1991	Infiltration wells	Scrudato et al, 1993 & Yuen, 1995
	Worcester County, Maryland	1991	Leach trenches	Yuen et al, 1995
	Yolo County, California	1990	Leach trenches	Yolo, 1991
	New River Bioreactor, Florida	2001/2008	Air injection and moisture addition	University of Florida, 2008
	Road Landfill, Columbia	2006	Aerobic in situ stabilization	Hudgins, 2006
	Landfill in Arizona	2003	Aeration of landfill bosy	Hydro Geo Chem, 2003
Sweden	Helsingborg	1990	Infiltration wells	Oonk et al, 1996
Portugal	Resioeste	2002/2005	Concentrate re-infiltration	Loeblich, 2005
	Suldoro	2000/2005	Concentrate re-infiltration	Loeblich, 2005
Canada	Toronto, Ontario	2007	Full scale aeration system for 18 years	ARGE Biopuster 2006
	Quebec	2007	Aeration by Smell-Well system just before landfill mining	Smell-Well 2007

Germany	Bornhausen & Bornum	1989	Sprinkling system and leach trenches	Yuen et al 1995
	Lingen	1986	Sprinkling system and leach trenches	Yuen et al 1995
	Leppe	2003/2008	Water infiltration	Hupe et al, 22008
	Oberweier	1986/1999	Re-infiltration of concentrate by injection wells	Henigin, 1999
	Göda-Buscheritz	1993/1995	Small scale re-infiltration of concentrate with 2 injection wells	Peters , 2003
	Wischhafen II	1998/2006	Re-infiltration of concentrate	Wehre, 2006
	Dettendorf	2003/2005	Controlled Ire-infiltration of leachate concentrate	Lautenschlager, 2006
	Milmersdorf	2002/2006	Low pressure aeration by Aero-Flott^R	Heyer et al., 2007
	Kustedt	2001/2007	Low pressure aeration by Aero-Flott^R	Heyer et al., 2007
	Old deposit Amberg	2001/2006	Low pressure aeration by Aero-Flott^R	Heyer et al., 2007
	Halle Lochau	2008	Infiltration trenches	Rettenberger, 2009
	Erbenschwang	1994-1997	Infiltration by lances	Bauer et al., 1997
	Dreieich	?	Infiltration by lances	?
	Doerentrup landfill, Lippe	Start 2007	Low pressure aeration by Aero-Flott^R	Heyer et al., 2008
	Old Schenefeld, Pinneberg	?	Aeration by over-suction methods	Hupe et al., 2004
	Old Kiel-Drachensee, Kiel	?	Aeration by over-suction methods	Heyer et al., 2005
Austria	Vienna-Donaupark	Since 1991	High pressure aeration by Bio-Puster Method	ARGE Biopuster, 2006
	Berger landfill	2002/2006	High pressure aeration by Bio-Puster Method	ARGE Biopuster, 2006
	Fischer landfill	2002/2006	High pressure aeration by Bio-Puster Method	ARGE Biopuster, 2006
France	Vert Le Grand	2003	Re-infiltration of concentrate	Aran et al, 2003
Korea	Pilot tests	?	Conversion from anaerobic to aerobic conditions	Qi et al., 2003
Japan	75% of Japanese landfills	2000/2003	Semi aerobic landfill concept	Matsufuji et al, 2000 & Gi et al, 2003
Italy	ASM Brescia SpA	2000/2007	Leachate recirculation	Bertanza, 2007
	Landfill "C",	2007	Aeration	Cossu et al., 2007
	Landfill Legnago	2007	Aeration	Cossu et al., 2007
	Landfill Modena	2007	Aeration	Cossu et al., 2007