Leachate emissions from landfills

Final Report

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1. Background and objectives

It is the policy of the Swedish Environmental Protection Agency (SEPA) to develop sustainable strategies for existing as well as future solid waste landfills. In order to support this policy, SEPA is considering the launching of a major research programme on various aspects of sustainable landfilling. To ensure the best possible focusing of such a programme, the Agency has organised two thematic seminars in September and October 1999. During these seminars important issues relating to sustainable landfilling have been or are to be discussed, and if possible, consensus on the research needs should be reached.

The theme of one of the seminars is "Emissions – processes and models", and SEPA has retained VKI to prepare a short report on which part of the discussions at this seminar can be based. VKI has been requested to provide a summary of the existing level of knowledge on emissions of leachate from landfills. The report should focus on knowledge gaps and in particular point out areas in which the existing knowledge is insufficient to provide adequate support for the development of sustainable strategies for existing and future landfills. The report should further point out which R&D issues should be given top priority to enable:

- credible determinations and predictions of the leachate production in the short and long term;

- development of technical measures and other provisions that can enable the monitoring and control of the quantity and quality of the leachate both in the short and long term.

The report should address and summarise:

The methodology and themes of previous and ongoing R&D on leachate emissions from landfills;
The R&D results obtained and how they have influenced the design and operation of landfills;
The short and long term modelling of leachate emissions (conceptual design of models, assumptions, data needs, limitations and quality of results).

The preconditions and the findings of the study as well as the resulting recommendations are presented in the following.

2. Approach

In the initial chapters, landfill or disposal strategies defined in terms of leachate formation and emissions are discussed in general terms, and an overview is given of some of the factors influencing the quality and quantity of leachate from landfills. The characteristics of some of the main categories of landfill leachate are listed and associated with the various types of landfills. This initial part of the report is partly based on a study performed by Hjelmar et al. (1994, 1995) for the European Commission.

The information on ongoing R&D on leachate production and landfill processes compiled and reviewed in this study has been procured from open literature as well as from project reports and VKI's international network and personal contacts. Due to the limited time available for the study, a certain degree of selectivity in the procurement and compilation of information has been necessary, and consequently the review cannot claim to completely encompass all current and new developments. However, to ensure a wide coverage of the major research subjects and results concerning landfill processes and leachate emissions, a substantial part of the literature review has been based on the proceedings of the Sardinia Conferences (Christensen et al., 1991, 1993, 1995, 1997, 1999). This biannual conference is probably the most important European (and possibly global) forum for presentation and discussion of new ideas and trends within the field of landfilling. The latest Sardinia Conference was held in October 1999 and attended by the authors of this report, but time constraints prevent a full account of the relevant papers and discussions from this conference (the proceedings exceed 3500 pages).

The results of the review of the information procured have been organised in two ways. In Annex 1, the various R&D groups or institutions are listed by country, and a brief account of the nature of the main contribution of each group is given. In the report itself, the R&D work and results relating to leachate quantity and leachate quality are listed and discussed in terms of specific aspects. The implications of the new EU Council Directive on the Landfill of Waste (EU, 1999) on leachate quality and emissions are briefly discussed.

Based on the review, a number of recommendations on relevant issues that should or could be addressed by a new research programme on sustainable landfilling are presented and discussed.

3. Disposal strategy and leachate emissions

3.1 Disposal strategy

The primary objective of landfilling as a waste management technique is of course to remove from general circulation materials/products that are no longer useful in any respect, and which cannot be managed higher up in the waste hierarchy. This should be done in a sustainable manner, which eventually returns the basic constituents of the waste to the ecological cycle without excessive or prolonged maintenance or operation requirements.

A second and equally important objective is to ensure that the landfilled waste does not cause any unacceptable short or long term impacts on the local or global environment or on human health.

The major environmental concerns associated with landfills are usually related to the generation and eventual discharge of leachate into the environment. The most important aspects of disposal strategy are therefore expressed in terms of formation, fate and management of leachate. Both the quantity and quality of the leachate formed depend upon the characteristics of the waste, the design and operation of the landfill and the climatic conditions.

Landfilling methods and the associated regulatory controls have been based on the implied assumption that the waste will become harmless in terms of emission of leachate in a relatively short time due to stabilisation and mineralisation reactions. It is therefor also assumed that a landfill may be safely abandoned and perhaps even forgotten after a period of e.g. 30 - 50 years. This may have been true for the domestic waste produced in earlier times, but it is unverified (and unlikely) for the often very complex separate or mixed streams of organic and inorganic waste produced and landfilled in large quantities by modern industrial society. In addition, some of the landfilling techniques employed (e.g. the application of low permeability covers) are likely to reduce rather than increase the rate of stabilisation of the waste.

The "final storage quality" of the waste (that is the criteria determining, whether or not it will be environmentally safe to leave a landfill site to itself without active leachate management and environmental protection systems), and the time needed to reach this point is generally not well defined nor addressed explicitly in national or EU waste disposal legislation and guidelines. In practice, aftercare needs may vary considerably and depend on waste type and design, operation and siting of the landfill.

The employment of disposal strategies based on knowledge of leachate properties and their changes with time may help minimising the period of time needed to reach final storage quality for various types of waste.

Practically all landfilling scenarios can be referred to one or more of the following disposal strategies or schemes, which are based on leachate management:

A. Encapsulation or total containment ("dry tomb")

B. Containment and collection of leachate

C. Controlled contaminant release

D. Unrestricted contaminant release

The schemes A and B generally require active environmental protection systems (i.e. systems that depend upon maintenance and/or input of energy) whereas schemes C and D only may require passive environmental protection systems (i.e. systems that do not depend on maintenance and/or input of energy). Active environmental protection measures may in a number of cases be necessary during a first stage of landfilling but only passive systems are sustainable in the long term (the final stage).

Encapsulation/total containment:
Encapsulation of waste will prevent any infiltration and percolation of water and, consequently, any generation and emission of leachate beyond the moisture already present in the waste at the time of disposal - as long as the containment system remains intact. The main weakness of a disposal scheme based solely on encapsulation is that the landfilled waste and hence the potential risk to the environment may remain virtually unchanged and at a maximum for a very long period, until the containment system finally fails and an uncontrolled plume of leachate may be released. Total containment does not bring the waste closer to final storage quality, and it implies acceptance of an indefinite responsibility for a potential environmental risk on behalf of future generations.

Containment and collection of leachate:
This scheme, which is the most common landfill scenario, corresponds to the traditional manner of designing and operating MSW landfills ("sanitary landfills"). The leachate generated by infiltration of precipitation is contained by an "impermeable" or low permeable liner system, collected in a drainage system, pumped out, and normally subjected to treatment prior to discharge to a surface water body. A top cover of low permeability may reduce the leachate production. In order to reach final storage quality within a specified time limit, it may instead be necessary to enhance the leaching rate, e.g. by maximising the rate of infiltration of precipitation or even by adding flushing water and/or by recirculating the leachate. Since the containment and leachate collection scheme depends on active environmental protection systems and since it will only be reliable during a period, which does not exceed the life expectancy of these active systems, this strategy or scheme does not provide a long-term solution to landfilling. It may, when appropriate, be employed as a first stage in bringing certain types of waste towards final storage quality.

Controlled contaminant release:
This scheme implies that the release and emission of contaminants to the environment must be maintained at an acceptable level by controlling the quantity and/or quality of the leachate generated within the landfill. The leachate is allowed to leak into the surroundings as it is formed. An assessment must always be carried out to ensure that the impact of the emitted leachate on the environment is acceptable. Treatment of the waste may reduce both the contamination potential and the permeability. Installation of geologically stable, sloped top covers with surface drainage systems and surface vegetation with high evapotranspiration capacity could – if necessary - ensure a very low rate of infiltration of precipitation and, consequently, a very low rate of release of contaminants from a disposal site, also in the long term. Since contaminants are being removed from the landfilled material, however slowly it may happen, a continuous reduction of the contamination potential will occur. The controlled contaminant release strategy may represent a sustainable short and long-term solution for some inorganic waste types. For other waste types, a final controlled contaminant release stage of operation should be preceded by a short term, active stage of operation based on a different strategy, e.g. enhanced leaching and containment and collection of leachate.

Unrestricted contaminant release:
An unrestricted contaminant release scheme may simply be described as a landfill scenario where no precautions at all are taken to prevent or reduce the generation and emission of leachate. The environmental impact will depend on the leaching characteristics of the landfilled waste as well as on local physical and climatic conditions and the vulnerability of the surrounding environment. Since the scheme implies a total lack of control it is not generally acceptable for landfilling of waste with any substantial contamination potential. If preceded by a leachate containment and collection strategy or a controlled contaminant release strategy stage which has brought the waste to final storage quality, the unrestricted contaminant release strategy may be implemented as a final stage.

All of the above mentioned disposal schemes/strategies or combinations of these are presently being employed purposely or by default both in the various EU Member States and other countries.

3.2 Categories of landfills

Landfills may be categorised according to various criteria. Landfill categories are most commonly defined by the type of waste accepted for disposal at each particular category. Other criteria such as siting of a landfill (taking the vulnerability of the surrounding environment into account) and the requirements for environmental protection measures (e.g. liners, leachate collection systems) are often related to the waste acceptance criteria and to each other.

The assignment of a certain type of waste to a certain category of landfill is often based on the assumption that leachate quality or aspects of leachate quality can be predicted from knowledge or testing of waste characteristics. While this is indeed possible for some types of waste, particularly purely inorganic wastes, it may be more difficult for others, especially biodegradable wastes or mixtures containing biodegradable wastes. In such cases, the predictions must be based primarily on prior experience (e.g. field observations).

In practice, most waste classification systems and corresponding landfill categorisation systems are based on a ranking of waste in relation to "hazardousness", ranging from inert over non-hazardous to hazardous. The "hazardousness" criteria are primarily related to the measures needed in regard to landfill design, operation and siting in order to protect the environment. In some countries, these criteria are supplemented with other criteria, e.g. restrictions on the amount of organic, combustible, or biodegradable matter in the waste. Such criteria are usually more related to general waste management policy and/or to the desired short and long term behaviour of the waste. It should be noted that the "hazardousness" scale and the corresponding landfill categories at present are defined differently in practically all the different EU Member States in which they are applied.

Hjelmar et al. (1994) grouped the landfills occurring in the member states of the European Union in four main categories according to the types of waste accepted at each site. Some of the main categories could be divided into more specific subcategories, still based on accepted waste types. The sites may further be categorised according to the environmental systems employed. In table 3.1, an overview of the groups of landfills existing in Europe is presented with an indication of the usual practice (or requirements) with respect to collection and treatment of leachate. It should be noted that co-disposal (i.e. treatment of hazardous waste by placing it in limited quantities in MSW landfills) will no longer be permitted in the EU member states under the new Landfill Directive. The landfills shown in table 3.1 may produce various qualities of leachate, which can vary both between and within landfill categories. The leachate quality of the different landfill categories differ from each other primarily in concentrations of inorganic salts, degradable organic matter, trace elements, and trace organics and in pH and redox potential, depending on the waste accepted and on the design, operation and age of the landfill. For any particular landfill, the quality of the leachate and its variation with time play a major role in determining the disposal strategy and leachate management options available. The main types of commonly occurring landfill leachates are identified in section 3.4.

Table 3.1
Overview of landfill categories (Hjelmar et al., 1994 and 1995).

Landfill category	**Leachate collection and treatment?** **Yes**	**No**
Landfills for hazardous waste		
• Hazardous waste landfills	X	
Landfills for mixed organic and inorganic waste. Predominantly organic/MSW.		
• MSW landfills	X	X (Dumps)
• Industrial and commercial waste landfills (no MSW)	X	
• Co-disposal landfills	X	
Landfills for inorganic waste		
• Landfills for mixed industrial waste	X	
• Mono landfills	X	X
Landfills for inert waste		
• Inert waste landfills		X

3.3 Leachate quantity

Until recently it has been a dominant concern to minimise leachate formation because of its potential to pollute water. However, leachate is increasingly seen as the route by which the pollution potential of wastes may be released in a controlled manner. Although leachate minimisation is still deeply embedded in much national and EU legislation (including the new Landfill Directive), acknowledgement of the fact that water is needed as a reaction and transport medium is spreading. Future strategies are therefore likely to focus on control of the whole leaching process, rather than simply the minimisation of leachate quantity, and such strategies may sometimes call for measures to increase the volume of leachate. The ability to predict, interpret and control leachate volumes and levels within landfills will remain important.

Water balance calculations are used to predict leachate volumes at new landfills and to interpret levels and flows at existing landfills. They are usually satisfactory for the purpose of sizing disposal facilities, if a margin of error is allowed for. They are not normally suitable for estimating leakage rates from the base of lined landfills because even a significant leakage quantity is usually small compared with the total volume of leachate. The importance and costs of leachate treatment are such that regular (e.g. annual) re-evaluation of water balances is beneficial.

The water balance calculation compares the quantities of all liquids entering and leaving the landfill during a specified period. Any increase in storage may be present either as absorbed or free leachate and this depends upon the storage characteristics of the waste, the determination of which is uncertain and complex. Numerous inputs and outputs to the water balance equation may be considered but most are usually negligible. Effective rainfall (rainfall surplus or precipitation excess) is usually the major input and leachate removed for disposal is usually the major output, at containment landfills. The resulting volumes of leachate are reduced by two major factors:

- absorption by the wastes, particularly during the operational phase; and,
- run-off and lateral drainage from completed areas with low-permeability top cover.

Moisture contained in landfill gas and the moisture consumed during anaerobic fermentation are likely to negligible except possibly at MSW landfills in very dry areas where waste degradation may be moisture-limited.

Each of the major components of water balances is subject to errors in estimation, which may often be quite large. Some are systematic, such as inherent errors in the methods of estimating effective rainfall, and some are due to the difficulty and cost of obtaining accurate site-specific data, e.g. for the absorptive capacity of the solid wastes. The net effect of these errors depends on location and waste input rates. In cooler wetter areas of the EU, where rainfall is much greater than potential evapotranspiration and effective rainfall (ER) may be on the order of 800 - 1000 mm/a, the combined errors may lead to no more than a 30% uncertainty in ER. If the waste input rate (and hence the absorptive capacity) is low, then this would also be the size of the uncertainty in leachate quantity. At the other extreme, in warmer drier parts of the EU the true value of ER could easily be half or double the estimated value. If input rates of absorptive wastes such as MSW were also high then it would be very difficult to make reliable predictions of leachate production.

Actual leachate quantities have been recorded for landfills in different parts of the EU and are shown in table 3.2, reproduced below. In general they confirm the expectation from the rainfall surplus distribution of Europe that volumes are significantly lower in drier areas, with approximately a factor of ten between the extremes.

Table 3.2
Reported leachate volumes in Europe (Hjelmar et al., 1994).

Country	**Reference**	**Leachate volumes**
Sweden	Nilsson (1993)	Average for Sweden 250-300mm/a. 10-40mm/a from a clay-capped test cell containing wastes below field capacity.
Denmark	Hjelmar et al. (1988) Hjelmar (1989)	1. 350mm/a during operation (cf. R~714mm/a) 75mm/a after capping. 2. 320-400mm/a during operation (R~633mm/a). 56-89mm/a after capping.
Germany	Ehrig (1991)	Data from 21 operational sites: R~510-1160mm/a. Leachate ~25-340mm/a (4-35%R). Low values were from young landfills. High values were from older landfills where absorptive capacity was used up.
Spain	Gössele et al. (1993)	7mm/a during 2-year period (R~400mm/a). Site near Madrid.
Italy	Baldi et al. (1993)	82mm/a. Site near Pavia.
Greece	Kouzeli-Katsiri et al. (1993)	11-15mm/a collected but some also lost to groundwater. Total estimated at 40-60mm/a (R 387mm/a, ER 60-100mm/a). Site near Athens

Attempts to modify leachate volumes have usually been intended to reduce them. However, in some locations non-hazardous liquid wastes have been deliberately added to MSW landfills solely to provide enough moisture to promote degradation, and some leachate management strategies would require increased rates of leaching in order to reach final storage quality within a reasonable timeframe (e.g. 30 to 50 years). Modification measures include:

- Site location, so as to *avoid* groundwater discharge zones in order to minimise leachate formation and location *in* groundwater discharge zones so as to minimise the risks of groundwater pollution.
- Site engineering with liners, cut-off barriers, surface water diversion and low-permeability top cover and,
- Operating in discrete cells to minimise the area of waste exposed to rainfall.

It is customary in several countries to require that landfills are placed above the highest groundwater surface level in order to avoid intrusion of groundwater, and similarly, measures are often taken to avoid intrusion of surface water. In some cases however, an environmental protection principle based on placing the bottom of the landfill below the surface of the surrounding groundwater and thereby creating an inwardly directed hydraulic gradient, has been suggested (Joseph and Mather, 1993; Smart, 1993 and Lee and Jones-Lee, 1993).

The best available technology (BAT) for control of leachate quantity is completely dependent on the operating strategy. For encapsulation, it is vital to avoid or minimise leachate. For a flushing bioreactor or an inorganic leaching landfill, leaching rates would have to be greater than ER in many locations and would need to be artificially enhanced, e.g. by recirculation (flushing bioreactor) or maximisation of the percolation rate/addition of water (initial stages of inorganic leaching landfill).

3.4 Leachate quality

Leachate composition is influenced by several factors including waste composition, operational methods, and climatic conditions. Among these, waste composition is the most important factor. The participation of organic and inorganic components in biological, chemical and physical processes define the general leachate characteristics. The higher the content of organic degradable material in the waste, the more important are the biological processes.

For inorganic wastes the solubility of various components plays a major role in determining leachate composition. Waste components and reaction products are removed from the waste as it is leached or flushed by leachate and are subsequently transported out of the landfill with the leachate as solutes or as landfill gas. The waste and the leachate therefore change composition with time, both as a result of depletion of various components and of changes in the chemical environment (e.g. redox-potential, pH, sulphides, and ionic strength).

These are the processes, which eventually should lead the waste to “final storage quality”; i.e. a situation where the leachate is fully acceptable when discharged directly into the environment. Very little information is available on the time needed to reach final storage quality for the various types of landfills. For a number of inorganic pollutants (e.g. ammonia, chlorides, sulphates, some trace elements), the changes of concentration in the leachate are related more to the liquid/solid (L/S) ratio (i.e. the accumulated amount of leachate produced per unit weight of waste deposited) than to the chronological age.

Unfortunately, landfill leachate composition data seldom contain information on either the age or the accumulated L/S for the landfill in question. Besides, most landfills consist of sections of different ages, and leachates from different sections are often mixed or indistinguishable from each other. Time series of leachate composition over longer periods of time (decades) or relating the leachate composition to the amount of leachate produced are rare. Most of the available leachate composition data therefore describe the average leachate quality over a certain period of time.

The leachates from the landfill categories existing in the EU countries may broadly be divided into 5 main types:

Hazardous waste leachate:
Leachate with highly variable concentrations of a wide range of components. Extremely high concentration of e.g. salts, halogenated organics, and trace elements can be seen. This type of leachate comes from hazardous waste landfills. The limited data available show a tendency of decreasing concentration with time. However, due to the relatively limited amount of data from hazardous waste landfills, this tendency may not be generalised.

Municipal solid waste (MSW) leachate:
Leachate with an initial high load of organic matter (COD in the range of 20,000 mg/l and a BOD/COD ratio >0.5) reduced to a low organic load (COD in the range of 2,000 mg/l and a BOD/COD ratio <0.25) within a period of 2-10 years. High content of nitrogen (>1000 mg/l of which more than 90% is Ammonia-N) is expected for more than 50 – 100 years. The fate of the leachate was relatively uniform for all the data reviewed by Hjelmar et al. (1994). This type of leachate is relatively uniform for dumps and all landfills receiving MSW and mixed non-hazardous industrial and commercial waste. This type of leachate is similar to that observed at co-disposal landfills in the United Kingdom – however, this may partly be explained by the low loading rate of hazardous waste to other waste allowed in the UK.

Non-hazardous low organic waste leachate:
Leachate with a relatively low content of organic matter (COD does not exceed 4,000 mg/l and it has a typical BOD/COD ratio of <0.2) and a low content of nitrogen (typically total N is in the range of 200 mg N/l, but can be in the range of 500 mg N/l). Relatively low levels of trace elements concentrations are observed. This type of leachate comes from landfills only receiving non-hazardous waste exclusive of MSW. Representative of landfills for mixed non-hazardous industrial waste and commercial waste.

Inorganic waste leachate:
Leachate with relatively high initial concentrations of salts (sulphates + chlorides often in the range of 15,000 mg/l), a low content of organic matter (typically COD <1,000 mg/l) and low content of nitrogen (Total-N <100 mg /l). Trace element concentrations are often negligible. The concentration of most components decreases with time. This type of leachate is representative of landfills for inorganic waste (e.g. well burnt-out incineration bottom ash).

Inert waste leachate:
Leachate with low strength of any component. This type of leachate is representative of inert waste landfills.

Accurate prediction of the future composition of leachate from most types of landfills is difficult. Exceptions are some inorganic waste leachates, which are not significantly influenced by biological degradation, and inert waste leachate, which has a very low pollution potential. Improved control over inert waste inputs for landfilling may be expected to further reduce the concentrations of contaminants in inert waste leachate in the future.

Due to the dominant influence of biological activity, the future range of leachate composition from the complex mixtures of waste in MSW and co-disposal landfills appears reasonably predictable. But changes or variations in waste composition (e.g. separation of waste components and change of consumer habits), operating conditions (e.g. waste pre-treatment, thickness of layers, compaction) or different climatic conditions (landfilling in different parts of Europe/the World or individual countries or during different seasons) could strongly influence the processes in a landfill and render predictions difficult unless the specific conditions are considered.

Landfilled hazardous waste and non-hazardous industrial waste reflect the industrial activity in the region near the landfills. The leachate from these types of wastes may therefore vary considerably from landfill to landfill.

Some observations at German MSW, industrial and hazardous waste landfills (Hjelmar et al. 1994) show that the strength of leachate from landfills of comparable ages has decreased significantly over the last 15 years. The main reasons are believed to be increasing pre-separation of hazardous waste components and decreasing use of hazardous products in households and industry.

The composition of MSW, industrial and hazardous waste has changed significantly over the past years in several European countries. The effect of this on leachate composition is not clearly reflected in the data available because leachate from older and newer sections of landfills often are mixed prior to sampling and analysis and because newer landfills with extensive waste separation have been observed only for a short period of time.

The philosophy of landfilling and the approach towards "final storage quality" differs between countries. Some countries attempt to limit the contamination potential of the waste by reducing the content of degradable and/or soluble components prior to disposal, whereas other countries attempt to exploit the processes of "biological reactor landfills" to reach final storage quality within a limited period of time. Both approaches require that contaminants are transferred out of the landfill by percolation or flushing of the waste with leachate, and the time needed to reach final storage quality depends strongly on the effectiveness of the percolation/flushing process. Waste in landfills with very little formation and flow of leachate may require hundreds of years to reach final quality.

Based on a number of assumptions, Belevi and Baccini (1989) have calculated that it may take 500-1700 years before the content of organic C in the leachate from a traditional MSW landfill has been reduced to a level of 20 mg/l. They have also been calculated that it may take 55-80 years for the concentration of $NH_3 + NH_4^+$ to fall to 5 mg/l, 100-700 years for P to fall to 0.4 mg/l and 100-150 years for Cl^- to fall to 100 mg/l. In relation to groundwater and surface water protection, it is often the concentrations of ammonia, which are of major concern.

If the objective of landfilling is to reach final storage quality within a reasonable time limit, landfill operation and leachate management procedures must be adjusted to this purpose. It must be assured that a sufficient amount of water or leachate percolates through the waste during the time allocated to attain final storage quality. The leachate functions both as a reaction media and as a means of transfer of contaminants out of the landfill. It is estimated that a water percolation rate corresponding to an accumulated L/S of 3-4 m^3/t will be necessary to reach final storage quality in terms of COD, TOC and total nitrogen for MSW (Hjelmar et al., 1994). For AOX an even higher total percolation may be needed.

It should be pointed out that there is a high degree of uncertainty associated with the determination of the time needed to reach final storage quality as well as with the definition of final storage quality itself. A substantial research effort is needed in this area. Hjelmar et al. (1994 and 1995) have prepared rough estimates of the time needed to reach final storage quality for the various types of leachate under different conditions, see table 3.3.

Top covers applied to many landfills in Europe in recent years will allow less than 100 mm/annum of water to infiltrate and regulations in many countries require even lower rates of infiltration. Even allowing for the approximate nature of the estimates in table 3.3 it is clear that many existing landfills will not reach final storage quality for several hundreds of years unless a complete change in post-closure leachate management strategy is adopted.

Table 3.3
Crude estimates of the number of years needed to reach final storage quality for different types of leachate at two different rates of leachate production. An average landfill height of 12 m is assumed (Hjelmar et al., 1994 and 1995).

Rate of production of leachate	Hazardous waste leachate	MSW and co-disposal leachate	Non-hazardous low organic waste leachate	Inorganic waste leachate
Medium: (200 mm/y)	600	300	150	100
High: (400 mm/annum)	300	150	75	50

4. Survey of R&D efforts relating to leachate quantity and quality

It is evident that landfilling techniques and thus the focus of research related to landfill leachate have changed with time. Early studies were often primarily focused on hygiene and simple issues of nuisances connected with landfilling. Later it became important to reduce landfill volumes, and research efforts were directed towards the effects on leachate production and composition of different volume reduction techniques (e.g. compaction and shredding). At the same time cases of contamination of groundwater by leachate, often from abandoned landfills, were observed, and leachate containment and, consequently, leachate handling became important issues, leading to the experience and acknowledgement of the difficulties involved in the management of leachate. It thus became relevant to study measures to reduce the production of leachate and methods to treat leachate, e.g. by re-circulation. Methods aiming at producing leachate with modified properties have also been studied. Many landfill/leachate technology issues have been studied without a clear reference to a landfill strategy framework. However, during recent years it has become increasingly clear from knowledge gained on the long-term quality and fate of the leachate that it is necessary to develop sustainable landfill strategies as well as the technologies to support such strategies. This includes pre-treatment and/or methods to enhance the rate of stabilisation/mineralisation and development of concepts and techniques enabling controlled transfer of the mobile contaminants from the landfilled waste back into the ecological cycle at an acceptable rate.

This chapter summarises a substantial part of the R&D efforts related to the above mentioned issues with emphasis on recent developments. It should be kept in mind that the presentation of an in-depth literature review is beyond the scope of this report. The aim is merely to provide an overview which may be used to determine which areas are fairly well investigated and understood and which areas of relevance for leachate emissions/the future landfill strategies are in need of further research. The description is divided into issues related to leachate quantity and leachate quality although definite ties exist between the two and several research projects encompass both aspects.

4.1 Leachate quantity

Since the early 1990’s a large number of studies have looked into the control of the amount of water allowed to seep into and percolate through the waste body in landfills. In this section, the description of the different projects and aspects are presented under the following specific headings: top cover, water balance, water content, leachate containment and drainage systems and modelling. Finally, the special conditions existing for solidified/stabilised waste are briefly addressed.

Top cover
During the early 1990's much attention was focused on minimising the amount of leachate through minimisation of the water flow through the top cover of the landfill. Development of less permeable covers, top drainage systems, capillary barriers and enhanced evapotranspiration by choice of plant cover were all methods investigated to promote the reduction of the quantity of leachate to be handled (see e.g. Mattravers & Robinson, 1991, Von der Hude & Jelinek, 1993, Knox & Gronow, 1993, Melchior et al., 1993, Rowe & Fraser, 1993, Ham & Bookter, 1997). Knox & Gronow (1993) have reviewed landfill cap performance and its application to leachate management. Actual percolation varied between zero and 200 mm per year, and they concluded that very low net percolation can be obtained, and that a minimisation of the leachate quantity is possible if desired. It is questioned whether this is compatible with the objective of minimising long-term liabilities from landfills. Alternatively a high-rate of recirculation of leachate incorporating a nitrification stage treatment may be used to flush out key pollutants, particularly ammonia, rapidly with the landfill acting as a denitrifying filter. In this way the total leachate treatment costs can be compressed into a much shorter time scale. See also table 3.2.

Water balance
Studies have also been carried out determining total water balances for specific landfills and looking into the parameters that influenced these (see for example Gössele et al., 1993, Nolting et al., 1995, Ham & Bookter, 1997, Giardi, 1997). This work has been continued and refined to the present time (see for example Zeiss, 1997). A description of the general findings of this research is given in section 3.3 of this report.

During recent years, investigations have also been carried out as to how the water balance varies in ordinary MSW landfills (see Andreottola et al., 1997, Zeiss, 1997) and how it is influenced by different construction and operating techniques (see Binner et al., 1997b). The influence of pre-treatment by different methods has been investigated to a lesser degree (see for example Dach et al., 1997) along with landfills containing specific waste types, for instance industrial sludge (see Baldi et al., 1993).

Water content
During the later years a substantial amount of research has also been focused on the importance of the water content of the waste and its distribution within the landfill. This research has encompassed investigations on the influence of the water content of the different types of waste at the time of landfilling, the water retention capacity of the different waste types (e.g. the influence of sludge disposal, see for example Röhrs et al., 1995, Cappai et al., 1999), the actual flow of water in the landfill (channelling etc., see for instance Bendz et al., 1997a, Burrows et al., 1997, Cossu et al., 1997, Giardi, 1997, Rosqvist et al., 1997) and how this is influenced by the mode of operation (degree of compaction, pumping strategies, gas extraction design and strategy, etc., see for example Cossu et al., 1997 and Binner et al., 1997b). This research has led to awareness to the fact that very diverse water regimes exist in a specific landfill, some parts being very dry, and some parts even containing pockets of water with very little solid content. Lately also the influence of the heterogeneity of the water flow on the actual leachate composition has been investigated (Bendz and Flyhammar, 1999, Rosqvist, 1999). In order to enhance the overall degradation or leaching of waste, it is very important to develop methods that can ensure as homogeneous a distribution of water as possible within the landfill.

Leachate containment and drainage systems
The design and effectiveness of the bottom liner and drainage and well systems under landfills have been addressed by several research projects. This includes research into the influence of temperature and specific organics on the bottom liners (see for example Müller & Müller, 1993, Rowe & Fraser, 1993, Collins, 1993), and the processes causing encrustation and biofouling of the drainage system (see for example Brune et al., 1991, McBean et al., 1993). The understanding of these issues has improved substantially over the last few years due to the accumulation of basic scientific information on the durability and specific permeability of bottom liners (natural or manmade) in the often relatively aggressive environment introduced by the presence of leachate (see for instance Gartung et al., 1999, Voudrias, 1999, Pierson et al, 1999, Kalbe et al., 1999). The influence of the redox potential in the

landfill on the occurrence of for instance clogging of the drainage system has also been investigated (see for example Bordier & Zimmer, 1999 and Manning & Robinson, 1999).

Modelling

Models describing the water balance of the landfill have been developed by incorporating the knowledge of the different parameters and their interaction since the early 1990s (see for instance Colin et al., 1991, Vincent et al., 1991). These early studies were part of a large EU project lead by the French Institut de Recherches Hydrologiques. The need for a model is primarily dictated by the difficulties in utilising knowledge obtained in small scale experiments, where only a few phenomena can be taken into account at the same time and extrapolation to a larger scale can be difficult. At the same time knowledge obtained in full scale, where all factors cannot be controlled and maybe not fully observed, also leads to the difficulty of extrapolating to different situations than the one actually observed. A model potentially has the possibility of solving these difficulties.

The project led – as one of its results - to the development of a 2-dimensional numerical flow model and a methodology for identifying the hydraulic properties of a waste product, e.g. density, permeability, water content, water retention capacity and hydraulic conductivity.

Models of varying degrees of complexity have been used to estimate the rate of formation of leachate. Two commonly used models are the top layer model (Kjeldsen & Christensen, 1998) and the HELP model (Capodaglio, 1999 and Kjeldsen & Christensen, 1998). The latter model has been widely used internationally, and a knowledge base now exists as to where it provides a suitable description of the leachate quantity and where it is less useful (Röhrs et al, 1995, Zeiss, 1997, Capodaglio et al., 1999, Marques & Hogland, 1999).

The HELP (Hydrological Evalualtion of Landfill Performance) is a numerical code developed by the U.S. Army Corps of Engineers Waterways Experimental Station for the US EPA, with the objective of providing a tool for the evaluation of alternatives in landfill design (Schroeder et al., 1994). The model performs a complex hydrological simulation of the processes in the landfill, which leads to leachate generation. It takes the following phenomena into account: leachate accumulation on the surface, melting of snow, surface run-off, evapotranspiration, plant growth, accumulation in subsurface layers, vertical flow in unsaturated layers, lateral flow in subsurface layers and losses through soil layers and liners. The input data requirements are substantial. HELP uses specific climatic, vegetation, soil, waste and design data. The user can provide the input data, or they can be generated by the model as default values based on the conditions in the USA. The model calculates daily values of surface run-off, evapotranspiration and vertical and lateral flow in the various layers, including the leakage flow of leachate through the bottom of the landfill. According to Kjeldsen & Christensen (1998), the HELP model does not account for effects caused by ageing of liner systems (e.g. cracks and macropores caused by roots and worms), surface run-off during short, intensive bursts of rainfall (the rainfall intensity is averaged over 24 hours) and transport of contaminants through clay layers by diffusion. The overall conclusion of Kjeldsen & Christensen is that the HELP model is a well tested tool which in its latest version has become more user-friendly than earlier, and that it requires some adjustment to local conditions before can be used outside the USA. Capodaglio et al. (1999) strongly recommend that input information regarding the water content and the hydraulic properties of the waste be carefully evaluated and, if possible, made the object of specific field investigations prior to use in the HELP model.

In Sweden, substantial research efforts have been spent gaining insight into the flow patterns and the elements controlling the water balance and the leachate formation at landfills, both during operation and aftercare (e.g. Bendz et al., 1994, Bendz & Bengtsson, 1996, Bendz et al., 1997b). This work has led to the proposal of relatively sophisticated models for water movement in municipal solid waste (Bendz et al., 1998 and 1999b).

Other modelling efforts are e.g. described in Andreottola et al. (1997), Demirekler et al. (1999), Beaven & Powrie (1999).

Solidified waste landfills
Most of the information on leachate quantities has been based on the assumption that the landfilled waste behaves like a porous medium and that the leachate is formed as water (infiltrating precipitation) is percolating through. In some cases, however, the waste is solidified and the water flows around the surface of the waste rather than percolating through it. The flow pattern depends on the shape and form of the solidified waste and the cover material. Substantial research efforts have been spent to stabilise (chemically and/or physically) various wastes, particularly hazardous waste, prior to landfilling. In France, for instance, hazardous waste cannot be landfilled unless it has been stabilised chemically and/or physically (see e.g. Flyvbjerg and Hjelmar, 1997). In Sweden, APC residues from an MSW incinerator (Högdalen) is being stabilised with a special type of cement before they are landfilled (Sundberg & Tuutti, 1994). If the solidified waste materials have monolithic properties (a certain minimum size, a certain strength and a hydraulic conductivity of less than approximately 10^{-9} m/s) water will flow around the surface of the waste form rather than percolate through it, and the contaminants will be transferred from the waste to the water phase by diffusion through the surface of the waste material. If the waste material looses its strength and crumbles or cracks, this will of course increase the surface of the material and change the potential flow pattern in a landfill. The result may be an increase in the flux of contaminants. Much research has been directed at the determination of the long term stability and durability of solidified/stabilised waste forms, but there is currently no general agreement on the criteria and test methods. The assumptions concerning flow patterns used for predictions of the flux of contaminants from stabilised/solidified waste landfills are often primitive, and could be improved significantly through research efforts.

4.2 Leachate quality

The factors influencing the quality of landfill leachate and its change with time have already been discussed in a more general way in section 3.4. In this section, recent R&D efforts related to leachate quality will be discussed in terms of landfill processes, recirculation and flushing, leachate composition, strategies, pre-treatment and modelling. Finally, some of the research projects related to monofills and old landfills are also discussed.

Landfill processes
Substantial amounts of research have been carried out on the degradation processes in the landfill, with the main focus on the hitherto most common type of landfill: the municipal solid waste (MSW) or sanitary landfill, which is characterised by a high content of biologically degradable waste. The mechanisms and processes of waste degradation and stabilisation in these types of landfills are fairly well known (see for example . Lagerkvist, 1991, Ham et al., 1993, Blakey et al., 1995, Kylefors & Lagerkvist, 1997, Andreas et al., 1999, Hanashima, 1999) and have also been the subject of modelling exercises (see f. Ex. Colin et al., 1991, Gil Diaz et al., 1995, Clarke et al., 1995, Swarbrick et al., 1995, Bogner & Lagerkvist, 1997, Martin et al., 1999). There is a general agreement as to the development over time of the different phases of the degradation leading to quite different leachate compositions. At the same time there is an acknowledgement of the fact that often there is a great variability within the landfill body itself resulting in the simultaneous occurrence of different degradation phases in various parts of the landfill.

Some studies have looked at the impact on leachate quality of the design of the landfill and the auxiliary systems (e.g. drainage and well systems) and the operating techniques (see Matsuto et al., 1991, Binner et al., 1997a). Ecke & Lagerkvist (1997) have compiled the results from research carried out in 35 test cells in 8 industrialised countries across the world. All test cells contained municipal solid waste, and the addition of e.g. ashes or sludge was studied to a lesser extent. Some of the earlier studies have looked into the influence of compaction or other means of volume reduction on the leachate quality. The results suggest that shredded refuse produce higher peak leachate concentrations than unprocessed refuse, while lack of daily cover results in a decreased COD production. Aerobic preprocessing of the waste also leads to a leachate containing less organic material. Addition of moisture alone does not seem to improve the leachate quality, it actually seems to have the opposite effect, while addition of anaerobically digested sludge does seem to result in a better leachate quality. It was also shown that addition of lime as a buffer does not seem to improve leachate quality. Koliopoulos et al (1999) cite results from an experimental UK test landfill, where fast degradation/stabilisation seems to be obtainable based on pre-treatment (wet pulverisation), leachate recirculation and the addition of inert material (20 %).

Relatively few studies have been published on the processes occurring in industrial landfills. It is likely that the confidential nature of many studies of industrial landfills prevents the publication and dissemination of a substantial amount of information, which actually exists on the processes occurring within these landfills. Gade et al. (1997) have published one such study where geo-chemical equilibrium calculations were used to predict the expected mobilisation of contaminants based on a description of the geo-chemical processes within the waste, e.g. crystallisation of secondary minerals. In the specific case, even a wide variation in the geo-chemical environment in the equilibrium calculations did not seem to induce mobilisation of the fixated metals. This was in accordance with the actual leachate concentrations observed.

In many countries, the traditional MSW landfills are gradually being replaced by landfills containing more inorganic waste, particularly MSW incinerator residue landfills (see section 5). Research into the behaviour of MSWI residue landfills should therefore be intensified. Some studies of these landfills have been reported. Meima et al. (1997) has e.g. investigated the geochemical processes controlling the leaching of contaminants in a 20-year old landfill containing MSWI residues. Belevi et al. (1993) has studied the influence of organic carbon on the long-term behaviour of bottom ash monofills. Belevi (1996) has also observed the formation of ettringite crystals within a young landfill containing well burnt-out MSWI bottom ash. Belevi and other researchers at EAWAG in Switzerland have studied the behaviour of landfilled incinerator residues for more than a decade.

Recirculation of leachate

For a number of years the main strategy for landfilling has been the establishment of an in-situ bioreactor where anaerobic degradation of untreated waste was enhanced as much as possible, for instance by leachate recirculation and landfill extraction. The ability of recirculation to enhance the water flow in the landfill and thus promote the biodegradation and the leaching of the easily leachable components has been widely investigated (see for example Trauger & Stam 1993, Shimaoka et al., 1993, Kouzeli-Katsiri et al., 1993, Maier et al., 1995, van den Broek et al., 1995, Yuen et al., 1995, Ham & Bookter, 1997, Blakey et al., 1997, Novella et al., 1997, Walker et al., 1997, Burton & Watson-Craik, 1999, Pouech et al., 1999). The effect of combining new and old waste, thus allowing the more decomposed waste to help degrading organic leachate components in the leachate within the landfill has also been looked into (see Ham & Bookter, 1997) together with the impact of co-disposal of MSW with inert material (Wingfield-Hayes et al., 1997). The influence on leachate quality of pre-treatment of the leachate before recirculation has been investigated (see f. Ex. Woelders et al., 1993). Yuen et al (1995) have compiled results from a large number of recirculation studies looking at recirculation alone at different rates and recirculation in combination with a number of technical modifications (e.g. pH neutralisation, addition of sludge or nutrients, waste shredding). They conclude that leachate recirculation, even with various supplementary techniques, is not able to provide a complete solution to the treatment and elimination of the contamination potential of leachate. However, the substantial cost savings gained in the partial in-situ treatment of leachate warrant the investment in recirculation. Additionally, recirculation promotes the stabilisation of the landfilled waste through the provision of optimum moisture conditions, a more effective transfer of microbes, substrates, and nutrients throughout the waste body, and the dilution of high concentrations of inhibiting substances.

A special UK concept called the “flushing bioreactor” intensifies the recirculation processes trying to optimise a homogeneous water content of the waste and utilise the recirculation process to enhance the leaching of the soluble components, especially ammonia, see for instance Knox (1993), and Knox & Gronow (1995).

Leachate composition
A large number of studies have been carried out on the actual composition of leachate from a large number of MSW landfills, the possible correlation between the parameters and in a few cases the speciation of the metals (see f. Ex. Silvey & Blackall, 1995, Clement, 1995, Gómez Martín et al., 1995, Flyhammar 1995, Jensen & Christensen, 1997). These studies show that there is a wide range of variation in the different parameters analysed within the same landfill and among different landfills. Leachate quality also varies on a seasonal basis.

Some studies have looked at the change of leachate composition with the different degradation phases (see Kylefors & Lagerkvist, 1997), and some at the influence of landfill operation techniques (Armstrong & Owe, 1999). Other studies have looked into the expected long-term composition of the leachate through lysimeter studies and thus to the long-term emission potential (see Heyer & Stegmann, 1995, Beaven & Walker, 1997, Heyer & Stegmann, 1997).

Studies of leachate composition also include leachate from other types of landfills than MSW landfills, for instance industrial landfills (see f. Ex. Zanetti & Genon, 1995, Genon et al., 1995), where lysimeter studies have been performed to evaluate long-term quality of industrial leachate, and (Aulin & Neretnieks, 1995, Genon et al., 1995), other "mono" landfills and landfills with co-disposal of for instance industrial or municipal sludges or other industrial waste products (Röhrs et al., 1995, Puura & Neretnieks, 1999). Some studies have also looked into how leachate quality varies with leachate quantity (see f. Ex. Gómez Martín et al., 1995). Hjelmar (e.g. 1989, 1995) has followed the development of the composition of the leachate from a MSWI bottom and fly ash landfill as function of the cumulative amount of leachate produced (or the liquid to solid ratio) over a period of more than 25 years. He has also published data on the composition of leachate from several landfills containing various types of incinerator residues (e.g. Flyvbjerg and Hjelmar, 1997, Hjelmar, 1995).

In the early studies mainly macro-components of the leachate were measured (e.g. BOD, COD, ammonia, nitrate, chloride, sulphate, etc.), but more recently also the contents of micro-components have been looked into (hydrocarbons, metals, chlorinated aliphatics, pesticides, plastisizers, etc.), see for instance Öman & Hynning (1991) and Öman (1995). A number of studies have also focused on the fate of these components in the landfill (primarily MSW landfills) dependent on the redox conditions in the landfill (see for example Christensen et al., 1993, Kromann et al., 1995, Öman et al, 1997, Meersiowsky & Stegmann, 1997, Ejlertsson et al., 1997 & 1999, Flyhammar & Håkansson, 1999, Lagier et al., 1999a, Lagier et al., 1999b, Mersiowsky et al., 1999). A simple model has also been developed for the evaluation of the distribution and fate of organic chemicals in landfills (Kjeldsen & Christensen, 1997). The influence of the changes in redox conditions, and the change over time in the composition of the organic matter in a landfill on the retention of the heavy metals in the landfill has e.g. been studied by Botzkurt et al (1997), Aulin et al (1997) Revans et al (1999), Lagier et al (1999), and Flyhammar et al (1999). All in all, the above-mentioned studies have led to an increased awareness of the influence of a possible long-term change in the redox conditions and buffering capacity on the leaching of a number of substances regarded as potential environmental and human health hazards. The influence of the heterogeneous water regime in a landfill on these processes is also of concern, see for instance Bendz & Flyhammar (1999).

Recent studies have provided knowledge on the quality of leachate from both fairly old MSW landfills (25 to 40 years), newer landfills, and test cells, thus enabling the drawing up of possible long-term trends (see Beaven & Walker, 1997, Heyer & Stegmann, 1997, Kjeldsen & Christophersen, 1999, Kruempelbeck & Ehrig, 1999). These studies confirm the suspicion that MSW landfills may be a potential source of groundwater and surface water contamination for a very long time (more than a 100 years), and imposes the requirement that the collection and treatment systems for the leachate must be kept operating and well functioning for this long span of time. See also section 3.4 and table 3.3.

Modelling
A number of efforts have been carried out to model the development of the quality of leachate from MSW landfills, see for instance Muntoni et al. (1995), Demirekler et al. (1999) and Steyer et al (1999).

The latter model includes equations for the development of pH, BOD/COD-ratio and sulphate content of the leachate with time (together with other parameters describing the stabilisation of the landfill waste and the necessary time required. Specific models have also been developed to estimate leachate quantity and quality for industrial waste (mainly sludge) landfills (Zanetti & Genon, 1991, Baldi et al., 1993 and Zanetti & Genon, 1993), a landfill for mechanically – biologically pre-treated MSW (Theisen et al., 1999) and landfills for incinerator residue (Crawford et al., 1999). Models describing the flux of contaminants out of landfills containing coal fly ash (e.g. Hjelmar 1990, Hansen & Hjelmar, 1992) and incinerator residues (e.g. Hansen & Hjelmar, 1992, Hjelmar et al., 1994), both during the operational and aftercare phases, have been developed and applied.

Strategies
The knowledge gained on how long it will take before a sufficiently low concentration is reached in the leachate, has led to a growing awareness of the need for new landfill strategies. This often encompasses the need for pre-treatment of the waste before landfilling (often also including a ban on the landfilling of waste with a large organic content) together with a need for active enhancement of the stabilisation of the waste over a much shorter time span (e.g. 30-50 years). For examples of strategic papers originating in the scientific world, see for instance Seinen et al (1993), Johannessen et al. (1993), Hjelmar (1995), Driessen et al. (1995) and Bendz et al., 1999. The paper by Driessen et al. describes some of the winning contributions to a contest sponsored in 1994 by the Waste Processing Association (VVAV) in the Netherlands. The winning contribution was called THE RECYCLING LANDFILL, a concept where regulation of water and gas flow in the landfill optimises the degradation of the organic matter and the leaching of the more soluble waste components. Optimal processing is to be obtained through regulation of the redox processes to ensure degradation of more persistent anthropogenic compounds. This concept is now the object of a large-scale project with the focus on the detailing of the necessary processes. Details on some of the ideas are given in De Cleen & Weststrate (1999) and in Mathlener (1999). Another approach to a low-emission landfill has been described by Zach et al (1999). The primary reduction measure in this approach is mechanical-biological pre-treatment with the aim of reducing the carbon (methane) and nitrogen emissions and incorporates the remaining carbon and nitrogen into long-term stable humic substances. See also the discussion of landfilling strategies in section 3.1.

Pre-treatment of MSW
A number of research projects has been focused on the influence on leachate quality of different types of pre-treatment, including mechanical, biological (aerobic and anaerobic) (see for example Krogmann 1993, Chang, 1993, Heerenklage & Stegmann, 1995, Ham and Bookter, 1997, Raninger & Nelles, 1997, Soyez et al., 1997, Leikam & Stegmann, 1997, Theisen et al., 1997) and of course incineration (see for example Krogmann, 1993 and the references listed under composition). Here especially the German and Austrian research has focused on mechanical and biological pre-treatment of waste before landfilling. In Austria test methods to characterise the biological reactivity of mechanically and biologically pre-treated waste has been developed (Binner et al., 1997a). The prudence of mechanical and biological pre-treatment of MSW prior to disposal has been questioned by UK researchers stating that this will only prolong the time needed to reach final storage quality (Gronow, 1999).

Mono-landfills
Mono-landfills where only one type of waste or very similar waste types are landfilled have not been the subject of nearly as extensive research as the municipal solid waste landfills. The main type of mono-landfill investigated receives incinerator residues or similar waste from high temperature processes (see f. Ex. Belevi et al., 1993, Higuchi et al., 1995, Hjelmar, 1995, Muntoni, 1995, Zevenbergen et al., 1995, Kruempelbeck & Ehrig, 1999). As for incinerated waste, research has also been focused on the pre-treatment/ stabilisation of the residue before landfilling (see. F. Ex. Catalani & Cossu, 1999, Higuchi & Hanashima, 1999, Hjelmar et al., 1999a, Lundtorp et al., 1999a,b), and some studies have looked at the influence of water addition or not on leachate composition at aerobic landfills for incinerator residue (see Stegmann, 1993). Mining waste is another example of bulk waste materials that are placed in monofills.

Old landfills
During recent years a fair amount of research has been directed at possible methods to enhance the stabilisation of already closed landfills. Methods investigated have been, for instance, aeration of old landfills (see f. Ex. Heyer et al, 1999), controlled addition of water (see for example Kabbe et al, 1999), enhancement of water flow through the landfill by e.g. blasting of new channels, and in some countries mining of treatment of landfilled waste (see for example Göschl, 1999, Zanetti et al, 1999, and Godio et al, 1999,). This last concepts is mainly brought into use in connection with industrial landfills, where the mined waste products are expected to be of some commercial value.

5. The EU Landfill Directive

This section briefly addresses the potential needs for research in the field of leachate formation and emission related to the newly adopted EU Landfill Directive, which entered into force when it was officially published on 16 July 1999 (CEC, 1999). For a more complete discussion of the Landfill Directive and its implications for landfilling in Europe and Sweden, the reader is referred to Bendz et al. (1999a).

The EU Landfill Directive does not explicitly address landfill strategy and sustainability. The overall objective (article 1) states only the desire to *"by way of stringent operational and technical requirements on the waste and landfills to provide for measures, procedures and guidance to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment, including the greenhouse effect, as well as any resulting risk to human health, from landfilling of waste, during the whole life-cycle of the landfill."* This cannot, of course, be accomplished without applying specific landfill strategies and corresponding landfill technologies exhibiting strong elements of sustainability. However, with the exception of the gradual phasing out of disposal of biodegradable waste (article 5), which is justified by a desire to reduce the production and emission of the strong greenhouse gas methane, the actual or envisioned short and long term behaviour of the waste after landfilling is not mentioned at all. The Directive defines 3 classes of landfills (article 4): landfills for inert waste, landfills for non-hazardous waste and landfills for hazardous waste. The only distinction between the three classes of landfills is the degree of "hazardousness" of the waste to accepted at the landfills and the corresponding stringency of the environmental protection systems, which increases from inert over non-hazardous to hazardous waste landfills. The Directive practically neglects the fact that non-hazardous waste consisting of mainly organic, biodegradable waste (which will still be landfilled in substantial amounts even after the full implementation of the restrictions in article 5), will behave very differently from mainly inorganic, mineral non-hazardous waste types such as e.g. MSW incinerator bottom ash and various industrial and mining residues, and that organic and inorganic waste types therefore require different landfilling strategies both in the short and long term and that, consequently, they should not be landfilled together.

Whereas the Landfill Directive does not directly address or provide guidance on these issues, it does not in its present form prevent individual EU Member States from separating different non-hazardous waste streams and placing them in dedicated landfills or monofills with different strategies adjusted to the properties and expected behaviour of the waste. Nor does it in itself prevent the Member States from jointly developing rational waste acceptance criteria which can take the different behaviour of different types of non-hazardous waste into account and address the issue of landfill strategy and sustainability. During the negotiations of the Landfill Directive (1990 – 1998), it was not possible to come to an agreement on the criteria for acceptance of waste at the different classes of landfills. Most of the disagreements were therefore deferred to Annex 2 "Acceptance criteria" which at the moment expresses only the principles upon which the development of the acceptance criteria must be based. Annex 2 must be developed into concrete acceptance criteria over a period of 2-3 years from July 16 1999 by the Technical Adaptation Committee (TAC), which consists of representatives of the Member States and the Commission.

Among the principles listed in Annex 2 is the requirement that the future acceptance criteria should be derived from considerations pertaining to protection of the desired waste-stabilisation processes within the landfill. Article 16 states that the amendments to the Annexes (by the TAC) shall only be made in line with the principles expressed in the Annexes. Article 16 also states that specific criteria and/or test methods and associated limit values should be set for waste to be accepted at each class of landfill, including if necessary specific types of landfill within each class. If this is seen together with the requirement of the overall objective to prevent negative effects from landfilling during the whole life-cycle of the landfill, it becomes clear that it is both necessary and possible within the framework of the Landfill Directive to define more than one type of non-hazardous waste landfills and to require that they be designed and operated in a sustainable manner based on different disposal strategies. This would also be the only way to create a rational basis for the development of risk-related waste acceptance criteria. Since this was not done before the Directive entered into force, it has become the task of the TAC to do so when amending Annex 2. Not all members of the TAC are likely to agree to this interpretation of the nature of the job ahead, and it is p.t. very uncertain what the outcome of the work of the TAC will be. If it is not possible to agree on a general system based on the principles described above, there should still be a possibility that individual Member States can create a rational and strategy-based system on a national scale, if such a system can be contained within the common system and if it can be seen to be environmentally "better" (the Landfill Directive is a minimum directive based on Article 130s of the Rome Treaty).

As a result of the implementation of the EU Landfill Directive, there is no doubt that the amount of MSW/biodegradable waste landfilled will be reduced drastically in some countries (this transformation is already well underway in Sweden, Denmark and several other countries due to national waste management policies restricting or prohibiting the disposal of organic wastes). Since much of the MSW is being or will be incinerated, landfilling of APC residues (hazardous waste) and bottom ash from MSW incinerators is likely to increase, even if the utilisation of bottom ash increases. There will be a need to develop sustainable landfill strategies and technologies, particularly for inorganic non-hazardous waste. There will also be a need to develop and apply various pre-treatment methods, particularly to hazardous waste such as MSWI APC residues prior to landfilling. Other research needs with specific reference to the Landfill Directive include the development of risk-related acceptance criteria and associated test methods and limit values for each type of landfill defined. Such criteria would in many cases be based on an understanding of the processes occurring within the landfill and on an understanding of the formation and characteristics of the leachate. For certain types of waste, mainly inorganic, it would be advantageous if a relationship between the results of laboratory tests (acceptance tests) performed on the waste and the short and long term behaviour of the waste in terms of leachate formation and emission could be established, possibly using hydrogeochemical modelling.

6. Recommendations of future research issues

The review and discussion of previous and ongoing research and development related to emissions of leachate from landfills lead to the following conclusions and recommendations for future research:

The major concerns over short and long-term impacts of landfills are associated with leachate formation and emission, and landfill strategies are therefore generally described in terms of leachate management and fate. Considering the state-of–the-art of R&D on issues related to leachate emissions from landfills and the explicit and implicit requirements of the new EU Landfill Directive, it is quite evident that there is a strong need for major national research programmes directed towards the development of sustainable landfill strategies, concepts and technologies. It is therefore strongly recommended that such a programme is initiated in Sweden. It is further recommended that close co-operation is established between such a programme and similar activities in other countries, e.g. Denmark and the Netherlands.

Some of the elements that should be addressed by such an R&D programme are:

- Development of new landfill concepts and designs (e.g. landfills that are placed on top of the ground rather than below the surface – this would allow easy access to environmental protection systems if necessary and it would allow transport of leachate by gravity). It would include defining different types of landfills for wastes that behave differently, particularly in terms of the quality of the leachate produced and in terms of the strategies employed to minimise short and long term impacts on the environment caused by the leachate. New concepts and designs should be subjected to life-cycle analysis in order to prevent undesirable and unintended sub-optimisation.
- Development of concrete definitions of and criteria for "final storage quality" of the waste, identification of "critical" components (e.g. ammonia) and development of landfill designs and operational measures that would minimise the time needed to reach this stage, i.e. a stage where the quality of the leachate or the flux of contaminants are compatible with the surrounding environment, and active environmental protection systems are no longer needed.
- Development of landfill design and operational measures that will allow the transformation of the landfill operation from an initial phase with active environmental protection systems to a final phase without or with passive environmental protection systems (i.e. systems that does not require maintenance or inputs of energy).
- Development of methods to establish a relationship between the (selected) properties of waste to be accepted in a certain type of landfill and the behaviour of the waste after landfilling, particularly its influence on the stabilising processes and on the properties of the leachate produced. Identification of desired and undesired behaviour and properties. Development of risk-related criteria for acceptance of waste in the various types of landfills, and subsequent development/adjustment of test methods and associated limit values. Some of this work would support the work of the TAC on Annex 2 of the Landfill Directive.
- Development of methods for pre-treatment and/or stabilisation of certain, typically hazardous, waste materials (e.g. APC residues from MSW incineration) in order to modify their properties and adjust them to the requirements of sustainable disposal.
- Development of methods and technologies to ensure a uniform distribution of the flow of water through the landfill and of measures to enhance or reduce the rate of infiltration/percolation as required by the chosen strategy. Quite sophisticated models describing the flow of water have already been developed. Rather than developing these models further, they should be applied to new and old landfills to help accomplish more uniform flow conditions. Some further model development might, however, be necessary in order to describe the flow regime within landfills containing solidified waste.
- Investigation of the possibilities for accelerated "flushing" (in-situ stabilisation) of old landfills.
- Investigations should be carried out to improve the understanding of the short and long term processes occurring and the properties of the leachate produced in landfills containing inorganic waste materials, e.g. incinerator residues, mining waste, etc. This would comprise experimental work, field verification and the use of hydrogeochemical equilibrium models and models describing the role and fate of trace organics and possibly also models describing slow kinetics.
- Investigations should be carried out to assess and if necessary improve the durability and long term reliability of active and passive environmental protection systems in landfills as well systems aimed at controlling the water flow into and within landfills.
- A database containing waste characteristics of relevance to leaching, classification and acceptance at various types of landfills should be established (co-ordination with pending European initiatives may be advantageous).

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Appendix 1: Research on leachate emissions and related subjects: Research groups

This appendix provides a country by country overview of some of the institutions/research groups, which have published studies on leachate emissions and related subjects. The list is not exhaustive in terms of research groups shown and only selected work and publications are presented for each institution. As discussed in Chapter 2, most of the information has been drawn from the proceedings of the Sardinia conferences. Only very limited information on research projects and research groups in the USA has been listed.

Australia

Australian Nuclear Science & Technology Organisation
Bio-reactor landfill containing household waste, operation of a test cell with controlled leachate recycle to optimise the degradation processes (Van den Broek et al., 1995).

Griffith University
Landfilling below the water table and developing of this specific technology. From water saturated landfills the extent of leachate impact on the groundwater quality is small. Within the saturated landfill a high degree of biological decomposition and contaminant fixation occurs. However, a saline and ammonium rich leachate is produced (Hancock & Phillips, 1993).

University of Melbourne
Active landfill management by leachate recirculation: a review and an outline of a full scale project. This reference gives an overview of landfill stabilisation enhancement techniques and then discusses the objectives, principles and advantages of an active landfill management achievable by leachate recirculation. A summary of the research and findings of leachate recirculation is presented and research areas still requiring further attention are identified (Yuen et al., 1995).

Findings from a full-scale bioreactor landfill study (Yuen et al., 1995).

University of New South Wales
Physical and bio-chemical modelling of solid waste (MSW) degradation. Development of a model (Swarbrick et al., 1995).

University of Queensland
A model to simulate the degradation of MSW in landfills. Development of a model (Clarke et al., 1995).

Austria

Department of Waste Management, Universität für Bodenkultur, Vienna
Materials for leachate collection systems. Damage to drainage and leachate collection systems due to incorrect load assumptions, unsuitable materials and unsuitable operational measures (Lechner and Lahner, 1991).

The immobilisation of waste aims at a reduction of mobility and a durable retention of such pollutants, in the long-term, that can neither be destroyed nor decomposed. For the treatment of wastes by immobilisation several different methods can be applied (Chemical immobilisation, physical immobilisation) (Lechner et al., 1995).

Test methods and characterisation of the biological reactivity of wastes (MSW). Alternative parameters to describe the reactivity of mechanically-biologically pre-treated waste were tested. A method for representative sampling. This investigation was performed in order to meet Austria legislation (Binner et al., 1997a).

Examination of the impact of different construction designs and operating techniques on reactor landfill (MSW). Results concerning water balances and element balances. Results are based on field observations (Binner et al., 1997b).

An approach to a Low-emission landfill where simple pre- and aftercare measures are used to reach the goal of a low emission waste disposal site at moderate costs (Zach et al., 1999)

Mining University of Leoben
Mechanical-biological pre-treatment of waste (MSW). The results are based on field observations (Raninger & Nelles, 1997)

Long-term behaviour of mechanical biological pretreated material under landfill conditions (Raninger et al., 1999)

Canada

University of Alberta Edmonton
In order to improve the prediction of leachate flow through MSW landfill, a model has been evaluated with respect to leachate quantity. Two alternative approaches are to either 1) calibrate a current model (HELP), or 2) apply a two-domain flow model to account for channelling (Zeiss, 1997).

University of Waterloo
Clogging of leachate collection systems. Useful design considerations as a means of minimising biofouling difficulties are considered (McBean et al., 1993).

University of Western Ontario
Long-term behaviour of barrier systems (Rowe & Fraser, 1993).

Leachate characteristics for MSW landfills, field observations (Rowe, 1995).

Modelling leachate production from MSW landfills. A three dimensional model has been developed and preliminary results showed good agreement between modelled data and observed data (Demirekler et al., 1999).

Effect of landfill operations on the quality of MSW leachate (Armstrong & Rowe, 1999).

Czech

Fuel Research Institute
Important changes in sanitary landfills during their ageing (Straka et al., 1993).

Denmark

Technical University of Denmark (IMT)
Degradation of specific compounds (chlorinated aliphatic compounds) within the MSW landfill, laboratory experiments (Christensen et al., 1993, Kromann et al., 1995).

Speciation of heavy metals in leachate from a MSW landfill. The experiments were performed as laboratory experiments (Jensen & Christensen, 1997).

Landfilling: Principles and environmental impacts (Christensen & Kjeldsen, chapter 6.1 in Christensen (ed.), 1998).

Landfilling: Hydrology (Kjeldsen & Christensen, chapter 6.2 in Christensen (ed.), 1998).

Landfilling: Leaching landfills (Hjelmar & Christensen, chapter 6.3 in Christensen (ed.), 1998).

Landfilling: Reactor landfills (Kjeldsen, Willumsen & Christensen, chapter 6.4 in Christensen (ed.), 1998).

Stabilisation of APC-residues with $FeSO_4$ (Lundtorp et al., 1999b).

On-site treatment and landfilling of MSWI- air pollution control residues (Lundtorp et al., 1999a).

Composition of leachate from old landfills in Denmark. A data base containing leachate quality parameters from 106 MSW – landfills has been developed (Kjeldsen & Christophersen, 1999).

VKI

Leachate from incinerator ash disposal sites (Hjelmar, 1987).

Groundwater contamination from an incinerator ash and household co-disposal site (Hjelmar et al., 1988).

Characterisation of leachate from landfilled MSWI ash (Hjelmar, 1989).

Leachate from disposal of coal fly ash (Hjelmar, 1990).

A new approach to landfilling of waste in Denmark (Johannessen et al., 1993).

An approach to the assessment of the environmental impacts off marine applications of municipal solid waste combustion residues (Hjelmar et al., 1994).

Composition and management of leachate from landfills within the EU – a comprehensive study based on a survey of the landfill situation in Europe. It includes a discussion of waste disposal strategies and landfill categories, state of the art of leachate management in the EU (1994), discussions of and data on leachate quantity, leachate quality, leachate pollution potential and environmental impact, leachate treatment/management options, leachate discharge criteria, monitoring procedures, recommendations and economic consequences of the recommendations made (Hjelmar et al., 1995).

Incineration of MSW: range of composition of MSWI residues and leachability of MSWI residues (bottom ash and fly ash). Field data, including a time series covering MSWI residue leachate quality and quantity over a 20-year period. Disposal practices and strategies for the various types of residues are discussed. (Hjelmar, 1995).

Disposal strategies for municipal solid waste incineration residues (Hjelmar, 1996).

Landfilling: Leaching landfills (Hjelmar & Christensen, chapter 6.3 in Christensen (ed.), 1998).
Development of a process for treatment of APC-residues from MSW incinerators prior to landfilling. Stabilisation of dry/semidry APC residues and fly ash using CO_2 and H_3PO_4 (Hjelmar et al., 1999a).

An approach to the development of rational limit values for regulatory testing of waste prior to disposal or utilisation (Hjelmar et al., 1999b).

Finland

University of Jyväskylä
Influence of waste moisture on leachate characteristics (Jokela et al., 1999).

VTT, Technical Research Centre of Finland
Several studies of waste leachability related to landfilling and utilisation, including: Influence of environmental conditions on leaching from materials to be used in earth constructions (Wahlström & Laine-Ylijoki, 1997).

Water and Environmental Research Institute
Occurrence, attenuation and toxicological significance of hazardous chemicals in uncontrolled landfills – co-disposal risks reconsidered (Assmuth et al., 1991).

France

Agence pour la Pécupération et l'Élimination des Déchets
EU-programme: Water balance and pollution flows in secure industrial waste landfill sites. The objective is to help the owner of controlled industrial landfills to solve the problem of production and release of effluents in providing him with procedure for establishing a forecast qualitative and quantitative water balance (ENVPROT 3C).

Ecole Nationale Superieure d'Ingénieurs de Limoges
Fate of heavy metals trapped in landfill under sulphur species: Effects of oxidising and complexing macromolecules (Lagier et al., 1999a).

Interaction of high molecular weight compounds with copper in landfill leachate (Lagier et al., 1999b).

Ecole Nationale Superieure des Mines de Paris
Waste behaviour modelling, identification and quantification of the processes generating leachates. Simulation of the moisture flow in the waste and the solute transport + biodegradation processes. Comparison between measured and computed leachate quantities showed good agreement (Vincent et al., 1991).

Institut de Recherches Hydrologiques
EU-programme: Co-ordinated projects on mechanisms, quantification and impact of pollution generated from existing and abandoned waste disposal sites. The objective is to acquire a better knowledge of mechanisms and reaction kinetics of processes generating diffuse pollution (in atmosphere, runoff, groundwaters and soils) from existing and abandoned industrial sites receiving toxic and dangerous waste in order to set up the concept and collect quantitative data needed for comparison and evaluation of different alternatives for the design and management of industrial wastes disposal sites (STEP, 1998).

Waste behaviour modelling, identification and quantification of the processes generating leachates. The model contains a hydraulic function, a biological function, and a physico-chemical function (Colin et al., 1991).

SOLAGRO – Toulouse
Leachate recirculation control in a bio-reactor landfill (Pouech et al., 1999).

University of Savoie
Leachate quality of 25 French landfills receiving domestic refuse and industrial refuse. A literature study (Clement, 1995).

Germany

BUGH, University of Wuppertal

Pollution potential and long term behaviour of sanitary landfills (Ehrig & Scheelhaase, 1993).

Long-term behaviour of municipal solid waste landfills. Control data from more than 50 German landfills give a broad overview of the emission behaviour of leachate development of municipal solid waste landfills (Kruempelbeck & Ehrig, 1999).

Long-term emission behaviour of mechanical biological pre-treated MSW (Höring et al., 1999).

Bundesanstalt für Materialforschung und – Prüfung (BAM)

Investigations of the effect of 4 different specific organic compounds found in leachate on geotextile properties (Müller & Müller, 1993).

ISA der RWTH Aachen

Long-term emission behaviour of sanitary landfills. The biochemical emission potential was mainly influenced by the fine-grained fraction. During this study a decline of organic substances was determined during time of deposition (Kabbe et al., 1995).

Potsdam University

Mechanical-biological pre-treatment of MSW, German Federal Research programme (Soyez et al., 1997).

Research and Development centre of hazardous waste

Geochemical processes within the solid waste (hazardous waste, field observations). Crystallisation of secondary minerals are believed to fixate heavy metals and no signs of mobilisation of metals was observed. Geochemical equilibrium calculations were used to predict the expected mobilisation of contaminates (Gade et al., 1997).

Crystallisation, adsorption, and aqueous speciation effects on metals in hazardous waste landfills (Gade et al., 1999)

Technical University of Berlin

Water balances of landfill sites. Long-term investigations on selected landfill sites (Gössele et al., 1993).

Use of water balances for landfill site monitoring (field observations), improvement of the quantification methods for essential water balances. MSW-landfill (Nolting et al., 1995).

EU-programme: Long-term investigation on selected landfill sites. The objective is to extrapolate the existing German data for a long-term evaluation of leachates and migration of pollutants (ENVPROT 4C, 1995).

Technical University of Braunschweig

Incrustation processes in drainage systems of sanitary landfills – problem related to long-term effective functioning of landfill drainage systems (Brune et al., 1991).

Impact of the temperature inside the landfill on the behaviour of barrier systems. It is recommended that organic material is removed before landfilling in order to avoid development of high temperatures (Collins, 1993).

Mechanical and biological pre-treatment of waste before landfilling. Influence of pre-treatment of MSW before compacting regarding to compactibility and quality and quantity of emission (Chang, 1993).

Leachate properties of newer sanitary landfills. The quantity of organic and inorganic materials in household sanitary landfills has reduced compared to older studies. A shortening of the acid phase has been observed (Gromadecki, 1995).

Technical University of Darmstadt
Capillary barriers (coarse sand + fine sand) instead of common surface sealing practice (Von der Hude & Jelinek, 1993).

Water balances in pre-treated waste, MSW (Mechanically- biologically pre-treated and thermally pre-treated waste). The experiments were performed as lysimeter experiments (Dach et al., 1997).

A model for the simulation of processes in a mechanically-biologically pre-treated MSW-landfill. Results were compared to results from lysimeter experiments (Theisen et al., 1997).

Technical University of Hamburg-Harburg
Design and management of a dry landfill system. This study involves pretreatment of the waste (thermal or biological primary treatment)(Stegmann, 1993).

Effect of pre-treatments of the waste on landfill emissions, Mechanical, biological and thermal pre-treatments (Krogmann, 1993).

Long-term behaviour and residual emission potential of MSW-landfills. Laboratory studies (Heyer & Stegmann, 1995).

Overview on mechanical-biological pre-treatment of residual MSW (Heerenklage & Stegmann, 1995).

Long term behaviour of landfill (MSW). Characterisation of remaining amounts of hazardous component in waste (laboratory-scale tests system). Emissions into the leachate phase have to be expected for many decades or even centuries to come (Burrows et al., 1997).

Mechanical-biological pre-treatment of solid waste (MSW) and the landfill behaviour determined in a test system. Landfill behaviour of pre-treated waste is significantly improved e.g. reduction of COD, total N, and volume of waste (Leikam & Stegmann, 1997).

Long-term behaviour of PVC products and fate of phthalate plasticisers under landfill conditions (Mersiowsky et al., 1999).

New experiences with drying effects in covered landfills and technical methods for controlled water addition (Heyer and Stegmann, 1999).

University of Hamburg
Effectiveness of different liner systems for top cover. Water balances and a description of different liner systems (Melchior et al., 1993).

Technical University of Dresden
Influence of composition of waste on emissions. Some old MSW-landfills in GDR showed that the current and long-term hazardous and pollution potential is smaller than in West Germany (based on field data). This is due to disposal of ash, which creates a higher buffer capacity in the waste (Andreas et al., 1997).

Characterising landfill phases at full-scale with the aid of test cells. The development of an east German landfill during 1974-1993 was analysed using data from defined degradation study and different types of landfills (Acidogenic, methanogenic, semi-aerobic and aerobic) were used as references (Andreas et al., 1999).

Greece

National Technical University of Athens

Recirculation of leachate. Recycle of leachate to fresh deposits of refuse had a decreasing effect in the concentrations of all important parameters but significantly increased the volume of leachate produced (Kiuzelli-Katsiri et al., 1993).

Italy

Controlli Sicurezza Ambientale

Hydraulic behaviour of waste (MSW). Water balances and pumping tests (field investigations) (Giardi, 1997).

IMAGE

Flushing of mechanical-biological and thermal pretreated waste (Catalani & Cossu, 1999).

Mechanical and hydraulic properties of MSW incineration slags (Cappai et al., 1999).

Regione Autonoma della Valle d´Aosta

Balefilling of MSW reduces the volumes used for disposal; the management is easier and the daily cover is reduced. There is a significant reduction of the spaces occupied in the landfill. The production of leachate over one year has been measured (Mancuso et al., 1995).

Politecnico di Torino

Modelling emissions from landfill disposal; hydraulic model (quantity of leachate), physico-chemical model showing difficulties by correlating chemical analysis of the leachate and the kind of waste introduced in the landfill (Zanetti & Genon, 1991).

Long term leachate quality – Two models representing: filling conditions and long term conditions (needs data for validation) (Zanetti & Genon, 1993).

Prediction by laboratory tests of industrial leachate quality – long-term leachate quality (Zanetti & Genon, 1995).

Quality of industrial waste landfill leachate, field data (Genon et al., 1995).

University of Cagliari

Leaching behaviour of coal ash in mono landfills. Landfill construction and operation procedures are discussed (Caramuscio et al., 1993).

An integrated model for the prediction of landfill emissions. The possibility of foreseeing characteristics of leachate and biogas with regard to quality and quantity represents a particular useful tool. The model simulate the behaviour of emissions from and MSW landfill (Muntoni et al., 1995).

Leaching properties of MSW combustion ashes related to heavy metal content and mobilisation (Muntoni, 1995).
Investigations aiming to assess MSW-landfill leachate flow regimes, well efficiency and waste hydraulic parameters, pumping tests. Investigations are performed as field-tests (Cossu et al., 1997).

Environmental Sanitary Engineering Centre (CISA)

New technique for landfill barrier systems (Lavagnolo & Tresso, 1993).

University of Napoli
Hydraulic behaviour of leachate at the bottom of landfills. Establishing of maximum saturation depth and evaluation of leachate leakage rate through the bottom liner of a landfill (DÄntonio & Porozzi, 1991).

University of Pavia
Modelling of leachate quantity and quality for industrial sludge landfill. The model contains a quantitative and a qualitative part. The model allows good evaluation of monthly leachate production and quality predictions (Baldi et al., 1993).

Leachate generation in landfills: model sensitivity. Several models are available but only a few of them are in theory suitable for application to the general case and even fewer are complete enough and validated to a degree that can be considered satisfactory. The HELP model was evaluated in this study (Capodaglio et al., 1999).

University of Trento
MSW model for the assessment of leachate production in a MSW sanitary landfill. Leachate quantity modelling (Andreottola et al., 1997)

Japan

Fukuoka University
Recirculation of leachate. Self purification capacity of the existing solid waste layers in landfills. Piling of waste on existing solid waste layer (Shimaoka et al., 1993).

Incineration residues. Leachate characteristics at different types of landfills (Higuchi et al., 1995).

Impact of daily cover soil in the stabilisation of a landfill (incinerator residues and crushed incombustible solid waste. The experiments were performed as lysimeter studies (Shimaoka et al., 1997).

Activated cover soil and leachate recirculation – new landfill system: semi aerobic landfill performed as lysimeter experiments (Matsufuji et al., 1997).

Pollution control and stabilisation process by semi-aerobic landfill type. A semi-aerobic landfill type enhances the aerobic biodegradation of MSW, consequently reducing the pollution load by leachate (Hanashima, 1999).

Wash-out solid waste landfill system. A system to wash out the MSW before landfilling has been developed to ensure acceleration of landfill site stabilisation. At present, incineration residue and non-combustible shredded residue are assumes as municipal solid waste. Ohter solid wastes will be confirmed by experiment (Higuchi & Hanashima, 1999).
Insolubilisation of Pb in fly ash using the exhaust gas from incineration plant (Shimaoka et al., 1999).

Hokkaido University
Stabilisation mechanism of leachate (semi-aerobic conditions and high content of organic matter). Leachate collection pipes play an important role to supply oxygen into waste layer. Aerobic zones are formed and have a high BOD-removal capacity (Matsuto et al., 1991).

The Netherlands

Energy Research Foundation (ECN)
The sustainable landfill – approach for waste management. Landfill concept (Driessen et al., 1995).

Waste characterisation to modify waste quality prior to disposal (Van der Sloot et al., 1997).
Predominantly inorganic equilibrium disposal: Part of the total concept sustainable recycling and storage of solid waste (Van der Sloot et al., 1999a).

Waste characterisation by means of leaching tests to assess treatment, reuse and disposal options (Van der Sloot et al., 1999b).

IWACO
A method has been developed to strongly influence the conditions inside a landfill based on the properties of the individual non-chemical waste materials. pH and redox potential are demonstrated to be key parameters. Some new landfill concepts are presented emphasising the mechanisms that determine the processes in the landfill in such a way that emissions are controllable particularly in long term. Involves classification of the waste (Seinen et al., 1993).

Leaching of heavy metals from MSW incineration bottom ash in a disposal environment. Mineralogical change during long-term MSWI bottom ash weathering. Laboratory experiments (Zevenbergen et al., 1995)

VAM, Wageningen
Possibilities of emission control of landfilled MSW after separation of biowaste and refuse-derived fuel. The effect of leachate recirculation on the microbial processes in a MSOR landfill (MSOR=mechanically separated organic residue) (Woelders et al., 1993).

South Africa

University of Witwatesrand
Co-disposal of sewage sludge in a MSW landfill. Quantifying potential for leachate generation using the HELP-model. Pilot-scale tests (Röhrs et al., 1995).

Cape Metropolitan Council
Impact of recirculation on stabilisation of MSW-landfill. Lysimeter experiments (Novella et al., 1997).

Spain

EMSHTR
Leachate quality comparison between two different landfills receiving different spectra of wastes (MSW and NSIW) (Relea et al., 1995).

University of Basque Country
Landfill leachate: Variations of quality with quantity. Water balances and measurements of the leachate quality. Field observations (Gómez Martín et al., 1995a).

Systematic control of the physico-chemical characteristics of the leachates from five landfills (MSW). There is a wide range of variation in the different parameters analysed within the same landfill and among the different landfills (Gómez Martín et al., 1995b).

University of Cantabria
Biological degradation – estimation of material losses in sanitary landfills. Development of a model (Gil Diaz et al., 1995).

Sweden

Chalmers Technical University (CTH)
Leachate modelling in full-scale cells containing predominantly MSW incineration residues. Simulations using the HELP model (Marques and Hogland, 1999).

Royal Institute of Technology (KTH)
Material balances for an industrial landfill. This investigation includes a detailed material balance of all material that goes and has gone into a studied industrial landfill, with emphasis on toxic metals. The rate of accumulation is much larger than the rate of depletion from the landfill with the leachate and the gases. Field data (Aulin & Neretnieks, 1995).

A methodology with which valuable insights may be gained into the long term leaching processes occurring in an inorganic waste deposit (Crawford et al., 1995).

A generalised model of combustion residue leaching. The aim of the work was to develop a calculation tool that can be used to predict long term changes in leachate chemistry in landfills of combustion residue or slag type wastes (Crawford et al., 1999).

Solute transport though preferential flow paths in landfills (Rosqvist, 1999).

On the long-term environmental impact of waste co-disposal. Co-disposal of organic waste with gypsum-containing construction waste and co-disposal of sulphidic mine waste with alkaline fly ash (Puura & Neretnieks, 1999).

The aim of the work is to develop, test and apply experimental and theoretical methods to assess the long-term leaching from landfills. The work concerns modelling of leaching from solid waste, methods for estimating the long-term leaching, and long-term leaching properties from inorganic waste. A model which can simulate the long-term evolution of the chemistry in the waste and the concentration in the effluent water over very long times has been developed. Research concerning leaching of heavy metals from waste disposal – long term considerations. *(homepage, www.kth.se)*

Linköping University
Solidification of the waste using an additive in order to achieve a leaching process that is dominated by diffusion from the surface of the solidified waste (Carlsson, 1991).

The formation of phthalate monoesters during digestion of MSW under landfill conditions (Ejlertsson et al., 1999).

Luleå Technical University (LuTH)
Research focusing on biological degradation of waste in municipal solid waste (controlled two step degradation), biogas production is stimulated and seen as a source of energy (Lagerkvist, 1991).

Decomposition – organic carbon cycling in landfill. A model approach (Bogner & Lagerkvist, 1997).

An overview of 35 test cell research programmes is presented. Evaluation with respect to process engineering aspects (pre-treatment, physical design, construction, and operation) and remaining research questions are formulated (Ecke & Lagerkvist, 1997).

Leachate quality at different degradation phases. Time (measured as L/S ratio) needed for landfills to stabilise (MSW-landfill). The presented data derive from laboratory tests and field experiments (Kylefors & Lagerkvist, 1997).

Researches all aspects of landfill technology such as: siting, design, operation and closure. The emphasis of the research is the study of different waste treatment techniques that can be employed at the landfill or in the landfill, e g different biological processes. The aim of the research is to find tools for a sustainable waste disposal, i.e. to return material wastes to nature without endangering the function of the recipient. LST is the core of the Landfill Group (LG), a multi-disciplinary research group focusing on landfill technology and adjacent fields. (*The division of Landfill Science and Technology, LST, homepage, www.sb.luth.se*)

Lunds Technical University (LTH)
Leachate quality and environmental effects at active municipal landfills (MSW). Correlation between some leachate characteristics. Field data (Flyhammar, 1995).

Fermentation of solid wastes in landfill reactor cells (Bramryd, 1997).

The flow regime in MSW-landfills and detection of preferential flow in the macropores (Rosqvist et al., 1997).

Flow regime in landfills. Implications for modelling (Bendz et al., 1997).

The mobilisation of heavy metals in partly stabilised MSW during oxidation (Flyhammar & Häkansson, 1999).

Channel flow and its effects on long-term leaching of heavy metals in MSW landfills (Bendz and Flyhammar, 1999).

Statens geotekniska institut (SGI)
Numerous studies of the geotechnical properties and the and leaching properties of mainly inorganic mineral wastes. For instance:

Leaching properties of natural and stabilised flue gas cleaning residues from waste incineration (Kullberg & Fällman, 1989).

Characterisation of residues. Release of contaminants from slags and ashes (Fällman, 1997).

Swedish Environmental Research Institute (IVL)
Leachate quality – identification of specific organic compounds in leachate (Öman & Hynning, 1991).

Emissions of organic compounds. A conceptual model has been developed to be used for predictions of emissions of organic compounds. Three processes occurring in landfills have been included in the model; sorption, evaporation and transformation (Öman, 1995).
Changes with depth and with time of leachates from a pilot-scale landfill (Öman et al., 1999).

Work implies research on environmental effects from waste treatment and disposal, as well as development and testing of waste management techniques and systems, e.g. waste minimisation, recycling, treatment and land filling. Studies concerning organic waste. Methods for characterisation of organic waste and system analysis for organic waste management (*homepage, www.ivl.se*).

Sveriges lantbruksuniversitet (SLU)
Decomposition processes in waste disposals (*homepage, www.jti.slu.se)*.

Switzerland

EAWAG
Long-term behaviour of municipal solid waste landfills (Belevi & Baccini, 1989).

Influence of organic carbon on the long-term behaviour of bottom ash monofills. Organic carbon is an important source of additional acids if microbial degradation takes places (even under alkaline conditions. Microbial degradation may accelerate the pH decrease in bottom ash mono landfill leachates and thus increase heavy metal mobilisation (Belevi et al., 1993).

United Kingdom

Aspinwall
Field measurements of the infiltration of rain water through caps of various thickness' and gradients (Mattravers & Robinson, 1991).

In-situ monitoring of the unsaturated zone beneath Stangate east landfill site: Sixteen years of detailed data (Robinson et al., 1999).

Imperial College of Science, Technology and Medicin
A stochastic flow and transport model for landfill leachate production (Butler et al., 1999).

Knox Associates
A review of landfill cap performance and its application for leachate management.
Discussion of whether the landfill should be covered or not. Covering caps could lead to very low net percolation. It is questioned whether leachate minimisation is compatible with the objective of minimising long-term liabilities from landfills. Alternative a high-rate recirculation of leachate incorporating a nitrification treatment stage is used to flush out key pollutants rapidly, particularly ammonia, with the landfill acting as a denitrifying filters (Knox & Gronow, 1993).

Observations drawn from a review of monitoring data from two large-scale test cell studies. The aspects covered are among others acceleration of degradation rates and leachate quality (Knox et al., 1999).

M.J. Carter Associates
Landfilling below the water table – principles and advantages. Active leachate abstraction from landfills located partly below the level of the water table can maintain the leachate level in the site below the water table producing a hydraulic gradient into the landfill hence preventing the migration of contaminants. The principal advantages of this method of landfill design are that it does not necessitate the development of a sophisticated engineering design with the associated costs (Smart, 1993).

Royal Holloway University of London
The hydraulic properties of in-situ landfill waste (MSW), field-investigations (Burrow et al., 1997).

University of Nottingham
Acceleration of high-solids digestion by additional phosphate (Martin et al., 1999)

University of Southampton
Determination of total pollution load produced by MSW-landfills, laboratory experiments (Beaven & Walker, 1997).

Bioreactor (high rate flushing). Pulverised wastes (MSW) was used and a deep saturated zone was maintained, data from laboratory experiments (Walker et al., 1997).
Analysis of waste flushing and flow to wells using MODFLOW and an effective stress dependent hydraulic conductivity (Beaven & Powrie, 1999).

University of Strathclyde
Investigations concerning pre-treatment of MSW, leachate recirculation, co-dispersal with inert material. Field scale investigations (Wingfield-Hayes et al., 1997).

Evaluation of the long-term behaviour of three different landfills. The biodegradation was evaluated, analysed and modelled based on the biogas and leachate emissions, as a result of different disposed waste composition, waste treatment and conditions (Koliopoulos et al., 1999).

Accelerated landfill refuse decomposition by recirculation of nitrified leachate (Burton & Watson-Craik, 1999).

Water Research Centre plc
Bio-reactors – Microbiological review (Blakey et al., 1995).

Bio-reactors – accelerated waste stabilisation, leachate recirculation (Blakey et al., 1997).

USA

State University of New York
Leachate recirculation: offers the potential to accelerate refuse stabilisation reducing long-term environment impact (Scrudato et al., 1993).

University of Pittsburgh
Leachate recirculation leads to accelerated decomposition of waste, MSW. A field study (Maier et al., 1995).

University of Wisconsin
Decomposition of refuse in landfill determined by measurements of the cellulose to lignin ratio. A decrease over the 24-year sample ages indicates decomposition of the refuse. The aim of the work is to characterise refuse and leachate samples and to evaluate the effect of variables in promoting or retarding refuse decomposition (Ham et al., 1993).

Decomposition of solid waste (MSW). Large-scale lysimeter tests have been performed. The investigations gave information about the: water balances, leachate production in a landfill with and without top cover using soil, information about decomposition of, and leachate production from shredded and unproduced refuse. The work also included research about adding new lift of refuse to cells which were already five years old indicating that partially decomposed refuse has the ability to treat leachate as it passes through. Furthermore, shredding of the waste influence the leachate quality as the decomposition rate increased (higher methane production and concentrations of contaminants over a shorter period). Finally, acceleration of landfill stabilisation by leachate recirculation was investigated (Ham & Bookter, 1997).

Analysis of long-term leachate characteristics (Krug & Ham, 1997).