ENVIRONMENTAL IMPACTS OF LANDFILL BIOREACTORCELLS IN COMPARISON TO FORMER LANDFILL TECHNIQUES

MICHAEL BINDER and TORLEIF BRAMRYD*
Department of Ecology, University of Lund, Ecology building, Lund, Sweden
(author for correspondence, e-mail: torleif.bramryd@planteco.lu.se)*

(Received 10 November 1999; accepted 25 August 2000)

Abstract. Former and present landfill techniques at the Filborna plant in Helsingborg, South Sweden are compared with respect to impacts on the environment. This includes the potential for nutrient recovery and heavy metal immobilisation in the waste residue. The results show that optimised landfill bioreactor-cells have a higher turn-over rate for organic matter compared to the former landfills, whereas the retention capacity for heavy metals in both systems was surprisingly high. Full scale leachate data, as well as a laboratory leaching experiments confirmed the role of bioreactor cells as anaerobic filters enabling a separation of nutrients from a mixed waste, while the toxic metals are retained. The conclusion of this article is that by simple measures, the biological processes can be optimised, resulting in higher turn-over rates for organic matter and thus accelerated waste stabilisation.

Keywords: bioreactor-cell, decomposition, heavy metals, landfill, leachates, nutrients, stabilisation, waste

1. Introduction

Solid waste could pose a major environmental problem, at the same time as it can be a valuable resource for material recovery and the extraction of nutrients and energy. In many countries major research therefore focuses on new integrated systems for improving the efficiency and environmental standards for resource recovery techniques from municipal solid wastes (MSW).

Fermentation in landfill bioreactor-cells is an ecologically based technique which opens possibilities for both bioenergy and nutrient extraction. Stabilised anaerobic conditions result in an effective immobilisation of heavy metals and other pollutants. In a stabilised anaerobic environment most heavy metals, in contrast to nutrients like magnesium, potassium, sodium and calcium, form insoluble sulphides (Bramryd, 1997; Reinhart and Al-Yousfil, 1996). Thus the landfill bioreactor-cell (hereafter called bioreactor cell) can act as an anaerobic filter, enabling a separation of the nutrients from a mixed waste, whereas the toxic heavy metals are bound up in the fermentation rest. This separation makes it possible to use the leachates as fertiliser in e.g. energy plantations, forestry, a.s.o., where the nutrients can be brought back to an ecological cycling (Bramryd, 1997).

The investigation presents a comparison between former and present landfill

Water, Air, and Soil Pollution **129:** 289–303, 2001.

techniques and evaluates environmental impacts from both systems. The main idea is to indicate that the classification of former landfills as environmental hazards no longer is appropriate. As a reaction to ground water pollution problems in the past, modern landfills (bioreactor cells) are designed to provide a proper lining system to keep environmental impacts low (Reinhart and Al-Yousfil, 1996; Wall and Zeiss, 1995). This includes an impermeable bottom liner together with a leachate and biogas collection system to recover all mineralisation products evolved during waste degradation and to ensure anaerobic conditions. In a highly optimised bioreactor cell the waste is pre-treated in various ways. An essential first step is shredding of the material and to provide a high moisture content. Factors like C/N-ratio, P/N-ratio, pH, physical structure, moisture, a.s.o. can be controlled by adding leachates, sewage sludge, food industry residues, water, a.s.o., depending on the quality of the incoming waste. Under such optimised conditions heavy metals will be retained in various forms while most nutrients remain soluble and can be recovered through the leachates. The effectiveness in waste stabilisation and turn-over rate of modern bioreactor cells is therefore higher compared to that of the former landfills.

The size of the bioreactor cell depends on the amount of incoming waste as well as on technical limits (e.g. length of extraction systems). The filling time should be no longer than 2 yr. To reduce gas emissions during the filling period a daily cover should be provided.

2. Material and Methods

2.1. SITE DESCRIPTION

The Filborna solid waste treatment facility in Helsingborg, South Sweden, is a central waste treatment and recycling plant for the district of Northwest Scania with a population of approximately 220 000 people. The facility is owned by the Northwest Scania Recycling Company, NSR, established by six municipalities in the area. The incoming waste is a mixture of domestic, commercial and light industrial wastes and originates from the cities Helsingborg, Ängelholm and Höganäs and the communities of Bjuv, Båstad and Åstorp. The total amount of recycled and treated waste products is around 330 000 tons per year.

In 1989/1990 the first bioreactor cell (bioreactor cell 100) was constructed as a part of a research program sponsored partly by the Swedish National Board for Industrial and Technical Development (NUTEK). The project included scientists from different universities in Sweden and had a broad international co-operation. After this, the bioreactor cell technique was performed in full scale, with a total of 4 to 5 new bioreactor cells, each filled within a period of 2–3 yr.

Bioreactor cell 100 consists of four test-cells, each with the dimension of $40 \times 40 \times 10$ m and a mean density of 0.9 t m^{-3}. The cells contained approximately 15 200 m^3, and were filled with approximately 13 700 t of domestic and light industrial waste (15%). The test-cells were filled simultaneously between June 1990 and April 1991. After filling the first two metres, the filling ceased for two months to achieve a pre-composting of the waste.

Bioreactor cell 400 with the dimension of 190 × 35 × 8 m was filled during 1993 and 1994 and had a total volume of 35 000 m^3, containing 30 100 t of waste. The waste composition is similar to that in the test-cells. Garden waste was excluded since it was no longer allowed to be landfilled at this time.

Bioreactor cell 500 with the dimension of 120 × 90 × 4 m was filled during 1992 and 1995 and had a total volume of 51 500 m^3 containing 44 290 t of waste. Again the waste composition is similar to the test-cells. This cell is now situated beneath a new industrial waste cell (not investigated) and at a depth of approximately 7–18 m beneath the top-surface.

Bioreactor cell 600 with the dimension of 60 × 170 × 20 m was filled during 1995 and 1998 and had a total volume of 200 000 m^3 containing 170 000 t waste. The waste in this cell was in contrast to the others, consisting of shredded material which was irrigated with leachates prior to disposal.

The 25 yr old landfill contained a mixture of household and light industrial wastes, with a high cellulose content. After filling and compaction it was covered with a 30 cm thick clay layer and thus was predominantly anaerobic.

The 50 yr old landfill was constructed according to the Bradford-technique (Fredriksson, 1995). The waste was spread on the ground by hand or bulldozers without compaction and was covered with a thin soil-layer. Thus the degradation mainly took place under aerobic conditions. Bulky wood and paper products were burned openly on site.

2.2. SAMPLING TECHNIQUE

The samples from the different landfill systems at the Filborna plant in Helsingborg were obtained by a drilling machine which bored holes into the corresponding cells. From the 50 yr old landfill segment, samples were collected with a spade, hereby avoiding plots of disposed ashes. This landfill was easy to reach due to construction work performed on the former deposition site.

The excavated waste was separated by hand into a crude (containing metals, plastics, wood pieces and glass) and a fine fraction. After drying, the fine fraction was passed through a sieve with a mesh-size of 50 mm. This sieved fraction was used for further analyses.

Leachates from the Filborna Bioreactor cell 100 were collected and measured between 1990 and 1995. Each of the four cells was equipped with three lysimetres with separate leachate collection and measuring systems. All cells had an additional overall leachate collection system leading to a container which tipped over after complete filling to register the total amount of produced leachates.

2.3. CHEMICAL ANALYSIS AND STATISTICS

To determine the total concentrations of calcium, cadmium, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorous, lead and zinc in the waste residue, two grams of the dried and sieved fine fraction were digested in 20 mL of concentrated nitric acid under slight heating. After filtering, the samples were analysed with the Inductively Coupled Plasma Spectrophotometry (ICP)-technique according to Balsberg-Påhlsson (1990). Kjeldahl-N was analysed according to Bremner (1965) and Balsberg-Påhlsson (1990).

To determine concentrations in the eluate of the performed leaching test, six 60 g wet-samples from each landfill segment were taken. Different sub-fractions within a landfill segment were included to obtain representative results for the whole segment. These samples were put into 500 mL plastic bottles and suspended with 300 mL de-ionised water. The bottles were subsequently placed in a rotor-machine and rotated for two hours. The solution was filtered and analysed with ICP according to Balsberg-Påhlsson (1990).

To determine waste pH, wet-samples from the original waste fine fractions were taken and suspended in de-ionised water. Using a Metrohm digital pH-meter, the pH of the suspensions was determined.

Mean-values and standard deviations were calculated with Microsoft Excel 97. For *t*-tests, one-way-ANOVA, and F-tests, the program SPSS version 8.0 for Microsoft (Pc) was used. ANOVA-tests were based on a significance level of $p < 0.05$, while *t*-tests regarded significance-levels ranging from $p < 0.05 = {}^{*}$, $p < 0.01 = {}^{**}$, and $p < 0.001 = {}^{***}$. Significances in the result and discussion chapter are sometimes directly indicated with superscript (e.g. xxx***). The relevant statistical results are shown in the appendix.

3. Results

3.1. LOSS ON IGNITION

The loss on ignition (Figure 1) was highest in the three year old bioreactor cell 600 and lowest in the five year old bioreactor cell 400. The two landfill segments (50 and 25 yr) had comparably higher losses in organic matter than the newly established bioreactor cells, except for bioreactor cell 600.

3.2. COMPARISON BETWEEN TOTAL ELEMENT STORAGE AND MAX. LEACHABLE FRACTION

For all investigated elements the concentrations in the leaching solution were much lower than the total storage in the waste residue (Figures 2 and 3). The heavy metal concentrations in the eluate were extremely low and for cadmium and lead

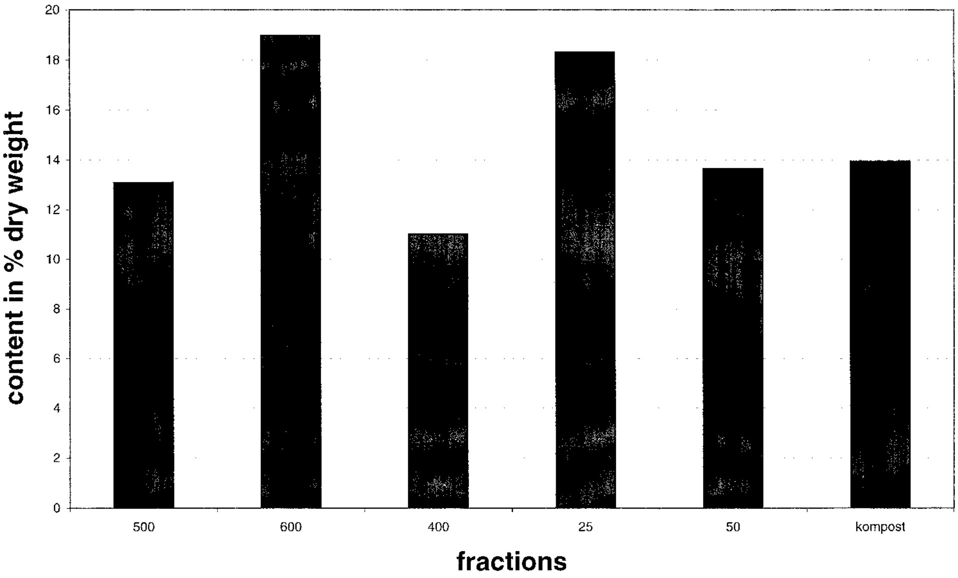

Figure 1. Loss on ignition in percent of dry weight for the different sites in Filborna, Helsingborg. 400 = five year old bioreactor cell, 500 = four year old bioreactor cell, 600 = three year old bioreactor cell, 25 = 25 yr old landfill segment, 50 = 50 yr old landfill segment. Kompost = reference material from a sieved compost fraction.

TABLE I

Percentage of recovery of the actual nutrient storage in the waste residue for the corresponding Filborna sites: 400 = 5 yr old bioreactor cell, 500 = 4 yr old bioreactor cell, 600 = 3 yr old bioreactor cell, 25 = 25 yr old landfill segment, 50 = 50 yr old landfill segment

	Ca	Cd[a]	Cr	Cu	K	Mg	Mn	Na	Ni	P	Pb[a]	Zn
500	0.13	–	0.39	1.18	30.78	0.34	0.03	69.85	3.34	1.45	–	0.59
600	12.12	–	1.10	0.04	57.17	9.64	4.21	89.04	14.38	0.84	–	1.82
400	4.77	–	0.40	0.12	57.02	9.25	0.69	88.55	8.12	0.30	–	0.05
25	3.68	–	1.08	0.04	66.42	12.57	1.99	88.59	10.08	0.57	–	0.19
50	2.82	–	0.01	0.01	16.95	12.96	0.41	18.31	1.75	0.00	–	0.00

[a] Concentrations were below the detection-level.

even below detection level. Calcium, potassium, magnesium, and sodium are more soluble and therefore are found in higher concentration in the leaching solution.

Sodium and potassium (Table I) showed the highest percentage of recovery for all investigated elements. The values in Table I show that the toxic heavy metals are fixed in the fermentation rest while the nutrients can be recovered to a higher extend. Only the easily leachable nickel forms an exception in the eluate and can be found in higher concentrations than even calcium.

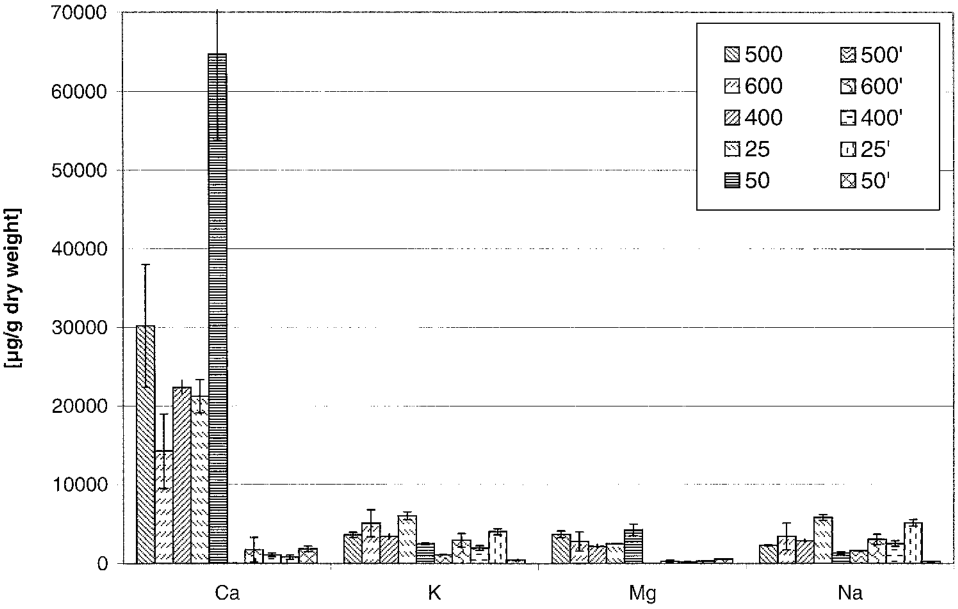

Figure 2. Comparison between total nutrient storage and maximum leachable fraction. Concentrations in μg g^{-1} dry weight. 400 = Filborna bioreactor cell 400, 500 = Filborna bioreactor cell 500, 600 = Filborna bioreactor cell 600, 25 = Filborna 25 yr old landfill, 50 = Filborna 50 yr old landfill. Blank numbers stand for the total nutrient storage, while numbers marked with '′' stand for the leachable fraction.

3.3. LEACHATE ANALYSIS

Due to periods of no leachate production the results from the leachate analyses are dispersed and contain gaps. Thus statistical tests cannot be performed. However, no tendencies between pH and the leaching of the different components could be seen (Figures 4 and 5). For potassium, nickel, chromium and copper the concentrations in the leachates were highest in year 1993, as was pH. For the other elements, concentrations seem to level out with time, especially for lead and cadmium.

Concentrations of heavy metals in the leachates were generally low except for zinc and nickel. Zinc concentrations, in comparison, were outstandingly high (1.65 mg L^{-1}) during the first year. However, a general trend for nutrient- (except potassium) and heavy metal concentrations in the leachates shows a decrease with time. For potassium on the other hand, a typical bell-shaped curve was obtained.

TABLE II

Result of the ANOVA-test concerning the total element storage in the waste residue Comparison between the different sites in Filborna, Helsingborg. A star indicates a significant difference ($p < 0.05$) between the sites for the corresponding element. 400 = bioreactor cell 400 (5 yr), 500 = bioreactor cell 500 (4 yr), 600 = bioreactor cell 600 (3 yr), 25, 50 = the corresponding landfill segments in age

Ca	600	400	500	25	50	**Cd**	600	400	500	25	50
600					*	600				*	*
400					*	400					*
500					*	500					*
25					*	25	*				*
50	*	*	*	*		50	*	*	*	*	

Mg	600	400	500	25	50	**Fe**	600	400	500	25	50
600						600			*		*
400					*	400			*		*
500						500	*	*		*	
25						25	*		*		*
50		*				50	*	*		*	

K	600	400	500	25	50	**Co**	600	400	500	25	50
600					*	600					*
400				*		400					*
500						500					*
25		*			*	25					*
50	*			*		50	*	*	*	*	

Na	600	400	500	25	50	**Pb**	600	400	500	25	50
600				*		600			*	*	*
400				*		400			*		
500				*		500	*	*			
25	*	*	*		*	25	*	*	*		
50				*		50	*				

TABLE III

Result of the ANOVA-test concerning the element concentration in the eluate from the laboratory leaching test. Comparison between the different sites in Filborna, Helsingborg. A star indicates a significant difference ($p < 0.05$) between the sites for the corresponding element. 400 = bioreactor cell 400 (5 yr), 500 = bioreactor cell 500 (4 yr), 600 = bioreactor cell 600 (3 yr), 25, 50 = the corresponding landfill segments in age

Ca	600	400	500	25	50	**Mn**	600	400	500	25	50
600			*			600		*	*		
400						400	*				
500	*				*	500	*				
25						25					
50			*			50					
Cr	600	400	500	25	50	**Cu**	600	400	500	25	50
600		*			*	600		*		*	*
400	*			*		400	*		*		
500					*	500		*		*	*
25		*				25	*		*		
50	*		*			50	*		*		
K	600	400	500	25	50	**Mg**	600	400	500	25	50
600		*	*	*	*	600			*		*
400	*			*	*	400			*		*
500	*			*		500	*	*		*	*
25	*	*	*		*	25			*		*
50	*	*		*		50	*	*	*	*	
Na	600	400	500	25	50	**Ni**	600	400	500	25	50
600			*	*	*	600		*	*		*
400			*	*	*	400	*			*	*
500	*	*		*	*	500	*			*	*
25	*	*	*		*	25		*	*		*
50	*	*	*	*		50	*	*	*	*	
P	600	400	500	25	50	**Zn**	600	400	500	25	50
600		*			*	600		*		*	*
400	*		*	*	*	400	*				
500		*			*	500					
25		*			*	25	*				
50	*	*	*	*		50	*				

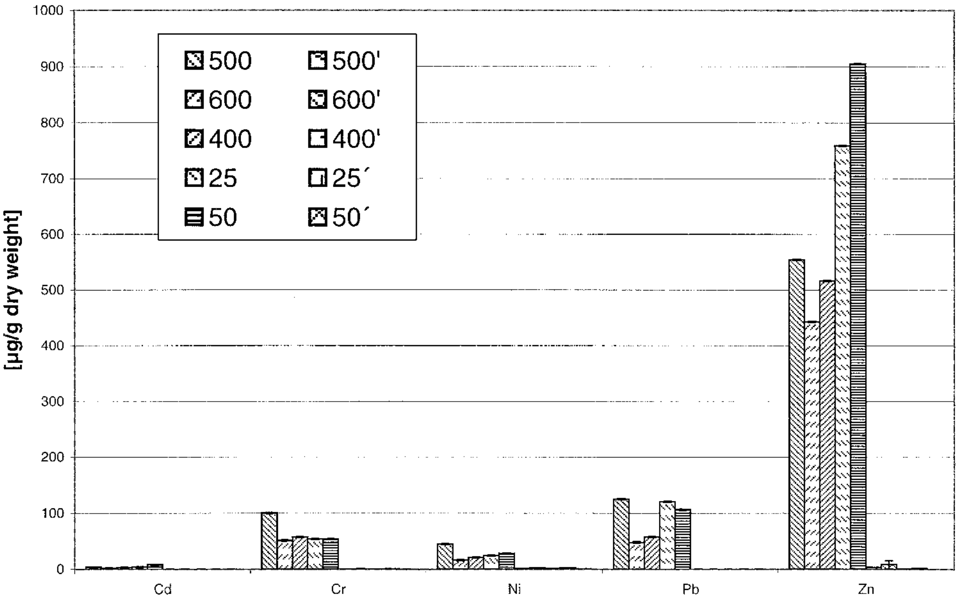

Figure 3. Comparison between total heavy metal storage and maximum leachable fraction. Concentrations in μg g^{-1} dry weight. 400 = Filborna bioreactor cell 400, 500 = Filborna bioreactor cell 500, 600 = Filborna bioreactor cell 600, 25 = Filborna 25 yr old landfill, 50 = Filborna 50 yr old landfill. Blank numbers stand for the total nutrient storage, while numbers marked with '′' stand for the leachable fraction.

4. Discussion

4.1. NUTRIENTS

The biological degradation processes (turn-over rate) in landfill bioreactor-cells depend on many factors which influence microbial activity. These variables are often hard to determine and differ sometimes extremely between, and within the same sites. Therefore general predictions or statements of landfill/bioreactor cell characteristics have to be conducted very thoroughly, and evaluations for optimisation should be site-specific rather than general. However, it is possible to point out general inhibiting and stimulating factors.

The turn-over rates of the decomposition processes in the old Filborna landfill segments have indeed shown to be different from the newly established bioreactor cells. This conclusion can be drawn by observing the total loss on ignition (Figure 1), but also at the total nutrient storage left in the decomposition residue (Figure 2 and Table II) in relation to the water-extractable fraction (Figure 2 and Table III). High nutrient values (K and Mg) in the water extractable fraction indicate ongoing decomposition processes and the extent can be used to estimate the actual degradation stage of the bioreactor cells.

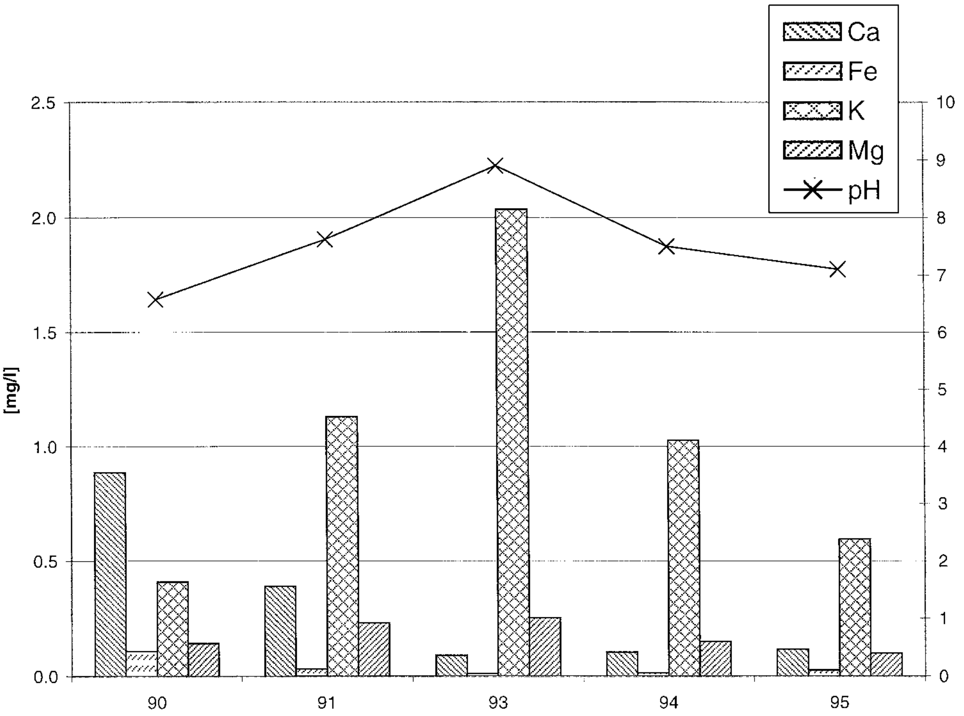

Figure 4. pH and mean concentrations (mg L^{-1}) for calcium, iron, potassium and magnesium in the leachates of the overall collection tank for the four Filborna test-cells. No leachates were measured in 1992 and after 1995.

In the 50 yr old landfill segment of Filborna the leachable fractions of magnesium and potassium were extremely low (Table I), although a relatively high amount was stored in the waste residue (Figure 2). Potassium is immobilised in the easily degradable organic matter, but due to the decomposition processes it becomes soluble. Its chemical characteristics show a low complex-forming ability and is associated with the first ions that leave the landfill (Brady and Weil, 1999). Therefore the leachable fraction in the 50 yr old landfill has already been washed out and was therefore significantly lowest during the leaching studies (Table III). The remainder of potassium is probably bound up as inorganic particles.

The potassium concentrations which were significantly $*$ ($p < 0.05$) highest in the eluate of the 25 yr old landfill segment (Table III) are therefore contradictory to the processes just described. The high concentrations can therefore not be based on prevailing decomposition processes. A lack of leaching in this landfill segment is a more reasonable explanation. The 25 yr old landfill segment was situated below bioreactor cell 500 with an impermeable bottom liner and leachate collection. Therefore not much of the infiltrating rainwater from above will reach this landfill segment. Inorganic metabolites will thus accumulate if no leaching agent is available. If the residue then is leached, as in the lab experiment, it results

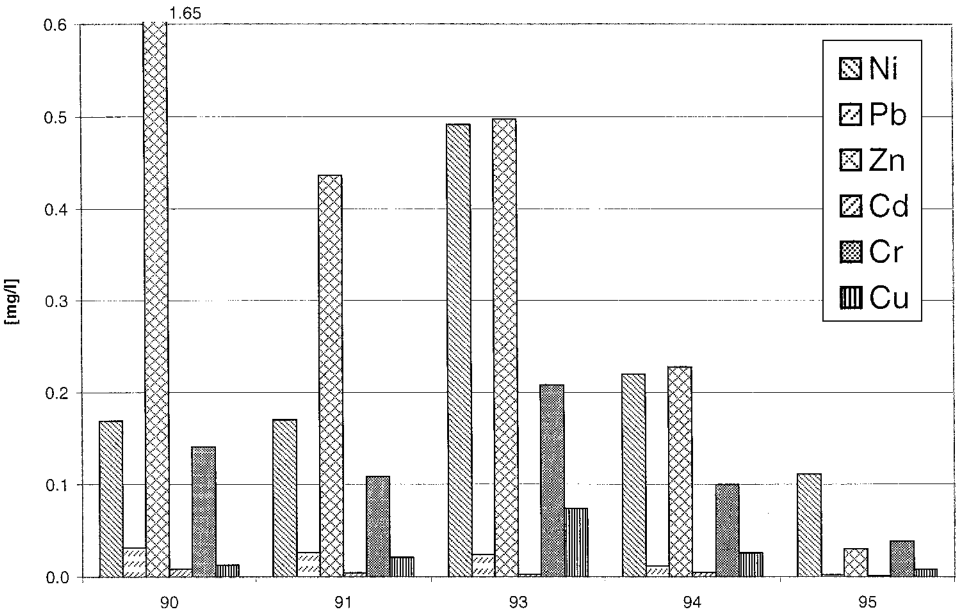

Figure 5. Mean concentrations (mg L^{-1}) of nickel, lead, zinc, cadmium, chromium and copper in the leachates of the overall collection tank for the four Filborna test-cells. No leachates were measured in 1992 and after 1995. The variations in the data were so large that error-bars would have been greater than the actual mean-value and are therefore not shown.

in the typical washout effect (Chen, 1996; Reinhart and Al-Yousfil, 1996) yielding very high concentrations (Figure 2).

Bioreactor cell 600 had the significantly $*$ ($p < 0.05$) second highest potassium concentrations (Figure 2 and Table III). This bioreactor cell is in its maximum of microbial degradation and microbial cultures are well established. They can retain nutrients in their biomass, although to a minor extent. This retention of nutrients might lead to a lower total percentage of potassium recovery as it was found in the 25 yr old landfill segment. Since the waste is only 3 yr old it is furthermore possible that potassium is still fixed in some undegraded waste particles and thus is found to a lower extent in the eluate.

The leachate data from the Filborna test-cells showed no significance effects. Therefore only assumptions can be derived from the obtained tendencies. However, the findings fit perfectly to the processes explained above. The leach-out of potassium from the test-cells (Figure 4) reflects the biological degradation processes. There is a tendency for increased concentrations in the leachates until the third year and then a subsequent decrease. This results in a typical bell-shaped pattern, indicating rather optimal degradation processes. Magnesium on the contrary does not follow the same pattern (Figure 4). Magnesium is even more leachable than potassium (Tyler, 1978; Brady and Weil 1999) and occurs to a large extent in green plant-material. The fixation to the organic matter is rather low and it is almost immediately leached from the waste with the onset of degradation. This results in an initial peak and subsequently decreasing concentrations.

The Filborna bioreactor cells 400 (5 yr) and 500 (4 yr) had the lowest loss on ignition (Figure 1) which indicates an advanced mineralisation processes. Furthermore the percentage of recovery (Table I) of potassium in the two cells was of the same magnitude. This indicates that the two cells might be in the same stage of degradation. The microbial activity has reached the same turn-over rate, in spite of the age difference. That bioreactor cell 600 (3 yr) had the highest loss on ignition might be misleading. This would suggest unfavourable degradation conditions, which can be discounted by looking at the percentage of potassium recovery (Table I). For this cell a different disposal method and waste-treatment technique was chosen. The waste in bioreactor cell 600 was shredded and irrigated with leachate prior to disposal. Shredding provides, among other things, a larger total surface area which is available for microbial degradation. Additional benefits of this waste treatment technique was the avoidance of insulation of waste in unopened waste bags and the supply of a sufficient moisture content. Leachates from mature landfills contain balanced populations of acidogenic and methanogenic bacteria which can inoculate the fresh material. Furthermore accelerated waste stabilisation can thus be achieved, especially if leachate re-circulation is practised (El-Fadel *et al.*, 1995; Onay and Pohland, 1998; Pohland and Al-Yousfi, 1994). Concluding from this, the best degradation conditions compared to any of the other cells should be found in bioreactor cell 600. Shredding probably resulted in a higher content of wood and paper particles in the fine fraction investigated, and thus providing the highest loss on ignition.

4.2. ENVIRONMENTAL POLLUTANTS

Heavy metal concentrations in the water extractable fractions were extremely low for all the investigated sites. Similar results, stating that only a minor portion of the heavy metals in landfills is mobilised in the leachates, have been found in earlier investigations (Christiansen *et al.*, 1994; Aulin and Neretnieks 1995). The differences between the amounts of heavy metals stored in the residual waste from landfill segments of different age are of minor importance, but still interesting. They reflect the change in magnitude of contaminants with time, and between the different waste producing generations. They are the result of substantial variations in solid waste composition which is not only due to socio-economic conditions but furthermore to location, season, waste collection and disposal methods, sampling and sorting procedures and many other factors (Bonomo and Higginson, 1988; Senior, 1990; Tchobanoglous *et al.*, 1993).

The heavy metal concentrations in the eluate of the 50 yr old landfill segment were surprisingly low and for nickel even significantly $*$ ($p < 0.05$) lowest (Table III and Figure 3). Even more interesting were the low values in the percentage of recovery for the different heavy metals during the leaching tests (Table I). During oxidising conditions in a landfill metallic and ferrous iron have been oxidised to form amorphorus ferric oxy hydroxides. This is a very strong sorbent and can bind at least part of the toxic metals (Aulin *et al.*, 1997). Also formation of metal carbonates can be expected. These findings are rather promising, and actually speak in favour of former landfills which sometimes are considered by some individuals, to be environmental hazardous. Westlake (1997) states that public water supplies have been contaminated by landfill leachates and takes it as a physical evidence of general knowledge that site-specific risk assessments have not been conducted in the past. As a reaction to that, new landfills (bioreactor cells) were designed to provide a proper lining system to keep environmental impacts low (Reinhart and Al-Yousfil, 1996; Wall and Zeiss, 1995). This includes an impermeable bottom liner (mostly consisting of clay, plastic or a related material) together with a leachate collection system, to recover the liquid originated from water infiltration into the cell, or ongoing decomposition processes. An appropriate top cover of the bioreactor cell with a low permeability furthermore limits water infiltration (precipitation and run-off water) into the cell and thus minimises leachate volumes (Murphy *et al.*, 1995). The generated biogas, which consists of 50–60% methane, (Bogner *et al.*, 1997; Bramryd 1997; El-Fadel *et al.*, 1995) needs to be extracted, to eliminate the impact of this severe greenhouse gas on global warming. After a proper containment system is established, other operational controls are important. The filling time has to be kept as short as possible and the open landfill area small. This will limit methane emissions from the landfill during the filling period, when extraction-systems are not working efficiently (Reinhart and Al-Yousfil, 1996). A daily cover (e.g. wood-chips) strongly reduces methane emissions as well (Boeckx and Cleemput, 1996; Bramryd, 1997). However, a major problem occurs in the aeration of bioreactor cells due to ruptures in the coverage, or of air funnels caused by animal activity (rabbits) on abandoned landfills/bioreactor cells. It is suggested that with aeration the stored heavy metals (e.g. as sulphides) will leach out. The results from the 50 and 25 yr old landfill segment (Figure 3) could disapprove that.

Bioreactor cells have the ability to work as *anaerobic filters* (Bramryd, 1997; Reinhart and Al-Yousfil, 1996) enabling the separation of nutrients from a mixed solid waste, while the toxic heavy metals are bound up in the fermentation reaction. As seen from the leachate data of bioreactor cell 100, the leaching of zinc was extremely high in the beginning. However, heavy metal concentrations in leachate were generally higher in the beginning and decreased with time. Heavy metal removal in ordinary landfills seems to be primarily leaching and to a lesser extent chemical precipitation (Chen, 1996). In controlled bioreactor cells, especially where leachate recirculation is practised, heavy metals can effectively be removed from the leachates and thus lower environmental impacts. This is due to the complex forming ability with the organic matter (e.g. lignin) and a stimulation of the reducing conditions providing the reduction of sulphate to sulphide which reduces leachate metals to very low concentrations (metal sulphides) (Reinhart and Al-Yousfil, 1996). Lignin is, next to clay particles, the main contributor for metal complexion. It enters the landfill in form of paper, demolition wood (e.g. furniture), to a minor extend in food and vegetable waste, yard waste (if still allowed to be disposed), and in the form of woodchips if they are used as a daily cover. Furthermore moderate to high molecular weight humic-like substances are formed from waste organic matter in a process similar to soil humification. Theses substances tend to form strong complexes with heavy metals (Reinhart and Al-Yousfil, 1996). If leachate re-circulation would have been practised in the Filborna bioreactor cell 100, the initial peak concentrations of heavy metals could have been buffered and the potential risk for pollution reduced. Nevertheless, the leaching test performed for the different sites in Filborna, Helsingborg (Figures 2 and 3) confirms the role of bioreactor cells as ecological filters.

5. Conclusion

Bioreactor cells, as new waste treatment techniques, can effectively immobilise heavy metals in the fermentation residue, while the nutrients, especially potassium, magnesium and calcium can be recovered. Results from this investigation indicated that former landfills, even under aerobic conditions, can provide the same potential for retaining heavy metals as present bioreactor cells. The risk of pollution from a modern landfill or bioreactor cell is found to be significantly lower due to recent research and development, concerning the understanding of the processes involved in the production, properties, migration, attenuation and control of landfill gas and leachates. Optimised bioreactor cells, especially where leachate re-circulation is practised, have a higher turn-over rate for the organic matter than ordinary landfills. Thus stabilised conditions are achieved more quickly. From this it can be concluded that the environmental conditions in landfills can be improved by simple operational controls, especially with the new bioreactor cell technique.

References

Aulin, C. and Neretnieks, I.: 1995, ‘A Material Balance for an Industrial Landfill’, in *Proceedings of the Sardinia ’95, 5th International Landfill Symposium*.

Aulin, C., Bozkurt, S., Moreno, L. and Neretnieks, I.: 1997, ‘The Influence of Humic Substances on the Long Term Mobility of Toxic Metals’, in *Proceedings of the Sardinia ’97, 6th International Landfill Symposium*.

Balsberg-Påhlsson A. M.: 1990, Handledning i kemiska metoder vid växtekologiska arbeten. *Meddn. Växtekol. Avd., Lunds University* **52**, 1–58.

Boeckx, P. and van Cleemput, O.: 1996, Flux estimates from soil mathanogenesis and methanotrophy: Landfills, rice paddies, natural wetlands and aerobic soils, *Environmental Monitoring and Assessment* **42**, 189–207.

Bogner, J., Meadows, M. and Czepiel, P.: 1997, Fluxes of methane between landfills and the atmosphere: Natural and engineered controls, *Soil Use and Management* **13**, 268–277.

Bonomo, L. and Higginson, A. E.: 1988, *International Overview on Solid Waste Management*, Academic Press, London, U.K., International Solid Waste Association.

Brady, N. C. and Weil, R. R.: 1999, *The Nature and Properties of Soils*, 12th ed., Prentice-Hall, London.

Bramryd, T.: 1997, *Biological Waste Treatment Techniques from an Ecological Viewpoint*, ISWA Yearbook 1997/1998, pp. 68–75.

Bremner, J. M.: 1965, 'Total Nitrogen', in C. A. Black (ed.), *Methods of Soil Analysis*, Part 2, American Society of Agronomy, Madison, Wisconsin, pp. 1149–1178.

Chen, P. H.: 1996, Assessment of leachates from sanitary landfills: Impact of age, rainfall, and treatment. *Environmental International* **22**(2), 225–237.

Christensen, T. H., Kjeldsen, P., Albrechtsen, H. J., Heron, G., Nielsen, P. H., Bjerg, P. L. and Holm, P. E.: 1994, Attenuation of landfill leachate pollutants in aquifers. *Critical Reviews in Environmental Science and Technology* **24**, 219–302.

El-Fadel, M., Findikakis, A. N. and Leckie, J. O.: 1995, Environmental Impacts of Solid Waste Landfilling, *Journal of Environmental Management 1997* **50**, 1–25.

Fredriksson, J.: 1995, Renhållningsverket i Helsingborg. En historik om sophantering och sopgubbar. Renhållningsverket i Helsingborg, Helsingborg, 71 pp. (in Swedish).

Onay, T. T. and Pohland, F. G.: 1998, *In situ* nitrogen management in controlled bioreactor landfills, *Water Research* **32**(5), 1383–1392.

Pohland, F. G.; Al-Yousfi, B.: 1994, Design and operation of landfills for optimum stabilization and biogas production, *Water Science and Technology* **30**(12), 117–124.

Reinhart, D. R. and Al-Yousfil, A. B.: 1996, The impact of leachate recirculation on municipal solid Waste landfill operating characteristics, *Waste Management and Research* **14**, 337–346.

Senior, E.: 1990, *Microbiology of Landfill Sites*, Boca Raton, Florida, CRC Press.

Tchobanoglous, G., Theisen, H. and Vigil, S.: 1993, *Integrated Solid Waste Management*, New York, McGraw-Hill Book Company, Inc.

Tyler, G.: 1978, Leaching rates of heavy metal ions in forest soil. *Water, Air, and Soil Pollut.* **9**, 137–148.

Wall, D. K. and Zeiss, C.: 1995, Municipal Landfill Biodegradation and Settlement, *Journal of Environmental Engineering* **121**(3), 214–224.