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Bioreactor landfills: Do they work?

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Abstract: This paper begins by providing an outline of various waste stabilisation techniques on which the concept of bioreactor or process-based landfills is based, followed by an overview of the research and development of this alternative landfill approach. The paper then presents a summary of the Australian experience. It also reports on the current state of bioreactor landfills and discusses the difficulties and problems associated with their full-scale operations. Areas where future research should be focused are also identified.

Keywords: waste, stabilisation, biodegradation, leachate, recirculation, wet cell

1. INTRODUCTION

Currently our municipal solid waste (MSW) landfill technology is primarily based on a permanent storage and containment or "dry cell" concept. Most of the research activities have been concentrating on the design of liner, cover, and hydraulic systems with the aim of sealing off a landfill from the external environment. The idea is to minimise the amount of water entering the waste sealed within a well-encapsulated landfill cell, and the waste can then be preserved in a relatively inactive state—discouraging the formation of leachate and landfill gas to reduce environmental impacts. While this dry cell approach may delay decomposition due to a lack of moisture, its long-term effectiveness is very much in doubt, as it has to rely on permanent encapsulating performance of a containment system, which is rather unrealistic. As a containment system ages and becomes less effective, there is a long-term risk that the suppressed biodegradation may turn active in the future.

With a better understanding of landfill decomposition processes and behaviour, there has been a strong trend in recent years to shift the philosophy of landfill design from the above permanent storage concept towards a bioreactor (or process-based) approach (Krol et al., 1994; Pacey et al., 1999). The bioreactor concept, in contrast to the permanent storage approach, allows active landfill management based on an understanding of the biological, chemical and physical processes involved. It focuses on enhancing the degradation processes to stabilise waste and aims to bring forward the inert state of a landfill in a relatively short time. It utilises a landfill as a bioreactor to treat waste rather than merely as a burial ground. It offers the potential to avoid the long-term environmental risks associated with the dry cell approach. Although laboratory tests and pilot-scale studies have demonstrated its advantages over the conventional dry landfills, there are still some technical and non-technical barriers yet to be overcome before we can truly translate this concept into everyday practical operations.

This paper first provides an outline of various landfill stabilisation enhancement techniques, including leachate recirculation, which is by far the most promising option. The outline is followed by an overview of the research and development of bioreactor landfills promoted by leachate recirculation. The paper then presents a summary of the Australian experience. It also reports on the current state of bioreactor landfills and discusses the difficulties and problems associated with their full-scale operations. Areas where future research should be focused are also identified.

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2. WASTE STABILISATION

An understanding of various phases of the microbially-mediated decomposition in a landfill environment is essential in order to provide a basis for the design, construction, operation and closure of bioreactor landfills. Soon after disposal of the waste, an anaerobic condition will become predominant in the landfill. A consortium of anaerobic bacteria will start biodegrading the organic matter, eventually converting it mainly into carbon dioxide and methane. The microbial conversion processes are complex and have been described elsewhere in the literature (e.g. Christensen & Kejeldsen, 1989; Aragno, 1988). With knowledge of the decomposition processes, it is not difficult to understand that most landfills proceed through a series of rather predictable events. Such a sequence has been described by Farquhar and Rovers (1973), Ehrig (1983), Chian et al. (1985), and Christensen and Kjeldsen (1989). Basically, the sequence can be separated into several distinct phases in terms of gas composition and leachate concentrations. These changes of leachate and landfill gas can be used as useful biodegradation indicators.

The fundamental factors that can affect the efficiency of degradation in a landfill system are summarised in Table 1. Detailed discussions of these factors can be found in the relevant references in column 3.

Various process-based stabilisation enhancement techniques have been investigated. They all aim to influence the fundamental factors controlling the degradation and stabilisation processes. They can be operationally grouped under the following headings.

2.1 *Shredding of Waste*

It has been suggested that shredding may help: (1) to increase the homogeneity of the waste by size reduction and mixing; (2) to increase the specific surface area of the waste for bio-degradation; (3) to remove moisture barriers caused by impermeable materials, and; (4) to improve the water content distribution in the waste. However, some investigations have suggested that shredding of waste may induce a negative effect on degradation (e.g. Christensen et al., 1992) by promoting excessive initial hydrolysis and acid formation that inhibit the onset of a methanogenic environment. Shredding may prove to be beneficial only if the over-stimulated acid production is to be controlled by pH buffering.

2.2 *Waste Compaction*

Results from limited studies (e.g. Dewalle & Chian, 1978) show that compaction could affect anaerobic decomposition. If a waste is relatively dry, increasing the compaction (or the dry density) may significantly speed up the degradation processes. This positive effect can be explained by the higher moisture content (by volume) available in the more compacted solids which may help to enhance the distribution of nutrient and the contact between substrates and bacteria. However, for wet waste, an increase in dry density may actually slow down methane production. This is due to the development of an undesirable early intensive acid phase, over-stimulated by high moisture.

2.3 *Buffer Addition*

In an unbalanced landfill ecosystem, a low pH environment caused by a vigorous acid production would inhibit the growth of methanogenic bacteria. This understanding has led to attempts to introduce buffer artificially into landfill systems. Results of small-scale experiments (e.g. Christensen et al., 1992) suggest that the addition of buffer generally has a positive effect on the degradation. If a landfill fails to generate methane due to a low pH, buffer addition is an obvious measure to help the establishment of a methanogenic condition.

Table 1. Summary of Influencing Factors on Landfill Degradation

Influencing factors	**Criteria / Comments**	**References**
Moisture	Optimum moisture content: 60% and above (by wet mass)	Pohland (1986) ; Rees (1980)
Oxygen	Optimum redox potential for methanogenesis: -200mV -300mV below -100mV	 Farquhar and Rovers (1973) Christensen and Kjelden (1989) Pohland (1980)
pH	Optimum pH for methanogenesis: 6 to 8 6.4 to 7.2	 Ehrig (1983) Farquhar and Rovers (1973)
Alkalinity	Optimum alkalinity for methanogenesis : 2000mg/l Maximum organic acids concentration for methanogenesis : 3000mg/l Maximum acetic acid/alkalinity ratio for methanogenesis : 0.8	Farquhar and Rovers (1973) Farquhar and Rovers (1973) Ehrig (1983)
Temperature	Optimum temperature for methanogenesis.: 40° 41° 34—38°C	 Rees (1980) Hartz et al. (1982) Mata-Alvarez et al. (1986)
Hydrogen	Partial hydrogen pressure for acetogenesis: below 10^{-6} atm.	Barlaz et al. (1987)
Nutrients	Generally adequate in most landfill except local systems due to heterogeneity	Christensen and Kjelden (1989)
Sulphate	Increase in sulphate decreases methanogenesis	Christensen and Kjelden 1989)
Inhibitors	Cation concentrations producing moderate inhibition (mg/l) : Sodium 3500-5500 Potassium 2500-4500 Calcium 2500-4500 Magnesium 1000-1500 Ammonium (total) 1500-3000 Heavy metals : No significant influence Organic compounds : Inhibitory only in significant amount	McCarty and McKinney (1961) Ehrig (1983) Christensen and Kjelden (1989)

2.4 Sewage Sludge Addition

Co-disposal of sewage sludge with MSW in a landfill may promote degradation by increasing the availability of moisture, nutrient and anaerobic micro-organisms in the waste. However, in situations where methanogenic conditions are already established, or the landfill environment is favourable to methanogenic development, addition of sewage sludge may not have any beneficial effect. Studies (e.g. Leckie et al., 1979, Leuschner, 1989) have reported that the addition of sewage sludge in some cases have actually induced negative effects. In these cases, the sludge added to the landfill system was low in pH (septic tank sludge), and the natural buffer capacity of the landfill environment was exceeded.

2.5 Pre-Composting Part of Landfill Waste

Researchers (Stegmann, 1983; Stegmann & Spendlin, 1986 & 1989; Doedens & Cord-Landwehr, 1989) have conducted both laboratory and full-scale tests which showed that the pre-composting of part of a landfill waste or the use of a pre-composted bottom layer (i.e. "thin layer" operation) provides a positive effect on leachate strength reduction. The basis of the concept is to allow the more readily degradable organic material in the waste to first degrade by aerobic processes via composting, thereby moderating the development of an otherwise intensive acid phase in the later anaerobic degradation.

2.6 *Enzyme Addition*

The hydrolysis process in a landfill anaerobic degradation system is promoted by enzymes produced by fermentative bacteria. Research has been conducted to study the possibility of controlling the hydrolysis process by manipulating the natural enzyme activity. Lagerkvist and Chen (1993) used laboratory-scale simulators to investigate the effect of adding industrial cellulolytic enzymes into MSW during both acidogenic and methanogenic states. Their results suggested that it is viable to intensify both acidogenic and methanogenic conditions by enzyme addition.

2.7 *Leachate Recirculation*

Among all the enhancement techniques, leachate recirculation is by far the most investigated process-based management option. Its main drive is being generated from the arguments that the recirculated leachate helps: (1) to promote an active microbial degradation by providing an optimum moisture; (2) to induce a water flux to provide a mechanism for the effective transfer of microbes, substrates, and nutrient throughout the refuse mass, and; (3) to dilute local high concentration of inhibitors.

There are also potential operational benefits claimed, including:

- the temporary storage of leachate and the partial in-situ treatment of leachate;
- the improvement of landfill gas production rate and total yield;
- the accelerated waste compression/settlement to create additional space for disposal and to allow earlier use of the site, and;
- the reduction in time and cost of post-closure monitoring.

However, the use of leachate recirculation to enhance landfill stabilisation is not straightforward, and often needs to be supplemented with other enhancement methods as described above. A successful application of the technique does demand a comprehensive knowledge of the whole stimulation process. The following section provides a summary of its research and development.

3. RESEARCH AND DEVELOPMENT

3.1. *Small-Scale Studies*

As early as the 1970s, researchers started exploring the potential of applying leachate recirculation in landfills to enhance the stabilisation of waste and production of landfill gas. This resulted in a significant amount of research conducted at laboratory or lysimeter-scale over the past two decades. Table 2 summarises some of the milestone laboratory and lysimeter-scale investigations related to this area.

The small-scale studies have provided sufficient evidences to suggest that the concept of bioreactor landfills is technically viable. However, the small-scale experiments have their limitations. While they can allow the flexibility to study a large number of operational variables under controlled conditions, it is obvious that they cannot accurately simulate the natural degradation processes in full-scale landfills due to scale effects. For example, almost all of the small-scale studies worked with shredded waste but very rarely the same treatment was given to the MSW in full-scale landfills. It also appears that the natural pH buffering capacity in a real landfill environment generally performs far better than that in a bench-scale simulator, possibly as a result of the presence of soil covers and a more diversified source of waste material. Also, the kind of recirculation rate and uniformity of moisture distribution that can be achieved in a laboratory test cannot be obtained easily in a full-scale landfill cell.

Table 2. Summary of Laboratory and Lysimeter-Scale Studies on Leachate Recirculation and Related Enhancement Techniques

Reference [Country]	Scale of Testing (No. of Cells)	Effects of Enhancement Techniques Investigated								Criteria Used in Assessment					
		LR	BA	SA	SW	AM	NA	TC	PA	lc	lp	gc	gp	ws	wt
Pohland (1975) [U.S.]	1m dia., 3m deep (4 nos.)	+	+	+						•	•	•		•	•
Leckie et al. (1979) [U.S.]	15mx15m, 3m deep (5 nos.)	+		-		+				•	•	•		•	•
Pohland (1980) [U.S.]	5mx5m, 3m deep (2 nos.)	+								•	•	•	•		•
Tittlebaum (1982) [U.S.]	1m dia., 2.4m deep (4 nos.)	+	+		?		?			•					
Robinson et al. (1982) [U.K.]	5mx5m, 1.6m deep (3 nos.)	+					+			•	•				
Hartz & Ham (1983) [U.S.]	0.2m dia., 0.75m deep (8 nos.)	+				+						•	•		
Mata-Alvarez & Martinez-Viturtia (1986) [Spain]	10 kg) (5 nos.)	+	+				+	+		•		•	•		•
Walsh et al. (1986); Kinman et al (1987) [U.S.]	0.9m dia., 1.2m deep (16 nos.)	+/-	+	+		-	+	+		•		•	•		
Barlaz et al. (1987) [U.S.]	208 litre (19 nos.)	+	+	-		?			+	•		•	•		
Stegmann & Spendlin (1986) & (1989) [Germany]	120 litre; & 5mx5m, 4m deep	+	?	?			?		+	•		•	•		
Leuschner (1989) [U.S.]	55 gallon (6 nos.)	+/-	+	+/-			+			•	•	•	•		
Doedens & Cord-Landwehr (1989) [Germany]	1.5m dia, 1.35 deep (4 nos.); 600 cu.m (3 nos.)	?				?				•		•	•		
Scrudato & Pagano (1991) [U.S.]	0.15m dia., 0.75m deep (1 nos.)	+								•					
Woelders et al. (1993) [Netherlands]	*0.3m dia., 100kg* (3 nos.)	+				+				•		•	•		
Otieno (1994) [Kenya]	0.45m dia, 30kg (4 nos.)	?			?				?	•					
Chugh (1996) [Australia]	200 litres (10 nos.)	+		+		+				•		•	•		

Abbreviations :
LR : Leachate Recirculation BA: Buffer Addition SA: Sludge Addition SW: Shredded Waste
AM: Accelerated Moisture Addition NA: Nutrient Addition TC: Temperature Control PA: Pre-composted/ Old Waste Addition
lc: leachate composition *lp: leachate production* *gc: gas composition*
gp: gas production ws: waste settlement wt: waste temperature
+ : Positive Effects - : Negative Effects ? : Uncertain / Inconclusive Results • : Criterion Used

Table 3. Summary of Reported Full-Scale Studies on Leachate Recirculation and Supplementary Enhancement Techniques

Reference	Location of Landfill	Scale of Cells	LR Method			Effects of LR & Supplementary Techniques				Criteria Used in Assessment					
			SPRY	INFIL	WELL	LR	BA	SA	PC	lc	lp	gc	gp	ls	lt
Barber & Maris (1984 & 1992)	Seamer Carr Landfill, Yorkshire, U.K.	1cell 2 ha.	•			+				•	•				
Croft (1991): Knox (1996)	Brogborough Landfill, Bedfordshire, U.K.	6 cells each 40mx20mx20m		•		+	+	+		•	•	•	•	•	•
Stegmann & Spendlin (1986 &1989)	Lingen Sanitary Landfill, Germany	2 cells each of 1 ha.	Not Reported			+			+	•					
Doedens & Cord-Landwehr (1989)	Bornhausen & Bornum Landfills, Germany	cells of 0.5 to 1.25 ha.	•			+			+	•					
Pacey (1989)	Mountain View Landfill, California, U.S.	6 cells each of 600 tons		•		?	?	?				•	•	•	•
Watson (1987): Vasuki (1988)	Central and Southern Solid waste Facility, Delaware, U.S.	3 cells of 3 - 7 ha.	•	•	•	+				•	•				
Kilmer (1991)	Worcester Country Landfill, Maryland, U.S.	4 cells each of 7 ha.	•	•	•	+				•					
Scrudato & Pagano (1991)	Seneca Meadows Landfill, New York, U.S.	11 cells of total 45 ha.	Not Reported			+				•					
Miller et al. (1991)	Alachua County Landfill, Florida, U.S.	1 cell 2.5 ha.		•		?				•	•	•	•		•
Reynold & Blakey (1992): Knox (1996)	Lower Spen Valley Landfill, West Yorkshire, U.K.	2 cells each of 1000t		•		+		+		•	•	•	•		•
Nilsson et al. (1995a & b)	Spillepeng Landfill, Malmo, Sweden	6 cells each of 8000m3		•		+	+	+		•	•	•	•	•	
Yuen et al. (1995, 1999, 2000 & 2001)	Lyndhurst Landfill, Victoria, Australia	1 cell 1.5ha.		•	•	+				•	•	•	•	•	•

Abbreviation :
LR: Leachate Recirculation BA: Buffer Addition SA: Sludge Addition PC: Pre-composted Bottom Layer
SPRY: Spray Irrigation INFIL: Infiltration WELL : Injection Well
lc: leachate composition lp: leachate production gc: gas composition gp: gas production ls: landfill settlement lt: landfill temperature
+ : Positive Effects - : Negative Effects ? : Uncertain / Inconclusive Results

3.2. *Full-Scale Studies*

Following the positive results demonstrated by small-scale studies, there has been an increase in the number of cases reported in recent years on the practice of leachate recirculation in full-scale operating landfills in countries such as the U.K., Germany and U.S. However, the research and development devoted to full-scale investigations are still relatively limited, due mainly to a poor regulatory awareness and negative perception. Landfill regulations in many countries still do not encourage the practice of leachate recirculation because of the concern that feeding back the highly polluted leachate into a landfill may concentrate the pollutants and overload the containment system.

Table 3 summarises some of the research-based full-scale studies on leachate recirculation and supplementary techniques. There were also many reported case studies, based on available records obtained from landfills practising leachate recirculation, which are not listed.

The experience obtained from the full-scale studies generally suggests that future studies of bioreactor landfills should be focused on the following areas:

- The improvement of leachate recirculation systems to distribute moisture uniformly throughout the waste mass;
- Investigation on the extent of channelling and dead zones of recirculation due to heterogeneity;
- The long-term performance of recirculation devices taking into account the potential reduction in efficiency caused by bio-fouling and siltation;
- Supplementary enhancement methods such as waste shredding, waste pre-wetting, and use of permeable alternative daily cover;
- Alternative numerical moisture transport models such as the recently proposed two-domain approach (e.g. Zeiss, 1997 and Bendz et al., 1997) for moisture distribution prediction; and
- The implementation of more full-scale bioreactor experiments to determine other biodegradation influencing factors such as waste composition, climate, and hydrological conditions, which can vary substantially from region to region.

3.3. *Summary of Research Findings*

Summarising the research findings, it is possible to obtain some useful indications on the general reaction patterns and outcomes that one may expect from leachate recirculation combined with other supplementary operations. These general reaction patterns and outcomes are summarised below:

(i) ***Leachate Recirculation Alone*** — This generally only accelerates early hydrolysis and acid production, which results in a high volatile acids concentration in the leachate. If the natural buffering capacity of the system is insufficient, the acidic environment will inhibit the growth of methanogens and delay methane production (e.g. Walsh et al., 1986; Kinman et al., 1987). However, limited full-scale data tend to suggest that MSW landfills generally provide a good natural buffering capacity (e.g. Barber and Morris, 1984; Millers et al., 1991).

(ii) ***Leachate Recirculation with pH Neutralisation*** — As buffer addition helps to mediate the acidic environment caused by any vigorous acid production, it thus enables early onset of methanogenesis (e.g. Pohland, 1975; Tittlebaum, 1982; Leuschner, 1989). This is by far the most important supplementary operation if the natural buffering capacity is inadequate.

(iii) ***Recirculation with Methanogenic Leachate*** — Both small and large-scale studies have shown that there are benefits to be gained in the recycling of old methanogenic leachate in young landfills (e.g. Woelders et al., 1993; Scrudato and Pagano, 1991; Chugh 1996). Such benefits include rapid reduction in leachate strength and early methane production, which are attributed to the high alkalinity and the seeding of methanogens from the methanogenic leachate.

(iv) *Leachate Recirculation with Sludge Addition* — Co-disposing with anaerobically digested sewerage sludge, generally serves the purpose of moisture enhancement, nutrient addition and microbial seeding. Both small and large-scale studies (e.g. Leuschner, 1989; Knox 1997) have produced positive results which suggest that it promotes early methanogenesis as well as higher gas production rates. However, one has to be cautious regarding the characteristics of the sludge as it has been demonstrated that, for instance, septic tank sludge exhibits a detrimental effect due to its low pH nature (Leuschner, 1989).

(v) *Leachate Recirculation with Waste Shredding* — Generally no conclusive findings have been reported to suggest that leachate recirculation combined with waste shredding would provide a better enhancement effect than without shredding (e.g. Tittlebaum, 1982).

(vi) *Leachate Recirculation with Nutrient Addition* — Combining nutrient addition with recirculation does not seem to provide any further enhancement as nutrient deficit is generally not a limiting factor (e.g. Tittlebaum, 1982).

(vii) *Leachate Recirculation with Temperature Control* — Laboratory studies have indicated that the optimum temperature range for anaerobic degradation lies between 34 and 38 °C, with or without leachate recirculation (Mata-Alvarez et al., 1986). In terms of full-scale studies, there are insufficient data available.

(viii) *Leachate Recirculation with Waste Modification* — This covers the mixing of old anaerobically degraded refuse (e.g. Barlaz et al., 1987) or the use of a pre-composted bottom layer/"thin-layer" operation (e.g. Stegmann and Spendlin, 1986 and 1989). Both have demonstrated positive effects on leachate strength reduction. The co-disposal of a high proportion of non-hazardous commercial/industrial waste with domestic waste has also proved to be effective in promoting early methanogenesis (e.g. Nilsson et al., 1995a and b), which appears to benefit from the natural pH-buffer offered by the less readily degradable commercial/industrial waste.

(ix) *Leachate Recirculation at Different Rates* — Laboratory research generally supports the view that a higher rate of recirculation provides a better anaerobic degradation (Hartz and Ham, 1983; Chugh, 1996). However, any secondary effects (e.g. drop in waste temperature), as a result of a high recirculation rate, should also be considered. Due to difficulties in managing large volume of leachate in practice, no full-scale experiment has yet demonstrated an effective and high recirculation rate comparable to laboratory tests.

(x) *Aeration of Leachate prior to Recirculation* — Aeration may be used to pre-treat the leachate to reduce its high organic load prior to recycling. This is particularly beneficial if the leachate is to be recycled by direct spray irrigation onto landfill surfaces with vegetation cover. The pre-treated leachate would sustain vegetation growth by providing nutrient (Robinson et al., 1982). However, direct injection of aerated leachate into the waste has not been investigated. The effect may be negative as the increased oxygen content carried by the aerated leachate may upset the sensitive methanogenic bacteria.

4. THE AUSTRALIAN PERSPECTIVE

Compared with many developed countries, the concept of bioreactor landfills is still relatively new to Australia. While there are proposals being made, it appears that currently no operating landfill has yet been designed and operated as a bioreactor, apart from one pilot-study and one full-scale research project as described below.

The pilot study consisted of a series of five test cells, each of about 10,000 m^3 conducted at the Lucas Heights Landfill, NSW. Van Den Broek et al. (1995) described the test cell design and construction. The project was linked to a co-study (Chugh 1996) based on a series of laboratory-scale (160litres) reactors investigating various parameters relating to the waste stabilisation process, including the sequential batch anaerobic process. The process involves the recirculation of leachate through different waste beds, operating at different stages of the waste stabilisation process using leachate as a means to provide moisture, dissolve the nutrients, inoculate the waste and remove inhibitory fermentation products. The study demonstrated that the process successfully converted approximately 80 % of the degradable organic portion of unsorted MSW to methane in 60 days under well-controlled laboratory conditions.

The full-scale research project based on an operational-size test cell of 180,000 m^3 was conducted at the Lyndhurst Landfill, Victoria. Yuen et al. (1995) described the test cell design and construction. The primary aim of the project was to assess the feasibility and practicality of full-scale bioreactor landfilling and to quantify the environmental and operational benefits that can be gained by performing leachate recirculation. The study findings are described and discussed in Yuen et al. (1999, 2000a & b, 2001) and O'Farell (1998).

The Waste Management Council, Victoria produced a report (WMC, 1995) on *The Waste Disposal Strategy for the Greater Melbourne Area*. It aimed to identify the best practice for waste disposal and suggested that "waste disposal technology is likely to result in a change from 'dry tomb' landfills to 'bioreactor' landfills where application of additional water to the refuse mass will result in enhanced degradation and less long-term management requirements". However, the *Draft Best Practice Environmental Guidelines for the Siting, Design, Operation and Rehabilitation of Landfills* recently released by the EPA, Victoria (2001) stated that "...enhanced biodegradation landfills are not considered to be acceptable practice... for a number of reasons'. The reasons as quoted include:

(a) Recirculated leachate places additional demands on the liner and leachate collection system.
(b) It is not possible to achieve the required level of control (water content, temperature, and oxygen levels) at a landfill which is below ground.
(c) Enhanced biodegradation landfills seek to turn a landfill into a waste treatment facility and are not compatible with achieving minimum risk.

While it is rightful for a regulatory authority to be cautious regarding the use of unproven technologies, the community also expects to see leadership in promoting improvements in waste management practices by working through innovative ideas and proposals with research and industry. It is rather discouraging to find that bioreactor landfills, which are the focus of much past and current research around the world, be described as 'not considered to be acceptable' in the draft Victorian landfill guidelines. Beyond this, the reasons quoted in the draft guidelines do not stand up to scrutiny.

For (a), there is no reason why the liner and leachate collection system should not be designed to take account of the 'additional demands' that might be placed upon it. In practise, this could be achieved along with an appropriate leachate management strategy. In the long-term, the demand on the liner and collection system will actually decrease considerably as the waste becomes stabilised.

As discussed in Section 3, it is clear that there are operational constraints and difficulties yet to be resolved, for example, the controlling of moisture content during leachate recirculation as stated in (b) above. However, any refinements and improvements can only be made if full-scale trials are to be encouraged.

It is hard to find any grounds and justification for the assertion in (c). There is little doubt that the use of a treatment facility to replace permanent disposal should decrease rather than increase the overall level of risk. During treatment, some elements of risk may be elevated for a period of time, but the long-term risk will be very much reduced as the waste becomes stabilised. Furthermore, it is during the relatively early phases of the life of the landfill that the operator and regulator have the best control of the site.

5. NON-TECHNICAL ISSUES

Apart from the technical barriers identified in Section 3, which are to be addressed by further research and field-scale experience, the viability of bioreactor landfills is also facing some non-technical issues as discussed below.

5.1. Poor Regulatory Awareness and Negative Perception

Current regulations generally still encourage landfills to remain dry. The recent Victorian EPA draft guidelines as described above can be taken as an example. However, the trend is moving positively for bioreactor landfills, at least in other developed countries. Taking the U.S. as an example, despite its rather prescriptive regulations, Pacey et al. (1999) interpreted that relevant U.S. federal codes are open to necessary amendments for bioreactor design providing that other statutory constraints are met (e.g. leachate head limits on the base liner and inclusions of a single composite liner). They also suggested that favourable federal policy toward bioreactor landfills has begun to develop. For example, in the federal *Climate Change Action Plan of 1993*, action item 37 contains, among others, the following relevant recommendations:

- Creation of a joint state/federal coordination program to facilitate siting/permitting of enhanced recovery (i.e. bioreactor) landfills, and
- Modification of environmental performance standards and regulatory requirements to remove unnecessary barriers to bioreactor landfills.

5.2. Inefficient Information Dissemination Regarding Performance and Economic Assessment

There has been an increasing number of bioreactor landfill trials. Gou and Guzzone (1997) reported a U.S. survey of the position of state regulatory agencies on leachate recirculation and bioreactor landfills. The report indicated that approximately 130 MSW landfills were employing leachate recirculation. Similar increase in trials can be observed in many other developed countries. However, there has not been an established mechanism allowing efficient sharing of information and experience among researchers and practitioners. To address this concern, an international bioreactor discussion group has recently been set up. The group offers its own web site <http://lst.sb.luth.se/bioreactor/> where researchers and practitioners can register as members to share experience and contribute to discussions.

5.3. Unrealistic Time Expectation and Commitment for Large-Scale Bioreactor Projects

Based on the experience of previous full-scale studies, it is clear that they must be regarded as long-term projects. A full-scale bioreactor landfill study, which involves the change in landfill behaviour corresponding to various stages of biodegradation development, demands a considerable longer investigation time than laboratory experiments. It would be virtually impossible to achieve the objectives fully within a 3 to 4 year duration that could otherwise be adequate for small-scale research.

6. THE WAY AHEAD FOR BIOREACTOR LANDFILLS

The recent trend in solid waste management, including Australia, to divert decomposable waste such as green waste away from landfills has certain implications. The concept of bioreactor landfills is logically incompatible with recycling/composting of organic waste. The two approaches belong to two extreme alternatives of an integrated management system — we need to dispose decomposable waste into landfills in order to make them bioreactors, which contradicts the idea of filtering out degradable waste for recycling/composting.

Thus a sensible integrated waste management system could possibly comprise one of the following options:

- To dispose MSW into landfills as it is collected. These landfills will be composed of both decomposable and inert wastes and can be treated as bioreactors. Under this option, the landfills will ultimately be used as permanent storage, but the waste will be stabilised in a relatively short time to reduce the long-term environmental risk.
- To sort MSW and dispose only quality organic waste in landfills. Under this option, the landfills are to be treated as batched anaerobic bioreactors. The end product will be good quality anaerobic compost and the landfills will be mined to recycle disposable space.
- To divert all decomposable waste from landfills for recycling/composting and dispose only inert waste (e.g. ash from incineration). Under this option, the landfills will still serve as permanent storage but of only insert waste with low environmental risk.

Whichever option is to be used, bioreactor landfills should be considered as part of an integrated waste management strategy, well planned and well defined to determine the best combination to suit a particular situation.

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