Chapter 4
Literature Review - Landfill Bioreactor Studies

Laboratory-Scale Studies

Many laboratory-scale studies have been conducted to investigate the effects of leachate recirculation on leachate quality, waste stabilization, waste settlement, gas production, attenuation of heavy metals, and other factors. The studies were primarily carried out in the United States, United Kingdom, and the former Federal Republic of Germany.

Moisture content, pH, temperature, availability of macro- and micro-nutrients and the presence of suitable microorganisms are the main parameters controlling the process of landfill stabilization and are therefore the parameters typically manipulated in the laboratory studies. Moisture content can be controlled by the addition of regulated quantities of water and/or leachate. The pH can be controlled by adding buffering compounds. Macro- and micro-nutrients are usually present in sufficient quantities in the waste and do not act as limiting factors in the stabilization process, hence nutrients are usually not added. Presence of suitable microorganisms responsible for stabilization can be ensured by adding anaerobically digested sludge in which acclimated anaerobic and facultative microorganisms are present. Several laboratory-scale studies are described below. The studies included are by no means all of the pertinent studies reported in the literature. Other studies include those of Mata-Alvarez and Martina-Verdure (1986), Barlaz, et al (1990), Buivid, et al (1981), Chian (1977), and Klink and Ham (1982).

Georgia Institute of Technology Experiment I (Pohland, 1975)

One of the first experiments on leachate recirculation was conducted at the Georgia Institute of Technology in the mid-1970's and supported by the USEPA. This experiment, which conclusively proved the effectiveness of leachate recirculation on waste stabilization, is described below.

Four test columns, each 0.9 m (3 ft) in diameter, were filled with 3 m (10 ft) of MSW and compacted to a density of 357 kg/m^3 (535 lb/yd^3). A 0.76-m (2.5-ft) soil cover was placed over the compacted coarsely-ground waste mass. The first column was a control cell with no leachate recirculation (single-pass cell). The second column was subjected to leachate recirculation only. In the third column, leachate recirculation was coupled with pH control (using NaOH) to maintain near neutral conditions. Leachate recirculation with pH control in addition to initial seeding (with wastewater sludge) was used for the fourth column. Leachate recirculation was accomplished by pumping through a distribution system located on top of the waste but below the cover soil. Approximately

945 l (250 gal) of water were added to all of the cells to produce leachate immediately. Leachate was drained to separate sumps from which samples were collected and analyzed at regular intervals for 1100 days after the start of the experiment.

For the control column, Chemical Oxygen Demand (COD) increased rapidly and peaked at about 19,000 mg/l after about 200 days and declined gradually to about 4,000 mg/l after 1,000 days. Total volatile acids (TVA) concentration showed a similar pattern, peaking at about 10,000 mg/l after 200 days and declining to 2,000 mg/l after 1,000 days. The pH did not show much variation and was in the acidic range of 5.0 to 6.5 throughout 1100 days of monitoring.

For the second column, with leachate recirculation only, the variation of COD, TVA, and pH with time was significantly different from the control cell. COD increased more rapidly than the control column, peaking at 11,000 mg/l after 100 days. After 150 days, COD decreased to a low of 4,000 mg/l and then decreased gradually to about 250 mg/l by day 500. TVA concentration variation followed the pattern of COD variation, peaking to 6,000 mg/l at 200 days, but increased again at 250 days, reaching 1,500 mg/l at 400 days and declined gradually to less than 200 mg/l by day 700. The pH remained around 5.0 for the first 200 days. As the COD and TVA concentrations dropped, pH increased to about 7.0 after 500 days and remained in the neutral region thereafter.

Column 3 with leachate recirculation and pH control, showed a more rapid decrease in TVA and COD concentrations than the second column. Both COD and TVA peaked after 150 days at 10,000 mg/l and 5,000 mg/l, respectively. After 200 days, COD concentration had decreased to less than 500 mg/l and TVA concentration to less than 250 mg/l. Due to the addition of buffers, pH was near neutral throughout the monitoring period.

The fourth column, with leachate recirculation, pH control and seeding, did not perform better than the pH-controlled leachate recirculating column (Column 3). Peak COD and TVA concentrations were 9,000 mg/l and 5,000 mg/l respectively, both occurring at about 60 days. While the TVA concentration declined to near zero at 400 days, COD concentration reached near zero at 650 days. Initially, pH dropped to nearly 5, but due to buffering, was in the neutral region after day 150 and throughout the remaining monitoring period.

The following important observations can be made from the results of this laboratory simulation.

- Leachate recirculating columns produced low COD/TVA leachates in a shorter time period as opposed to a more gradual decline in the control cell.

- The peak COD and TVA concentrations in the leachate recirculated columns were less than the control column.

- pH remained more neutral in the leachate recirculated column than the control column.

- pH control and leachate recirculation gave the best performance with rapid decline in COD and TVA concentrations.

- Inoculation with wastewater sludge did not accelerate the degradation process.

The most significant inference which can be drawn from this experiment is that leachate recirculation accelerates the waste degradation process as characterized by a rapid decrease in the COD and TVA concentrations. Although this was one of the first experiments in the area, it convincingly proved the effectiveness of leachate recirculation.

University of Louisville Experiment (Tittlebaum, 1982)
A laboratory-scale study, supported in part by the Illinois Institute on Environmental Quality, was conducted to demonstrate the advantages of leachate recirculation and to investigate the feasibility of leachate recirculation systems in providing leachate treatment. An additional objective was to determine of the effect of leachate pH and nutrient control on biological stabilization of shredded and unshredded refuse.

Four 0.9-m (3-ft) diameter steel test cells, equipped with leachate collection and redistribution (except the control cell) systems, were set up and filled to 2.4 m (8 ft) with domestic refuse compacted to a density of 240 kg/m^3 (400 lbs/yd^3). Test Cell 1 was the control cell with unshredded refuse. Cell 2, with leachate recirculation, contained shredded refuse with 70 percent moisture content and pH control (using NaOH). Cell 3 was operated similarly to Cell 2 except that it contained unshredded refuse. Test Cell 4 had nutrient control (phosphorus and nitrogen addition) and was similar to Cell 3 in all other aspects. Approximately 11 m^3 (200 gal) of water were added to start leachate production in Cells 2, 3, and 4. Tap water, equivalent to the total daily rainfall, was routinely added to all of the cells. Leachate from all the cells was periodically analyzed for 514 days. The data obtained showed that leachate recirculation resulted in marked decrease in the concentrations of TVA, Biochemical Oxygen Demand (BOD), COD, and Total Organic Carbon (TOC) in Cells 2, 3, and 4 in comparison to Cell 1. Cell 1 appeared to be acid stuck, maintaining high levels of TVA throughout the test period, although pH remained at neutral levels. Because all three leachate recirculating cells produced consistent leachate quality, nutrient control was found not to have any significant impact on leachate quality nor did shredding of waste increase the rate of stabilization. The BOD/COD ratios were observed to be close to those reported for municipal wastewater (between 0.6 to 0.8) in all four cells, indicating the biological treatability of leachate in wastewater treatment plants should off-site treatment of leachate be required. Based on the analytical data obtained for all the cells, the following conclusions were drawn.

- Leachate recirculation with pH control established anaerobic biological population in the fill rapidly.

- Nutrient control did not have any significant effect on stabilization of organic content of the refuse.

- Shredding did not have any effect on biological stabilization of the refuse.

- Leachate recirculation with pH control lead to accelerated biological stabilization of the organic content of the refuse thereby reducing the time required for ultimate site use (land reclamation).

- Leachate recirculation with pH control lead to significant reductions in BOD, COD, and TOC.

- Leachate recirculation with pH control can be used as an effective leachate treatment process.

German Experiment (Doedens and Cord-Landwher, 1989)
Test cell experiments on leachate recirculation were conducted in the former Federal Republic of Germany. Four steel cylindrical test cells, each 1.5 m (4.9 ft) in diameter were installed and filled with 1.35 m (4.4 ft) of shredded waste compacted to a density of to 20,800 to 23,200 kg/m^3 (1300 to 1450 lb /yd^3) wet weight to simulate the actual density achieved in field by compactors. The waste volume in each cell was 2.4 m^3 (85 ft^3) and the initial moisture content was 24 to 31 percent. All of the cells were air tight, temperature controlled (35°C), and equipped with leachate redistribution system and meters to measure leachate and gas flows.

Test Cell 1 received rainwater equivalent to 660 mm/yr (26 in/yr) of precipitation and all the leachate generated was redistributed to the cell. The remaining Cells (2, 3, and 4) received rainwater equivalent to 330 mm/yr (13 in/yr) precipitation (half that of Cell 1). Test Cell 2 was the control cell receiving rainwater only with no leachate recirculation (single-pass cell). Test Cell 3 received rainwater (330 mm/yr) (13 in/yr) and all the leachate generated was fed back to the cell along with rainwater. The fourth cell was initially brought to field capacity with leachate from a stabilized landfill. Thereafter, the cell received 330 mm/yr (13 in/yr) rainwater in addition to all of the leachate generated.

Test Cell 1 showed a more rapid decline in the COD concentration than any other cell. Test Cell 2, the control cell, took longer than any other cell to reduce COD concentration to levels comparable to other cells. After about 300 days from the start of the experiment, Test Cell 1 had the lowest COD concentration and Test Cell 2 had the highest concentration. Test Cells 3 and 4 produced approximately the same COD concentrations, which were higher than Test Cell 1 and lower than Test Cell 2. However, since varying quantities of water were added to each of the cells, the total mass loads emitted from the cells should be considered rather than concentrations. For example, although the COD concentration is less in Test Cell 1, the total load emitted would be more because the cell received twice the amount of water than that of other cells. Considering the loads withdrawn from the test cells during the test period (excluding the loads in recycled leachate), Test Cell 3 gave the best result with the lowest mass emission (during the test period) of COD, BOD, chloride, zinc, lead, and cadmium compared to remaining cells.

Cell 4 had the highest emission loads of COD, BOD, chloride, zinc, lead, and cadmium due to its initial saturation with stabilized landfill leachate. Cell 1 (with leachate recirculation) performed better than Cell 2 (control cell) with respect to emission loads of COD, BOD, chloride, zinc, lead and cadmium. Control Cell 2 (single-pass cell) produced more gas than any other cell (114 m^3/t dry matter (3650 ft^3/ton)), followed by Cell 3 at 111 m^3/t dry matter (3560 ft^3/ton) and Cell 4 at 105 m^3/t dry matter (3360 ft^3/ton). Cell 1 produced significantly less gas than any other cell (50 m^3/t dry matter (1600 ft^3/ton)). Excluding Cell 4, which was initially saturated with leachate, the two leachate recirculating cells performed better (with respect to leachate quality) than the control (single-pass) cell. The most significant inference from this experiment is that leachate recirculation lowers the emitted loads of COD, BOD, chloride, and metals.

Newcastle University Experiment (Otieno, 1989)
Lysimeter studies were conducted at Newcastle University, U.K. to investigate the effect of leachate recirculation on different types of wastes and under various operating conditions. Four lysimeters, each 0.5 m in diameter, were filled with various types of domestic wastes and compacted to different densities. Depth of the columns was not indicated. The lysimeters were equipped with leachate distribution piping, leachate monitoring systems, and gas monitoring systems. Lysimeter 1 was filled with fresh crude domestic waste with a moisture content of 61 percent, and a density of 383 kg/m^3 (648 lbs/yd^3) while Lysimeter 2 was filled with the same type of waste and moisture content but was compacted to a density of 418 kg/m^3 (702 lbs/yd^3). Lysimeter 3 consisted of shredded domestic refuse with a moisture content of 44 percent and density of 306 kg/m^3 (513 lbs/yd^3). Lysimeter 4 consisted of aged domestic refuse with a moisture content of 85 percent and density of 550 kg/m^3 (34 lbs/ft^3). Lysimeter 2 was operated under saturation conditions while all others were operated with free draining leachate. The lysimeters were monitored over a period of 400 days.

Leachate from Lysimeter 3 with shredded refuse and the lowest density, showed a marked decrease in COD concentration within a shorter time than Lysimeters 1 and 2. Lysimeter 4, with aged refuse, had a very low COD leachate throughout the test period. Lysimeters 1 and 2 leachates had approximately the same COD concentration which was significantly higher than Lysimeter 3. Similar results were observed with respect to TOC concentrations. Results were similar with respect to TVA and BOD concentration variations, with Lysimeter 3 showing a dramatic decrease within a shorter time when compared to Lysimeters 1 and 2 and Lysimeter 4 having low concentrations throughout. Clearly, Lysimeter 3 performed better than any of the other lysimeters with the exception of Lysimeter 4 containing aged refuse. The following conclusions can be drawn from the results of this experiment.

- Shredding of refuse increases the degradation rate thereby producing better quality leachate in a shorter period of time.

- Lower density helps in increasing the degradation rate.

- Operation under saturation conditions does not result in any benefits with respect to waste degradation, but rather may lead to higher strength leachates.

Georgia Institute of Technology Experiment II (Pohland, et al., 1992)

Another USEPA sponsored laboratory-scale experiment was conducted at the Georgia Institute of Technology to study the influence of leachate recirculation and single-pass operation on selected inorganic and organic priority pollutants codisposed with shredded municipal solid waste.

The experimental setup consisted of ten simulated landfill columns (steel cylinders) 0.9 m (3 ft) in diameter and 3 m (10 ft) in height. Each column was lined with 30-mil (0.076-cm) High Density Polyethylene (HDPE) liner and equipped with leachate collection and moisture/leachate distribution system. Each column was filled with 378 kg (832 lb) of shredded municipal solid waste. Organic and/or inorganic priority pollutants were added to the columns (except control columns) in varying doses. Metal sludges (constituting inorganic priority pollutants), prepared by mixing sawdust and metal oxides to obtain low, medium or high loadings were added to the columns. Two identically loaded columns, one with single-pass operation and another with leachate recirculation, constituted a pair of columns giving a total of five pairs of columns as shown in Table 4-1.

Table 4-1. Column Loading Characteristics (Pohland, et al, 1992)

Column	Operation	Initial loading height (cm)	Compact Density (kg/m^3)	Inorganic Pollutant Added*	Organic Pollutant Added#
1 CR	Recycle	29	313	None	None
2 C	Single Pass	30	301	None	None
3 O	Single Pass	29	309	None	Yes
4 OL	Single Pass	28	327	Low	Yes
5 OM	Single Pass	30	305	Medium	Yes
6 OR	Recycle	28	317	None	Yes
7 OLR	Recycle	29	309	Low	Yes
8 OH	Single Pass	30	305	High	Yes
9 OMR	Recycle	29	313	Medium	Yes
10 OHR	recycle	31	293	High	Yes

*Low: Cd=35 g, Cr=45 g, Hg=20 g, Ni=75 g, Pb=105 g, Zn=135 g, Medium: Low doubled, High: Medium doubled
#120 g each of 12 different organic compounds.

Leachate and gas samples were routinely analyzed for three years for admixed pollutants and other parameters. Overall, significantly greater volumes of gas at higher rates were produced in recycling columns vs. single-pass columns (averaging 42 m^3 (1500 ft^3) and 8.1 m^3 (290 ft^3) respectively) indicating an enhanced degree of waste stabilization. A prolonged acid phase was experienced in all columns requiring the addition of anaerobically digested sludge to initiate methane fermentation. During this time TVA concentrations reached 15,000 mg/l in recycle columns and 5 to 10,000 mg/l in single-pass columns. Leachate strength (as indicated by COD and TVA concentrations) decreased and gas production increased only after the onset of the methanogenesis phase after approximately 720 days. Thereafter, there was a dramatic decrease in COD and TVA concentrations along with an increase in pH and gas production in leachate recirculated columns with more moderate changes in single-pass columns. Gas production, also stable initially, dramatically increased with the onset of methane fermentation.

Priority pollutants caused a delay in the stabilization process in recycling columns and total inhibition in single-pass columns as demonstrated by lower pH values, gas production, and higher TVA concentrations relative to the control column. With respect to heavy metals, both recirculating and single-pass columns were capable of assimilating added pollutants, however recycle columns demonstrated greater capacity. Single-pass and leachate recycle columns exhibited little difference with respect to the release patterns of organic priority pollutants like dibromomethane, trichloroethane, and nitrobenzene. Leachate containment by recirculation, in addition to providing in-situ leachate treatment, resulted in efficient conversion to gas of many organic leachate constituents which otherwise would have been washed out.

Pilot-Scale Bioreactor Studies

A number of pilot-scale studies were conducted in the U.S. and other European countries to investigate the effects of leachate recirculation on landfill stabilization, leachate quality, landfill gas production and other parameters. Moisture content, waste density, type of waste, pH, temperature, nutrients, and seeding (addition of sludge) were typically controlled and manipulated in the pilot-scale studies. Several pilot-scale studies are briefly described below. A detailed compilation of test cell data has been provided elsewhere (IEA Expert Working Group on Landfill Gas, 1995).

Sonoma County, California (Emcon, 1976; Leckie, et al., 1979)

A pilot-scale landfill project was started in 1972 at Sonoma County, California, to study the effect of moisture on the rate of refuse stabilization, and on leachate quantity and quality. Five large-scale field test cells, each 15 m (49 ft) by 15 m (49 ft) by 3 m (10 ft), were constructed, filled with municipal solid waste compacted to 630 kg/m^3 (1000 lb/yd^3), and subjected to different operating conditions (moisture regimes). Each cell served a specific purpose and was operated accordingly as shown in Table 4-2. The cells were monitored for 900 days to evaluate leachate quality, gas composition, and settlement.

Cell A was the control cell, Cell B was initially brought to field capacity, Cell C received water at a rate of 3.8 m^3/d (1000 gal/d), Cell D was subjected to leachate recirculation, and Cell E was initially inoculated with septic tank pumpings. After construction, Cells A, B, and E received moisture only from infiltrating rainwater. The rate of leachate recirculation (in Cell D) varied from 1.9 to 19 m^3/day

Table 4-2. Test Cell Moisture Conditions, Sonoma County (Leckie, et al, 1979)

Cell	Purpose	Initial Liquid condition	Liquid Used in Initial Conditioning	Daily Liquid Application, m^3/d*	Liquid Used for Daily Liquid Application
A	Control Cell	None	None	None	None
B	High initial water content	Field Capacity	Water	None	None
C	Continual addition of water	None	None	0.76 - 3.8	Water
D	Leachate recirculation	None	None	1.9 - 3.8	Leachate
E	Microbial seeding	Field Capacity	Septic Tank Pumpings	None	None

* Other than infiltrating liquid

(500 to 5,000 gal/day). The leachate organic strength for Cells C and D with water input gradually declined. Leachate recirculation provided a more rapid decline in COD concentration than all other cells. The data from Cell D on gas composition also indicated an increased rate of biological stabilization. Based on the performance evaluation of Cell D and comparison with other cells, the following specific conclusions with respect to leachate recirculation were made.

- Leachate recirculation significantly increased the rate of establishment of anaerobic microbial population within the fill as suggested by gas quality.
- Leachate recirculation increased the rate of biological stabilization of the organic fraction of the refuse (as evidenced by reductions in BOD, COD, and TVA concentrations in leachate).
- Settlement was enhanced by liquid flow and accelerated microbial activity with leachate recirculation (20 percent reduction in height for leachate recirculating cell vs 7.6 percent for remaining cells).
- Continual flow-through of water increased rate of stabilization but created large volumes of leachate requiring ex-situ treatment.
- The addition of septic tank pumpings (inoculum) accelerated acid fermentation and was not beneficial in the absence of pH control and leachate recirculation.
- In the presence of leachate recirculation, the landfill acted as an anaerobic digester in treating leachate and therefore was found to be the most feasible and beneficial management strategy utilized in the study.

Georgia Institute of Technology Study (Pohland, 1980)
Pilot-scale investigations were conducted at the Georgia Institute of Technology to study the effects of leachate recirculation and to augment the results of initial laboratory-scale studies also conducted at Georgia Institute of Technology. Two simulated concrete landfill cells, each 3 m (10 ft) by 3 m (10 ft) by 4.3 m (14 ft) deep were constructed and filled with 3 m (10 ft) of shredded municipal solid waste compacted to a density of 319 kg/m^3 (537 lb/yd^3). One cell was left open to incident rain and the other was sealed completely to permit gas collection and eliminate evaporation. The cells were allowed to reach field capacity over a year's time. The sealed cell received tap water equivalent to rainfall received by the open cell through the distribution system. Both of the cells were equipped with leachate collection and distribution systems.

Nominal leachate production began on September 1, 1977, about a year after the completion of filling operations (August 13, 1976). Available leachate was recycled on a weekly basis. Daily recirculation of 760 l/day (200 gal) per cell was started on day 208. On day 346, the quantity of leachate recirculated was reduced to percolation capacity of the open cell. Recycling on alternate days was started on day 401 and was gradually reduced to 150 to 190 l/day per cell (40 to 50 gal/day).

Leachate samples were collected from both cells at regular intervals and analyzed for various parameters including BOD, COD, TOC, TVA, pH, phosphorus, chloride, and selected metals. Gas samples were also analyzed for carbon dioxide, nitrogen, methane, and hydrogen. TOC, COD and BOD, the critical parameters indicative of pollution potential of leachates, displayed similar pattern of decrease in concentrations for both cells. Data obtained during initial periods of weekly recirculation were somewhat erratic, more so for the sealed cell due to uneven distribution of TOC, COD and BOD after initiation of daily circulation. Although there was not much difference in concentrations of TOC, COD and BOD toward the end of the test period (520 days after leachate production began) concentrations were lower in the sealed cell than the open cell. TVA concentrations in both the cells initially increased and later decreased to levels below detection. The sealed cell provided a more congenial environment to methane formers by excluding oxygen. Gas production in the sealed cell increased to a high of 0.64 m^3/d (23 ft^3/d) with a CH_4 content of 57 percent, coinciding with the decrease in TVA concentration and increase in pH. Gas production decreased to 0.01 to 0.02 m^3/d (0.35 to 0.7 ft^3/d) by the end of the test period indicating that most of the readily available organics in the leachate were converted to gas within three months. Based on the differences in chloride concentrations between the two cells, moisture loss in the open cell due to evaporation was estimated between 20 to 30 percent of the incident rainfall.

This pilot-scale study supported the results of the previous laboratory-scale studies and demonstrated the advantages of leachate recirculation in rapid stabilization of readily available organic constituents accompanied with increased gas production rate in short time period.

Mountain View Landfill, California (Emcon, 1987; Pacey, et al,1987)
The objective of the pilot scale demonstration project conducted at Mountain View Landfill, California, was to study the effectiveness of the methods used to enhance methane gas generation. The key factors controlled and manipulated were moisture addition, buffer, inoculation, and leachate recirculation. However, as testified by refuse analysis, there was no effective control over moisture content due to excessive water infiltration into the test cells.

Six separate cells (designated A through F) were constructed for the study purpose. Each cell was approximately 31 m by 31 m (100 ft by 100 ft) and contained 14 m (47 ft) of waste. Cell F was the control cell and partial leachate recirculation was provided for Cell A. The other cells were not subjected to leachate recirculation. Composition of the cells at the beginning of the project (June, 1981) is shown in Table 4-3. The cell characteristics and monitoring results after 1597 days (through December, 1985) are presented in Table 4-4.

The results with respect to leachate recirculation were not in agreement with other studies. The total gas production rates were lower than the rates obtained in other lysimeter studies. Cell D, with no sludge addition, yielded the maximum amount of gas even though the moisture content (as compared

Table 4-3. Cell Composition After Construction, Mountain View (Pacey, et al, 1987)

Cell Component	Cell					
	A	B	C	D	E	F
Additions*	sbrw	sb	sbw	b(w)	s(w)	nõne
Dry Refuse Solids (million kg)	4.88	5.42	4.81	6.00	4.96	5.64
Refuse Associated Water (million kg)	1.63	1.81	1.60	2.00	1.65	1.88
Porosity (%)	50	49	50	49	51	48
Dry Sludge Solids (million kg)	0.16	0.13	0.07	0	0.06	0
Sludge Associated Water (million kg)	0.88	0.73	0.38	0	0.31	0
Sludge in Place (million kg)	1.03	0.86	0.44	0	0.37	0
Buffer (million kg)	0.010	0.010	0.009	0.010	0	0
Precipitation (million kg)	0.13	0.14	0.13	0.14	0.14	0.14
Total Dry Solids (million kg)#	5.05	5.56	4.89	6.01	5.02	5.64
Total Water (million kg)	4.34	1.95	3.81	2.38	2.34	2.02

*Additions: s= anaerobic digester sludge; b=buffer (calcium carbonate), approximately 9070 kg; w = water, 1700 m^3;(w) = water, 235-238 m^3; r=recirculation of leachate.

#Excluding Buffer which equaled approximately 9070 kg

to other cells) was low in the beginning and lowest at the end of the study period. Cell A (with partial leachate recirculation) had the highest moisture content at the end of the study period, yet produced less gas then Cell C (Cell C was identical to Cell A except without leachate recirculation). But leachate recirculation resulted in faster stabilization as indicated by volatile solids content, cellulose content, carbon-to-nitrogen ratios, and carbon-to-phosphorus ratios presented in Table 4-5.
There were discrepancies between measured and calculated gas production rates (based on loss of volatile acids). Except for Cell D, which had negligible infiltration, the measured gas production rates for all the other cells were less than calculated values. Cells A and B with highest water infiltration had lowest measured gas production rates. Calculated gas production values indicated that high moisture content (and possibly leachate recirculation) and the addition of sludge increased methane production. Inconsistencies in gas production data were attributed to gas leakage from test cells.

On the basis of refuse analysis from cells A, B, D and F, the following conclusions were made.

- Cells with higher moisture content, sludge addition, less settlement and lower internal temperatures had lower measured gàs production rates.

- The calculated average yearly methane gas production rates based on loss of volatile solids indicated that a higher moisture content, addition of sludge and leachate

Table 4-4. Cell Construction Characteristics and Monitoring Results (1597 Days), Mountain View (Pacey, et al, 1987)

Cell Component	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F
Additions#	sbrw	sb	sbw	b(w)	s(w)	none
Moisture Content at Construction (%)†	46	32	44	28	32	26
Moisture Content at Conclusion (%)	69	54	50	33	45	40
Specific Landfill Gas Yield (m^3/dry kg)	0.08	0.07	0.09	0.16	0.07	0.14
Specific Methane Yield (m^3/dry kg)	0.04	0.04	0.05	0.09	0.04	0.08
Conversion (% of ultimate)‡	19	17	22	40	16	33
Average Gas Production Rate (m^3 /dry kg)	0.02	0.02	0.02	0.04	0.02	0.03
Total Landfill Gas Produced (thousand m^3)	314	275	334	748	238	631
Average Cell Settlement (m)	2.0	2.2	2.3	1.3	2.3	1.9

#Additions: s= anaerobic digester sludge; b=buffer (calcium carbonate), approximately 9070 kg; w = water, 1700 m^3;(w) = water, 235-238 m^3; r=recirculation of leachate.

†After water addition.

‡Calculated ultimate yield = 0.23 m^3 methane/dry kg refuse.

Table 4-5. Refuse Chemical Analysis Summary, Mountain View (Pacey, et al, 1987)

	Cell* A	Cell* B	Cell* D	Cell* F
Sampling interval (m)	0-7.6	0-8.5	0-9.8	0-11.9
Moisture Content (%, wet weight basis)	68.6	54.1	33.3	40.0
Volatile Solids Content(%)	31.8	43.1	50.7	43.5
Cellulose (%)	16.3	25.6	32.8	26.6
Lignin(%)	13.4	14.0	13.6	14.2
Carbon to Nitrogen ratio	13:1	20:1	26:1	27:1
Carbon to Phosphorus ratio	6593:1	945:1	1345:1	1169:1

*Samples were not obtained from Cells C and E

Note: All parameters except moisture content measured on dry basis recirculation enhanced methane gas generation which is in contradiction to measured data. The contradiction was attributed to gas leaks and water infiltration.

- The relationship between moisture infiltration and measured gas production rates (i.e., cells with higher infiltration had lower measured gas production rates) suggests that the pathways of moisture infiltration and gas escape might have been the same.

Binghamton, New York (New York State Energy Research and Development Authority, 1987)
This study conducted for the New York State Energy Research and Development Authority (NYSERDA) was one of the first pilot-scale experiments to investigate the enhancement of landfill gas production by leachate recirculation. The objective of the study was to examine landfill gas production while varying the key parameters controlling anaerobic digestion, namely, moisture content, pH, temperature, and nutrients. Nutrients were controlled by varying the quantity of wastewater treatment plant sludge added to the waste. The pH was controlled by the addition of buffers.

Nine pilot-scale Polyvinyl Chloride (PVC)-lined landfill cells (designated Cell No. 1 through Cell No. 9), 6.4-m (21-ft) deep with 17 m (57 ft) by 23 m (75 ft) foot print, were set up at Nanticoke Landfill, Binghamton, New York. Each cell was equipped with leachate collection, leachate/moisture distribution, and gas collection and metering systems. The first cell was a control cell, the second cell received moisture only (no addition of sludge or buffer), and the third cell received moisture and buffer (lime). The fourth cell received anaerobically digested sludge but no buffer or water. The remaining three cells received both sludge and buffer in varying amounts. Each cell was an encapsulated system separated from other cells. Although nine cells were constructed, only seven were operated. (Cell No. 7 and Cell No. 8 were not operated). The cells were monitored for a period of two years.

Based on gas monitoring data, it was clear that the cells with sewage sludge yielded significantly higher quantities of gas than the cells without sewage sludge. Also, the methane content was higher in the cells with sludge than the cells without sludge. Table 4-6 present data on cell composition; Table 4-7 provides leachate quality data and gas production.

Leachate quality in high gas yielding cells (Cells 4, 5, and 6) was better (lower in strength with respect to COD, TVA and alkalinity) than the low gas yielding cells (Cells 1, 2, 3 and 9). The temperatures remained fairly constant throughout the monitoring period, averaging 10°C in all the cases. Test Cells 2 and 3 with no sludge maintained acidic conditions. Buffer addition was concluded to be ineffective in controlling pH due to short circuiting of leachate.

From the study, it was concluded that addition of sewage sludge (at a rate of 0.45 kg per 115 to 160 kg of municipal solid waste) and leachate recirculation resulted in improved gas production, gas quality, and leachate quality. However, the study also encountered several problems during

Table 4-6. Cell Composition Data, Binghamton, New York (NYSERDA, 1987)

Parameter	Test Cell						
	1	2	3	4	5	6	9
Refuse (Mg)	8.7	7.4	6.98	6.12	6.48	7.89	7.85
Sludge (m^3)	00	0	0	114	91	91	23
Water (m^3)	0	114	114	0	0	0	0
Lime Buffer (kg)	0	0	6800	0	6800	6800	6800
Condition	Control	Leachate Recycle	Leachate Recycle	Leachate Recycle	Leachate Recycle	Leachate Recycle	Leachate Recycle

Table 4-7. Leachate Quality Data from Day 350 to Day 600, Binghamton, New York (NYSERDA, 1987)

Parameter	Test Cell						
	1	2	3	4	5	6	9
TS (%)	0.16	0.54	0.44	0.11	0.10	0.23	0.05
TVS (% of TS)	7.5	48.2	41.2	32.5	33.1	36.6	29.8
COD (mg/l)	780	1,980	1,670	180	200	80	500
TVA (mg/l)	1,120	4,310	4,310	200	270	380	160
Alk(mg/l as $CaCO_3$)	130	1,460	1,750	825	650	2,130	225
pH	6.3	5.9	6.3	6.6	6.6	6.6	6.6
Avg. Gas production (m^3/d)	0.63	0.27	0.21	4.96	5.89	4.96	0.59
Avg. % CH_4	43.4	12.8	33.3	58.9	58.4	56.0	41.1
Normalized gas production (m^3/d/kg MSW x 10^{-6})	0.318	0.046	0.10	4.81	5.31	3.50	0.312
SC (mhos/cm)	660	2,930	2,160	1,510	1,850	2,890	490

TS=Total solids TVA=Total Volatile Acids
TVS=Total Volatile Solids Alk=Alkalinity
COD=Chemical Oxygen Demand SC=Specific Conductance

its operation, including an inability to accurately measure gas quantities and distribute the recirculated leachate throughout the cells, water traps in gas lines due to settlement, and problems due to freezing of pipelines.

Breitenau Landfill, Austria (Lechner, et al, 1993)
The Water Quality Institute of Vienna University of Technology and Waste Management Institute of Geology jointly conducted a pilot-scale research study on the reactor landfill starting in 1986. Three test cells, 17 m (5.2 ft) deep with 2929 m^2 (272 ft^2), 3798 m^2 (353 ft^2), and 4622 m^2 (429 ft^2) foot prints were constructed at the Breitenau Research Landfill, Austria and completely filled with 35 million kg (39,000 tons), 25.6 million kg (28,000 tons), and 33.2 million kg (37,000 tons) of MSW, respectively. The cells were controlled and operated with special attention to moisture content, waste homogeneity, and leachate recirculation such that the landfill cells served as bioreactors. Test Cell 1 served as a control, Test Cell 2 received leachate recirculation, and Test Cell 3 was filled with shredded refuse and received leachate recirculation.

It was observed that within a year of completion of the cells, both liquid and gaseous emissions from the cells dropped drastically. The degradation process in the landfill was observed to have followed the characteristic phases of a typical anaerobic reactor, namely, hydrolysis, acidification, methane formation, and maturation. Table 4-8 presents the average yearly leachate quality data for Test Cell 2 from 1988 to 1991 which shows a steady decrease in leachate strength. The period of decreasing leachate strength coincided with the period of steady gas production.

From the study it was concluded that under suitable operating conditions, the anaerobic degradation process could be accelerated with significant reduction in methane fermentation time. Some of the shortcomings of bioreactor operation observed were: production and escape of gas prior to completion of landfill, leachate ponding, and leachate toxicity due to high ammonium content.

Brogborough, United Kingdom (Campbell, 1991)
The purpose of the Brogborough Test Cell Project was to assess the various field techniques for enhancing landfill gas production. Six test cells were constructed (approximately 40 m (12 ft) by 25 m (7.6 ft)) adjacent to each other and separated by thick clay walls. Each cell was 20 m (6 ft) deep and filled with 15 to 20,000 metric tons (16 to 22 tons) of waste. Wastes were placed in lifts of 2 m (6.5 ft). Variables investigated were waste density and placement, waste composition, sewage sludge, leachate recirculation, and waste temperature in Cells 2 through 6, respectively. Cell 1 was the control cell. These variables were chosen for investigation because of their proven benefits and potential for incorporation into full-scale landfill sites. Cell configuration is summarized below:

- Cell 1 - control, thin layer construction (waste placed in thin layers up to 2 m (6.5 ft)
- Cell 2 - thick waste placement

Table 4-8. Leachate Quality Data for Test Cell 2, Breitenau, Austria (Lechner, et al, 1993)

Month/ Year	COD (mg/l)	BOD_5 (mg/l)	N (org) (mg/l)	NH_3-N (mg/l)	P (total) (mg/l)	Calcium (mg/l)	pH
Nov. 1987	8200	-	200	125	2.0	1200	6.6
Mar. 1988	27000	16500	720	600	3.2	2300	6.2
Nov. 1988	4300	930	1900	1600	6.4	35	8.3
Mar. 1989	3800	770	2100	1850	9.2	30	7.9
Nov. 1989	2200	130	1300	1150	3.6	33	8.1
Mar. 1990	2650	190	1650	1550	7.2	20	7.7
Nov. 1990	1000	70	630	580	2.8	60	8.0
Mar. 1991	900	38	630	420	2.8	43	8.1
Nov. 1991	660	36	500	440	2.0	55	8.3
Feb. 1992	770	21	550	440	2.0	44	8.2

- Cell 3 - leachate recirculation
- Cell 4 - air injection for temperature control
- Cell 5 - sewage sludge addition

Results indicated that a significant quantity of gas was produced within two years of initial deposition of waste. A mixture of nonhazardous industrial and commercial waste with domestic waste appeared to promote more efficient degradation based on gas production. Settlement was found to significantly impact the integrity of the cap and gas recovery piping. Based on the monitoring data of the test cells, the following preliminary conclusions were made.

- Gas production rates were in close agreement with theoretical expectations of 5.5 to 11.0 m^3/ metric t/year (170 to 350 ft^3/ton/year).
- Sewage sludge increased gas yield and quality.
- Mixed wastes enhanced gas production.
- The leachate-recirculated cell degraded organic matter faster as indicated by a significant decrease in TOC compared to other cells.

SORAB Test Cells (Brundin, 1991)
A series of test cells, also known as Energy Loaves, were constructed on an annual basis from 1989 through 1991 at the Hagby Landfill Site in Taby, Stockholm, Sweden. The investigators used a natural digester-type reactor in order to optimize parameters controlling digestion, to minimize degradation time, evaluate gas extraction devices, investigate processing of residuals, and characterize residuals. The first Energy Loaf was 90 m (295 ft) long, 40 m (130 ft) wide, and 6 m (20 ft) high, and filled with 8200 metric tons (9000 tons) of crushed solid waste overlaid with 30 cm (1 ft) of peat for insulation. Leachate recirculation was practiced to maintain an optimum moisture content and heat the system to 35 to 40°C. Landfill gas-fueled boilers were used to heat the leachate. Gas production was reported to be an order of magnitude higher than typical. Problems were encountered with water filling vertical gas extraction wells. A later Energy Loaf employed horizontal gas collection and leachate distribution pipes.

Full-Scale Landfill Bioreactor Studies

Lycoming County, Pennsylvania (Natale and Anderson, 1985)
Lycoming County Landfill is located 15.3 km (9.5 miles) South of Williamsport, Pennsylvania and is operated by the Lycoming County Solid Waste Department. This 53-hectare (130-acre) landfill facility serves Lycoming and other neighboring counties for a total population of 325,000. The initial fill area for Fields I, II and III was 13 hectares (31 acres) and development of additional fields has occurred when needed. The landfill operations began in June 1978, and the site is projected to be active through 2013, based on current landfilling rates. The landfill consists of six fields numbered 1 through 6, all of them lined with PVC, the newer fields having thicker and improved liner systems. Leachate recirculation was investigated over a seven-year period.

Leachate Management Facilities
The original leachate management techniques included collection, storage, recirculation, and off-site hauling. The liner system (in addition to the site's natural features of a mantle of compacted glacial till and low permeability bed rock) consists of:

- a 30-cm (1-ft) thick sand layer containing underdrainage collection system,
- a PVC membrane liner (single 0.05-cm (20-mil) liner for Fields 1, 2 and 3; 0.076-cm (30-mil) liner for field 4 and 0.076- and 0.13-cm (30- and 50-mil) liners for field 5),
- a 15-cm (0.5-ft) sand layer containing leachate collection system piping network,
- a 30-cm (1-ft) clay layer.

The leachate collection system consists of a series of 15-cm and 20-cm (6-in and 8-in) diameter perforated collection pipes placed in the sand layer on top of the PVC liner. The leachate collection system transports the leachate to the equalization lagoon. The PVC-lined leachate equalization lagoon with a permitted capacity of 4500 m^3 (160,000 ft^3) is equipped with floating aerators to keep the solids in suspension, prevent excessive odors, and provide aeration. The lagoon, from which the leachate is recirculated, also had a freeboard to handle leachate in case of emergency. Gas vents, consisting of 15-cm (6-in) diameter PVC piping in gravel-packed 1.2-m (4-ft) diameter concrete cylinders, are also provided.

Leachate Recirculation Techniques

Various techniques of leachate recirculation were tried to achieve effective distribution of leachate. Originally, it was planned to spray leachate on the operating face and other areas using spray headers. Spraying on the working face using a spray nozzle was also tried which allowed for flexibility in operation but was labor intensive and cumbersome. Spraying also caused odor problems to landfill operators and equipment. The next technique tried was to excavate small pits in the waste and fill them with leachate using a spray header. Due to the shallow depth of the landfill, the waste had limited absorption capacity and the technique was abandoned.

To increase recirculation volumes, another technique was tried incorporating trenches. Trenches were excavated on the completed sections of the landfill and filled with leachate. The absorption capacity of the trenches varied and resulted in leachate outbreaks in some parts of the landfill. Leachate outbreaks continued to occur and coincided with periods of peak infiltration and recirculation. The trench method was modified by filling the trench with auto-shredding derived waste or baled fiberglass wastes. These materials acted as wicks and transferred leachate to a larger area of the refuse thereby increasing the allowable recirculation volumes and permitting longer use of trenches. A combination of these techniques was also used. Bale-filled areas were connected to a auto waste-filled trench. An injection well was also installed in the bale-filled area using perforated concrete well rings. However, the impact of auto-shredding waste and fiberglass waste on leachate quality was not known.

Leachate Quantities

It was anticipated that due to absorption of moisture by the new waste, leachate generation would not occur until 16 to 22 years after the start of landfilling operations. However, leachate began to flow into the storage lagoon less than seven months after waste disposal began. Several factors were thought to account for the early arrival of leachate including lower waste volumes (less than design) leading to less leachate absorption, leachate channeling (resulting in inefficient absorption) and a large open area collecting precipitation. Also, the climate is humid with annual average precipitation exceeding evaporation.

Within three years of landfill opening (1978), the leachate level in the equalization lagoon rose above its permitted level twice. The situations were handled by increasing recirculation quantities. Off-site hauling was started in 1982 after it was clear that leachate management by recirculation alone was not possible using the existing leachate lagoon. The lagoon also collected a significant quantity of precipitation, approximately 20,100 m^3 per year (5.3 MG/year) between January 1980 and December 1982. Consulting engineers for the facility made recommendations for the effective management of leachate which included construction of a second storage lagoon and negotiation for leachate disposal contracts with a local wastewater treatment facility.

The data on leachate quantity were from different sources including daily logs, monthly reports, planning documents, summary sheets and reports from the National Oceanic and Atmospheric (NOAA) weather station at Williamsport. The leachate quantity data included precipitation data, leachate flow measurements, lagoon level records, leachate recirculation pump records, and leachate hauling and treatment records. Although the reliability and accuracy of each source of data varies considerably, the data yield valuable information on the leachate quantities involved. The volumes of recirculation based on four sources (daily logs, monthly reports, summary sheets, and planning documents) and different pumping capacity factors were sometimes conflicting. The average recirculation rate was 24 m^3/hr (100 gpm) based on the engineer's report and 27 m^3/hr (120 gpm) based on summary sheets for the period November 1979 through April 1981. The total quantity of leachate recirculated was around 24,600 m^3 (6.5 MG) between November 1979 and January 1981. Over the first three years, over 49,200 m^3 (13 MG) of leachate were recirculated. Recirculation rates approaching 3800 m^3 (1 MG) per month and 19,000 m^3 (5 MG) per year were recorded at the landfill. The average monthly volume of leachate hauled off-site was about 760 m^3 (200,000 gal) for the period of March 1982 to June 1985.

The leachate generation quantities were estimated using a water balance method and compared with quantities derived from the lagoon balance for Field 1 for the year 1982. The water balance method estimate of 7300 m^3 (2 MG) compared well with 6800 m^3 (1.8 MG) derived from a lagoon balance and 8400 m^3 (2.2 MG) of measured inflow into the lagoon.

It was estimated that the moisture storage capacity of the solid waste was not fully utilized and was verified by excavations which revealed dry cells which were previously considered to be at field capacity. The estimated breakdown of a water budget as of December 31, 1984 is provided in Table 4-9.

Thus, excess or unutilized moisture storage capacity was 7,600 to 45,000 m^3 (2 to 12 MG). The quantity of moisture storage capacity rendered unavailable due to clayey daily cover and cell configuration being impossible to estimate, the net available moisture storage capacity was estimated to be between zero and 38,000 m^3 (0 to 10 MG) as of December 31, 1984.

Leachate Quality

Samples of leachate were collected quarterly (beginning six months after landfilling commenced) and analyzed for approximately 20 parameters; 45 parameters were analyzed annually. Composite samples were taken from the lagoon through December 1979 following which grab samples were collected, typically from near the end of the leachate discharge pipe, representing raw leachate quality.

Table 4-9. Water Budget Lycoming County (Natale and Anderson, 1985)

Moisture Source	Volume, m^3
Percolation (1978-1984)	+121,100
Sludge water (1978 - 1984	+49,200
Off-site hauling (1984 - 1984)	-26,500
Net utilized moisture storage capacity	143,800
Solid waste moisture storage capacity	151,400 to 189,300

Like all leachate, the quality was highly variable, generally falling within the range reported in literature sources. The values of specific conductance, volatile acids, and manganese exceeded the upper limit of the typical ranges. The occurrence of manganese in the site soil is responsible for the high manganese content. The values of total solids, calcium, chloride and phosphate were below the lower limit of typical minimum values. The ratios of COD/TOC and BOD/COD, indicative of the age of leachate, placed the leachate in an early stage (less than five years) of landfilling when compared to typical ratios. The values of some of the key raw leachate parameters are shown in Table 4-10.

The samples were collected from each tanker whenever leachate was hauled for treatment offsite, representing leachate effluent quality. The lagoon effluent quality was less variable than raw leachate due to equalization, sedimentation, biological treatment, aeration, and dilution (due to precipitation). The lagoon effluent quality between March 1982 and January 1985 is summarized in the Table 4-11.

Gas Production

Based on the analyses of borings, samples, and mathematical modeling performed in 1983, it was concluded that:

- Field 1 was producing methane gas at a rate of 9910 m^3 (350,000 ft^3) CH_4/day (as of 1983), twice as much as a landfill without leachate recirculation.

- Significant gas production began in Field 1 in 1981 coincident with a sharp decline in COD and TVA and steep increase in pH.

- As of 1983, over 40 percent of methane generation capacity was exhausted in Field 1.

- Field 2 was producing methane at a rate of 10,200 m^3 (360,000 ft^3) CH_4/day (as of 1983) and was projected to increase to 22,400 m^3 (790,000 ft^3) CH_4/day in five years.

Table 4-10. Leachate Parameter Values, Lycoming County (Natale and Anderson, 1985)*

Parameter	No. of tests	Min. (1978-1985)	Max. (1978-1985)	Avg. (1978-1985)	Avg. (1981-1985)	Range
pH	27	5.8	8.6	7.0	7.2	4.7-8.8
Alkalinity	27	404	8,300	3,100	2,400	140-9,650
BOD_5	26	681	28,000	7,300	5,00	4-57,700
COD	27	475	29,947	10,000	7,300	31-71,700
TOC	19	350	8,500	3,200	2,500	0-18,800
Total solids	27	1298	23,210	9,300	7,100	1,460-55,300
Volatile Acids	19	223	30,730	6,600	4,000	70-27,700
Total Nitrogen	10	100.3	478.5	230	140	7-1,970
Total Phosphorus	10	0.03	7.2	1.0	0.46	0.2-120
Iron	27	19.5	1,095	280	230	4-2,200
Chloride	27	13	1,854	880	710	30-5,000

*All units in mg/l except for pH

Table 4-11. Lagoon Effluent Quality Lycoming County (Natale and Anderson, 1985)*

Parameter	No. of Tests	Min.	Max.	Avg.
pH	53	6.74	8.51	7.8
Alkalinity	2	1,020	1,054	1,037
BOD_5	54	608	4,066	2,000
COD	53	1,400	5,000	3,100
Total Solids	3	3,138	4,019	3,700
Total Nitrogen	4	112.1	164.4	130
Total Phosphates	7	BDL	2	1
Iron	31	19.08	161.5	56

*all units are in mg/l except for pH
BDL - below detection limit

Settlement

There was no measurable settlement at the landfill. The excavations and backfilling activities, relatively shallow depth of the landfill (less than 21 m (69 ft) at the deepest point), large amount of daily cover (limiting the settlement), stockpiling of cover materials, and absence of settlement plates may have obscured settlement detection. Settlement would extend the life of the landfill because the final site development is limited by elevation and not by volume or quantity. Thus, settlement allows additional waste to be placed on completed areas.

Conclusions

Based on the performance evaluation for the Lycoming County Landfill, the following conclusions were made.

- Waste degradation and methane generation were improved as a result of leachate recirculation.
- Quality of leachate stabilized more rapidly than landfills without leachate recirculation.
- Stabilization rates close to pilot-scale studies (with low recirculation rates and minimum daily cover) can be achieved.
- Clayey cover soil, high recirculation rates, and certain industrial residuals may inhibit the vertical flow of leachate resulting in incomplete use of moisture storage capacity as well as ponding within the landfill.
- The operational practices and design features for recirculation were adequate but their effectiveness could be improved.
- The major potential adverse impact of leachate recirculation involved leachate pollutant releases through irrigation drift and stormwater runoff.
- The leachate recirculation methods used were labor intensive and cumbersome although effective (injection well method being the most effective).
- Because of an inability to isolate storm water collecting on unutilized areas of the landfill from the leachate collection system, these areas generated significant quantities of leachate.
- Aerated leachate storage lagoons provided effective pretreatment of raw leachate.
- Leachate should be recirculated sufficiently to utilize moisture storage capacity rather than saturating the landfill which can lead to leachate outbreaks.

Seamer Car Landfill, United Kingdom (Barber and Maris, 1984)
The potential benefits of leachate recirculation including reduction of leachate volume (due to evaporation), reduction of leachate strength, rapid stabilization of wastes and enhanced gas production were confirmed by lysimeter and pilot scale studies reported by Barber and Maris (1984). The Seamer Car landfill investigation, initiated in 1979, was intended to determine the practicalities of leachate recirculation at full-scale landfill sites. The 2-ha site (5-acre), lined with a 0.3-cm (118-mil) HDPE, was filled with pulverized domestic waste placed at a density of 800 to 990 kg/m^3 (1350 to 1680 lb/yd^3). An area of one hectare (2.5 acres) was subjected to leachate recirculation by spraying, while the remaining one hectare served as the control area. Measured volumes of leachate were recirculated beginning in August 1980. Approximately 300 m^3 (79,000 gal) of leachate were recirculated for five months in 1980, 3780 m^3 (1 MG) and 11,400 m^3 3 MG) in 1981 and 1982, respectively, were recirculated.

Surface furrowing was found to reduce runoff and ponding problems in addition to increasing the infiltration rate significantly. The low permeability intermediate cover caused zones of saturation and lateral movement of leachate. Perched water table had developed within the recirculation area as determined by borehole investigations. All leachate was managed on-site over a three-year period, however landfill saturation eventually made off-site disposal necessary. The following conclusions were made from the investigations.

- Although longer times were required than laboratory-scale studies indicated, laboratory-scale benefits could be obtained at full-scale landfills.
- Regular surface furrowing alleviated surface ponding problems.
- Intermediate cover resulted in perched water table and lateral seepage of leachate.
- Rapid reduction in leachate organic strength was achieved by increasing the waste moisture content.
- Residual COD, ammonia, and chloride concentration in leachate suggest that further treatment/dilution would be necessary prior to final disposal.

Delaware Solid Waste Authority (Watson, 1993)
The Delaware Solid Waste Authority (DSWA) operates three landfills in New Castle, Kent, and Sussex counties in Delaware. The Central Solid Waste Management Center (CSWMC) in Sandtown, Kent County, Delaware began operations in October 1980 and has five sections, designated Areas A through E (Area E is actually two 0.4-hectare (1-acre) test cells). All of the cells are lined and equipped with leachate collection and recirculation facilities (except one of the test cells which does not have recirculation capabilities).

Leachate recirculation is applied to all the cells (excluding on of the test cells) and has been identified as one of the means (the other being landfill reclamation) of achieving the Authority's objective of maximizing the reduction, reuse, recycling, and resource recovery of solid waste and minimizing landfilling. The Authority refers to the term "Active Landfill Management" to include the basic features of leachate recirculation and landfill reclamation.

At CSWMC, leachate recirculation has been accomplished by various methods including vertical recharge wells, spray irrigation systems, and surface application. Recirculation by recharge wells was found to be simplest and most affective. The recharge rate for the wells ranged from 76 to 760 l/min (20 to 200 gpm). Spray irrigation, the second preferred option, was accomplished using traveling spray irrigators with a capacity of 380 l/min (100 gpm), 30-m (100-ft) spray radius, and maximum travel distance of 210 m (680 ft). Evaporation rates of over 30 percent were measured at CSWMC.

The total quantities of leachate generated and recirculated annually at CSWMC are shown in Table 4-12. The fill has been constructed in three stages in Areas A, B, and C with areas of 3.6, 7.3, and 8.1 hectares (8.8, 18, and 20 acres), respectively. At closure, trenches equipped with infiltrators are installed under the cap. The newest 8.9-ha (22-acre) cell (Area D) is double-lined including a 0.15-

Table 4-12. Total Quantities of Leachate Generated and Recirculated Annually, Delaware Solid Waste Authority (Watson, 1993)*

Year	Generated, m^3	Recirculated, m^3	Treated, m^3
1981	0	0	0
1982	2080	0	0
1983	8540	114	7600
1984	8540	117	7600
1985	5200	132	0
1986	7410	16300	0
1987	10600	10600	0
1988	12800	12800	0
1989	24200	19000	5200
1990	26800	13300	13500
1991	29500	13500	16000
1992	24600	8200	16400

cm (60-mil) geosynthetic/clay composite and 0.15-cm (60-mil) HDPE liner. Leachate recirculation will be accomplished using vertical wells followed by trenches at closure. In Areas A and B, the quantity of leachate generated declined as the quantity of leachate recirculated decreased. However, the quantity of leachate treated off-site was substantial. In the case of Area C, a large portion of leachate generated was recirculated resulting in a decrease in the quantity of leachate treated off-site.

Table 4-13 shows leachate quality data for Area B over a period of ten years. Rapid decline in the organic strength of leachate, enhanced by leachate recirculation, was observed after closure in late 1988. Areas A, B, and C generated gas early during the operating period and the composition was observed to be 55 percent methane and 45 percent carbon dioxide. Unfortunately, no gas generation rates are available.

Table 4-13. Leachate Quality Data for Area B, DSWA (Watson, 1993)*

	Sep. 1983	Mar. 1984	Jan. 1985	Jan. 1986	Jan. 1987	Jan. 1988	Jan. 1989	Jan. 1990	Jan. 1991	Jan. 1992	Jan. 1992
pH	5.39	7.00	5.7	5.74	5.75	6.15	6.75	6.80	7.16	7.16	7.39
COD	20,000	120	29,893	30,000	34,556	28,300	15,500	5,620	1,775	1,800	1,000
BOD	1,773	76	17,300	20,250	25,750	20,500	12,591	1,144	352	540	50
TOC	6,170	25	NA	10,000	10,000	1,900	4,950	1,178	238	540	290
TDS	NA	NA	14,800	18,600	15,999	14,713	6,558	7,726	6,497	5,100	4,900
TSS	39	19	965	137	NA	NA	1,558	502	413	170	50
Chloride	NA	NA	1,440	NA	1,500	1,683	925	1,450	650	1,100	1,200
Iron	NA	NA	972	1,050	672	1,005	596	116	104	70	12
AA#	NA	NA	203	NA	6,200	4,570	4,030	1,370	390	210	NA

*All quantities in mg/l except pH.
#Acetic acid
NA - data not available

The capital cost of leachate recirculation systems (for pumping stations and piping network) constructed by DSWA ranged from $10,000 to $200,000 (1993 dollars) which is significantly less than the cost of a leachate treatment plant, presently being considered by DSWA, and estimated between $1,000,000 and $6,000,000. The Authority found leachate recirculation to be the most economical way of handling leachate apart from the benefits of accelerated biodegradation and reduced long-term risks to the environment.

Based on the performance evaluation of leachate recirculating landfills, the Delaware Solid Waste Authority has successfully demonstrated that leachate recirculation results in many benefits including:

- inexpensive leachate treatment,

- accelerated biodegradation of organic portion of the waste,
- reduced long-term risk to the environment, and
- increased production of landfill gas.

German Experiences (Doedens and Cord-Landwehr, 1989)
In the former Federal Republic of Germany (now unified Germany), thirteen landfills were practicing leachate recirculation in 1981 using spray irrigation, spray tankers, and horizontal distribution pipes. These sites varied in size from two to 12 hectares (5 to 30 acres). For those landfills using spray irrigation, an average of 0.5 m^3/ha/d (50 gal/acre/d) of excess leachate were produced; 2 m^3/ha/d (200 gal/acre/d) were produced from those sites using surface percolation, and 4 to 5 m^3/ha/d (400 to 500 gal/acre/d) were produced from conventional landfills without leachate recirculation. Large storage volumes (1500 to 2000 m^3/ha (160,000 to 210,000 gal/acre)) were recommended.

It was observed that landfills practicing leachate recirculation since the commencement of landfill operations demonstrated a faster reduction of BOD and COD than landfills beginning leachate recirculation several years after the commencement of landfilling operation. Also, all of the landfills practicing leachate recirculation had a BOD of 1000 mg/L or less and a COD of 10,000 mg/L or less, four years after the start of landfilling operations. No increase in the concentrations of salts or heavy metals attributable to leachate recirculation was observed. Landfills where waste was placed in thin-layers (1.8-m (6-ft) thickness) were observed to have very low strength leachate.

Bornhausen Landfill, Germany (Doedens and Cord-Landwehr, 1989)
Stegman and Spendling (1989) suggested that a combination of thin layer waste placement and leachate recirculation resulted in faster waste degradation and consequently faster reduction in BOD and COD concentrations in the leachate. Waste is placed in thin layers of up to 2 m (6 ft) and loosely compacted as opposed to rapid vertical filling. Thin layers promotes natural ventilation and aerobic decomposition. Penetration of oxygen into the landfill (up to 0.9 m (3 ft) depending on the density of the waste) was documented. Experiments were conducted at the Bornhausen landfill, Germany, to study the thin layer process suggested by Stegman and Spendling.

Three test sites were set up with leachate recirculation. Approximately 600 m^3 (21,000 ft^3) waste were placed in 4-m (13-ft) layers during a period of six months. The following results were obtained.

- No increase in leachate concentration was observed after leachate recirculation was started. After 350 to 450 days, COD was less than 4000 mg/L and BOD was less than 1000 mg/L for all the test sites.
- The "thin layer" operation coupled with natural ventilation up through the drainage layer proved to be more effective than leachate recirculation.

Two other sites of approximately 0.5 hectares (1.2 acres) each at the Bornhausen landfill were constructed in 2.0-m (6.5-ft) layers, one with and the other without leachate recirculation. The time required for stabilization with leachate recirculation (230 days) was half of the site without leachate recirculation (460 days).

Another significant application of leachate recirculation at the Bornhausen landfill involved the introduction of highly concentrated leachate from new landfill cells over older cells in which a stabilized leachate was already being produced. Table 4-14 presents data which demonstrate the removal of BOD and COD by two-stage leachate recirculation (leachate from the new cell recirculated over an old cell). COD and BOD reduction from 90 to 99 percent was achieved, presumably through treatment as the leachate passed through the stabilized waste.

Table 4-14. BOD AND COD Removal by Two-Stage Leachate Recirculation, Bornhausen Landfill (Doedens and Cord-Landwehr, 1989)

Month/Year	COD (mg/l)		BOD (mg/1)	
	New	Old	New	Old
Feb, 1982	-	1473	-	60
Mar, 1982	5303	1278	1310	64
April, 1982	10390	1370	5320	59
Aug, 1982	19308	1273	11970	60
Dec, 1982	4898	1083	1807	82
Feb, 1983	19385	1350	19650	61
May, 1983	19675	1604	9200	173
July, 1983	10780	1364	6387	91
Sept, 1983	10615	927	8750	96
Nov, 1983	21720	1271	12450	39
Dec, 1983	21470	1226	14450	37
Jan, 1984	16425	1725	6450	75

Summary

The studies described in this chapter conclusively demonstrated the advantages of operating the landfill as a bioreactor and provided information necessary to design, construct, and operate the next generation of landfills, some of which are described in Chapter 5. Leachate and gas data from these studies are summarized and analyzed in Chapter 6. Furthermore, information derived from these and other studies provides the basis for design and operating recommendations made in Chapters 7 and 8. For convenience, major project descriptors and conclusions are provided in Table 4-15.

Table 4-15. Summary of Bioreactor Investigations

Location	Dimensions	Enhancement Techniques	Conclusions	Reference
Ga. Institute of Technology	4 columns: 0.9 m diameter, 3 m waste depth	recirculation, pH control, sludge addition	- recirculation with pH control produced low organic strength leachate faster - sludge had no effect	Pohland, 1975
Univ. Louisville	4 columns: 0.9 m diameter, 2.4 m waste depth	recirculation, shredding, pH control, nutrient addition	- recirculation with pH control produced low organic strength leachate faster - shredding and nutrient addition no effect	Tittlebaum, 1982
German Experiment	4 columns: 1.5 m diameter, 1.35 m waste depth	recirculation, initial saturation, vary water input rate	-recirculation reduced the emission of inorganic and organic pollutants -no increase in gas production or quality from enhancement	Doedens and Cord-Landwehr, 1989
Newcastle Univ.	4 lysimeters: 0.5 m diameter	recirculation, shredding, saturation vs. free draining, waste density	- shredding increased rate of degradation - saturation of no benefit - lower density increased rate of waste degradation	Otieno, 1989
Ga. Institute of Technology	10 columns: 0.9-m diameter, 3 m waste depth	recirculation, addition of priority pollutants	-recirculation increased gas volume and rate, decreased leachate organic strength - recirculation promoted attenuation of inorganic and organic pollutants	Pohland, et al, 1992

Table 4-15. Continued.

Location	Dimensions	Enhancement Techniques	Conclusions	Reference
Sonoma County	5 cells: 15mx15mx3m	recirculation, high initial water content, continuous throughput of water, septic tank pumpings addition	- recirculation increased rate of microbial community establishment - recirculation provided in situ leachate treatment	Leckie, et al, 1979
Ga. Institute of Technology	2 cells: 3mx3mx4.3m	recirculation, sealing of cell	-sealed recirculation more conducive to methanogenic conditions than open air cell	Pohland, 1980
Mountain View, Ca.	6 cells: ≈ 10,000 m^2, 14 m deep	recirculation, water addition, buffer, sludge addition	-inconclusive regarding recirculation effects due to gas loss -refuse analyses suggest water addition accelerates degradation	Pacey, 1987
Binghamton, NY	9 cells: 17mx23mx6.4m	recirculation, sludge addition	-recirculation and sludge addition improved gas and leachate quality	NYSERDA, 1987
Breitenau Landfill, Austria	3 cells: 3000 - 4600 m^2, 17 m deep	recirculation, shredding, sludge addition	- anaerobic digestion can be accelerated by enhancements - concerns with ponding and increase in ammonia concentrations	Lechner, et al, 1993
Brogborough, UK	6 cells: 40mx25mx20m	thin layer construction, air injection, mixed waste, sewage sludge addition	-large volumes of gas from cells with sludge and air addition -liquid addition may increase gas production	Campbell, 1991
SORAB Test Cells, Sweden	3 Energy Loaves: 95mx35mx5.5m	leachate heating, recirculation, shredding,	-gas volume order of magnitude greater than ordinary landfills	Brundin, 1991

Table 4-15. Continued.

Location	Dimensions	Enhancement Techniques	Conclusions	Reference
Lycoming, PA	52.6 ha, depth - max 21 m	recirculation: - spray - trenches - injection wells	- recirculation increases rate of waste degradation and methane generation - ponding and saturation lead to leachate outbreaks - injection wells most efficient	Natale and Anderson, 1985
Seamer Car Landfill	2 cells, 1 ha each 4 m deep	recirculation: spray irrigation	- Accelerated decline in leachate organic strength - clayey intermediate cover caused ponding - surface furrowing required	Barber and Maris, 1984
Delaware Solid Waste Authority	5 areas - 3.6 to 8.9 ha	recirculation: - spray - recharge wells - horizontal infiltrators	- recirculation accelerates the biodegradation of wastes - recirculation improved the quality of gas and leachate at low capital cost	Watson, 1993
Bornhauser Landfill, Germany	3 cells: 50 m^2 x 4 m deep 2 cells: 0.6 ha, 2 m deep	recirculation, thin layer compaction	- recirculation cut stabilization time in half	Doedens and Cord-Landwehr, 1989