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LANDFILL LEACHATE RECIRCULATION METHODS—EFFECTS ON LEACHATE FLOW PATTERNS AND DEGRADATION

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ABSTRACT

Leachate recirculation increases moisture content and flow and thereby increases biodegradation of solid organic materials and of the leachate. Channeling, the rapid confined flow through narrow pores, leads to rapid discharges and creates large dry pockets in landfills. An automated moisture flow measurement system was installed to compare leachate flow patterns and leachate COD degradation in four cells. In two cells leachate was recirculated in pulses of 128 L every two weeks. The same volume was recirculated continually in the other two. The flow patterns evolved quickly and stayed in the same locations throughout the eighteen-month test period. Continual recirculation cells did not exhibit higher average flows, but the variation of flows was much lower than in pulse-recirculation cells. Continually recirculated leachate produced more consistent flows throughout the cross-section of the waste. No difference in the COD degradation rates was demonstrated, possibly because of dilution effects of make-up water. Neither recirculation method prevented channeling. New approaches to moisture content measurement and to leachate recirculation must be developed to achieve higher and more consistent moisture contents and flows in heterogeneous waste layers.

INTRODUCTION

Landfill leachate recirculation enhances the moisture content and flow and thereby increases the biodegradation rates of solid organic materials in solid waste, BOD/COD in leachate, and gas production rates. Channeling, the confined flow of leachate through the large macropores, however, leads to rapid discharge of moisture between large waste particles and, therefore, limits the achievable moisture content and flow rates in the dry pockets in the waste layers. As a result, waste materials degrade slowly, generate little gas, and reduce leachate BOD and COD slowly. Conventional leachate recirculation with horizontal piles (or trenches or vertical wells) do not overcome the channeling effects. However, slow, continual recirculation appears to redistribute moisture into the small pores along the flow channels and generate a more consistent moisture content than do rapid pulse recirculation regimes. Two objectives were set for this study of two alternative leachate recirculation regimes: 1) To compare the effects of pulse and continual recirculation on the flow patterns in municipal solid waste materials over a full anaerobic degradation cycle, and 2) To determine the effects of the two recirculation methods on the resulting degradation rates of leachate COD. This study applied a new moisture flow instrument to measure flow on a one by one meter grid at two levels in pilot leachate recirculation cells.

CHANNELED FLOW THEORY AND EXPERIMENTAL RESULTS

Channeling, the rapid flow of moisture or gas through small fractions of the cross-section, has been mentioned and observed in municipal solid waste (MSW) layers and other solid porous media (soils, filter beds) by several researchers [1, 2]. Experimental results have confirmed the presence and the effects of channeling on the flow regime and the leachate generation patterns in MSW layers [3-5]. Recent studies [4, 5] (for short-term tests lasting a few hours to a few days, 6, for 3-month experiments) have generated values for means and standard deviations of key parameters: the fraction of cross-sectional area where channeled flow occurs, the practical field capacity FC_p, the breakthrough time t_{bt}, and the moisture storage at steady-state flow, the effective storage ES. Table 1 compares the experimental results with the visual values currently used or assumed for predicting leachate generation.

Notable discrepancies between one dimensional Darcian flow theory and the experimental findings are evident in the low fraction of cross-section with active flow A_{af} of 25 to 50 percent for channeled flow. The practical field capacity FC_p is, at 0.1 to 0.14, significantly and consistently lower than the HELP default value of 0.292. The lower measured values indicate that less moisture than assumed is stored in the channels before discharge begins. Measured breakthrough times t_{bt} (under channeling) are substantially lower, at fifteen minutes to maximum 1.5 days, than those predicted by using default hydraulic conductivity values (waste K sat of 1.0×10^{-3} cm/s) at twenty-five to thirty days. Finally, the effective storage ES, the moisture content at steady state flow, was found to average 0.19 over eight cells (vs. the HELP default storage value of 0.292). High rate infiltration was found to produce lower effective storage ($ES_{fast} = 0.15$) than slow filtration with a mean ES_{slow} of 0.22.

Table 1. Comparison of Default Values and Experimental Flow Parameters

Flow Parameters	Default Model Values	Experimental Results
Active flow cross-sectional area A_{af}	100%	25-50%
Field Capacity FC_p	0.292	0.1-0.14
Breakthrough time t_{bt} (for 1.5 m layer)	3.8 years	15 min to 9.3 hs
Hydraulic conductivity at breakthrough $K_{us\text{-}init}$	1.26 10^{-6} cm/s	1.0 10^{-2} cm/s
Hydraulic conductivity at steady state $K_{us\text{-}ult}$	1.26 10^{-6} cm/s	2.0-4.4 * 10^{-6} cm/s

In summary, these results from short to moderate duration tests (lasting from several hours to 3 months) show consistent and significantly different parameter values than those commonly used for leachate prediction. There remain, however, several important questions that the experiments reported in this article are intended to test: 1) Does gradual infiltration lead to better flow distribution?, 2) Do the flow channels shift locations over the duration of the full cycle of anaerobic degradation in sold waste layers?, and 3) Does gradual infiltration (and, possibly, better flow distribution) lead to more rapid biodegradation of BOD/COD in landfill bioreactor cells? The experiments reported here were designed to provide answers to these research questions.

RESEARCH METHODS

Leachate recirculation was carried out in four refuse cells. The basic experimental treatments consisted of leachate strength (low or high) and recirculation method (pulse or continual). Additionally, two positions of the flow sensor plates (top and bottom) and two time periods (early and late) were considered. As a result, the flow patterns were designed as a factorial experiment with three variables set at two levels each (2^3 factorial), while the effects of leachate recirculation on biodegradation rates were tested with a 2^2 factorial analysis.

Waste bins with dimensions of (L × W × H) 1.5 × 1.4 × 1.4m (2.1 m^2 surface area) were filled with randomly selected, typical residential MSW delivered to the Edmonton Clover Bar landfill. The cells were lined with a geo-membrane and were equipped with a leachate collection and recirculation system. The landfill compactor spread and passed over the waste three to five times to open and compact the refuse. Approximately 400 kg of pre-compacted refuse was packed into each bin to achieve an initial bulk density of 300 kg/m^3. After packing 100 kg refuse in the cell, a flow sensor plate was placed horizontally about 0.3 m above the bottom liner. On top of this plate, 150 kg more refuse was loaded. A second plate will be placed on top of this layer at about 0.8 m above the liner. On top of this second flow plate, another 150 kg waste was packed so the total refuse layer was about 1.3 m thick. The cells were capped with plastic sheets to minimize air exchange between the atmosphere and the refuse in the cell.

The experimental recirculation regime was carried out over an eighteen-month period from November 1995 until May 1997 for a total test duration of 543 days. Leachate was recirculated at a rate of 128 L every two weeks, either as a pulse or gradually. Under pulse recirculation the leachate was infiltrated equally over the surface area by a sprinkler system in one twenty-minute infiltration event every two weeks. For continual recirculation, a timed infiltration events applied 1.5 L through a fine sprinkler system under the plastic cover every four hours, equivalent to an infiltration rate of 4.41 mm/m^2-day. This rate is equivalent to a total infiltration of 1,610 mm per year which is higher than the annual precipitation in Edmonton of 600 mm per year, but lower than the infiltration rates of other lysimeter recirculation studies (e.g., 7, at 8.55 mm/m^2-day). Water was used for the first infiltration events until the cells discharged leachate. Then, the leachate volume was measured and water was added to make up the volume of 128 L (see Figure 1).

This moisture recording system consists of flow sensors connected to multiplexers, data loggers, and a personal computer. The moisture monitoring system consisted of two flow sensor plates (top and bottom) per cell. Each plate had sixteen equally spaced sensors on an area of one square meter. The data was read and stored every hour except for one hour following pulse recirculations, when the frequency was increased to once every ten minutes. The moisture flow data were then summarized for the bi-weekly periods and for the one-hour periods during and after recirculation events to test for sensor response to flow events. The flow sensors consisted of 1.1 cm i.d. tubes filled with glass beads and were calibrated to register within plus or minus 5 percent of 1.5 V at 10 mL/min (0.16 cm/s), 3.0 V at 20 mL/min (0.32 cm/s), and 4.5 V at 30 mL/min (0.48 cm/s) for an average leachate electrical conductivity of 700 mS/m. After day 360, the electrical conductivity decreased to 400 mS/m, which resulted in a slight decrease of output voltages of about 0.25 V. After the cells were dismantled, the sensors were re-calibrated and showed less than 10 percent change from their original voltages.

Every two weeks, a four liter sample of leachate was taken from the discharge of every cell and was analyzed for physical and chemical characteristics. Key

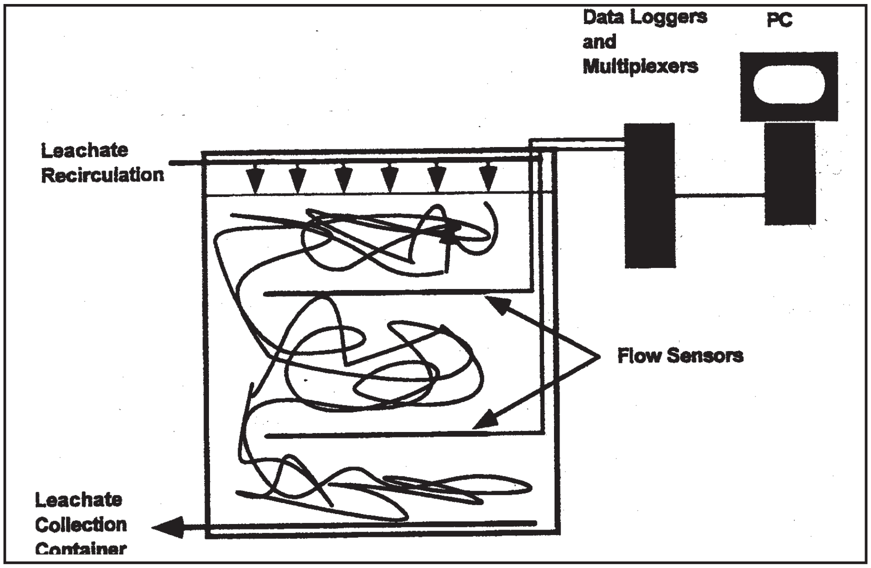


Figure 1. Leachate recirculation test cell.

parameters, in particular BOD and COD, the key dependent variables in this test, were measured every two weeks in the same rhythm as the recirculation regime. Although it was intended to maintain low leachate strength in cells 1 and 3 and high leachate strength in cells 2 and 4, these strengths could not be maintained throughout the test period because the wells could not be accessed in winter. Instead, leachate from the test cells was allowed to evolve through a normal cycle. Volatile fatty acids concentrations (bi-monthly) and redox potential were used as important indicators of anaerobic degradation and were compared with typical values in landfill test cells. Thus, the physical-chemical analyses provided both key dependent variables as well as indicators of the anaerobic degradation process.

The basic flow parameter values (field capacity, breakthrough time, and hydraulic conductivity) were determined for each cell and compared with previously reported values to verify typical channeling behavior. The flow sensor data were plotted and analyzed for trends and differences between sensors on each level and in each time period. The mean values and widths of the confidence intervals were analyzed by 2^3 factorial design with the recirculation method, sensor position, and time period as the three independent variables. The biodegradation variables (BOD, COD, BOD/COD ratio, redox potential) were plotted and compared with typical ranges for typical landfill and for bioreactor cells to verify typical degradation patterns [as shown e.g., 8-11, etc.]. Then, the apparent reaction rate constants k were calculated for each cell. These values were subjected to a 2^2 factorial analysis with recirculation method and strength as the independent variables.

RESULTS

The study results are presented in this section to accomplish the two study objectives: 1) to compare the performance of rapid pulse and slow continual recirculation on the spatial distribution of moisture flow patterns over time in the waste layer, and 2) to test the effects of recirculation method on the degradation of BOD/COD in the leachate. The results and analysis are presented under a) Moisture Flow Parameters, b) Flow Patterns, and c) Leachate Quality.

a) Moisture Flow Parameters

Practical field capacity FC_p (at breakthrough), breakthrough time t_{bt}, and hydraulic conductivity $K_{us\text{-}init}$ (at breakthrough) and the ultimate hydraulic conductivity $K_{us\text{-}ult}$ (at the end of the test) are estimated. These results are compared with the values from the literature and previous tests to validate the results of this research (see Table 2).

The practical field capacity, at $FC_p = 0.12$, and the corresponding breakthrough times, t_{bt}, at less than thirty minutes, in the two pulse recirculation cells are identical. These values are noticeably lower than the results for the continual recirculation cells where the practical field capacity, FC_p, ranged from 0.14 to 0.17 and the corresponding breakthrough times occurred at between twelve and twenty-six days, but at slightly higher moisture loadings than in the pulse recirculation cells. These results are consistent, in fact nearly identical, to previously recorded results for similar rapid infiltration cells (field capacity of 0.12 and breakthrough times of 15 to 20 minutes, see [7]). The practical field capacity of the continual recirculation cells with an average of 0.155 is somewhat higher than previously measured, but is to be expected because of the gradual infiltration. Concurrently, the breakthrough times t_{bt} for these cells were substantially longer than the highest values of twenty-four to forty-eight hours recorded in Zeiss and Uguccioni [6] for four-month tests. These differences are as expected due to the slower infiltration.

Apparent hydraulic conductivites $K_{us\text{-}init}$ (at breakthrough) are consistent among the pulse cells at $7.0 \bullet 10^{-3}$ cm/s and among the continual infiltration cells at 4.3 to 7.9 10^{-6} cm/s. These values are similar to previous numbers for rapid (pulse) infiltration, but about two orders of magnitude lower for the slow (continual) recirculation cells. The ultimate conductivities $K_{us\text{-}ult}$ at the end of the test period are between 3.1 and 4.0 10^{-6} cm/s for all four cells. These results are consistent with the values of 2.0 to 4.4 10^{-6} cm/s (as reported in [6]).

Table 2. Measured Flow and Degradation Parameters

Test Cell	Recirculation Option	Field Capacity FC_p	Breakthrough time t_{bt}	App. Hydraulic Conductivity at Breakthrough $K_{us\text{-}init}$ [cm/s]	App. Hydraulic Conductivity at Test End $K_{us\text{-}ult}$ [cm/s]	COD Kinetic Rate K [1/yr]
Cell 1	Pulse—128 L once every two weeks	0.12	< 30 minutes	$7.0 * 10^{-6}$ cm/s	$3.3 * 10^{-6}$ cm/s	1.20
Cell 2	Pulse—128 L once every two weeks	0.12	< 30 minutes	$7.0 * 10^{-6}$ cm/s	$3.1 * 10^{-6}$ cm/s	1.86
Cell 3	Continual—128 L over two weeks, applied in small doses every six hours	0.14	~ 20 days	$4.3 * 10^{-6}$ cm/s	$3.5 * 10^{-6}$ cm/s	2.04
Cell 4	Continual—128 L over two weeks, applied in small doses every six hours	0.17	~ 20 days	$4.3 * 10^{-6}$ cm/s	$4.0 * 10^{-6}$ cm/s	1.79

In summary, the moisture flow parameters in this experiment are consistent with previous results or show expected differences. The results confirm that similar flow channeling occurred in these test cells.

b) Moisture Flow Patterns

A principal objective of the research was to measure and track the moisture flow patterns over the experimental period of 543 days (approximately 18 months). The results of top and bottom sensor plates are shown for one pulse and one continual recirculation cell (see Figure 2) to contrast the flow patterns of pulse recirculation (Cell 1) with continual recirculation (Cell 3). The mean values, the half width of the confidence interval, and the 95 percent confidence range of the means for early and late periods are summarized in Table 3. The results between February 22 and May 15, 1996 have been omitted due to a microchip failure in the electronics boards. Fortunately, the system recovered after a restart in May 1996.

Top sensor readings in pulse recirculation cells 1 and 2 spread right at the start of the recirculation tests and maintain or increase this spread over the test period. The bottom sensors, in contrast, show a clustering of readings into a group of high values at between 3 and 4 volts with a smaller group of sensors showing dropping values at about zero volts at the end of the test period (see Figure 2). From observation, these patterns are consistent with the expected flow behavior because the upper sensors show a wide range of flow distribution while the lower ones show groups of high flow sensors interspersed with low flow readings. Early in the recirculation period, the average flow values are higher for the bottom plates, but later cell 4 shows a reversal of this pattern with the upper plate showing higher values (see Table 3).

Continual recirculation cells 3 and 4 show less spreading of sensor readings initially, with slightly increasing trends over the entire test period. Cell 3 shows a spread of values between 1 and 4 volts on top, with a tightly distributed range between 3 and 4.5 volts on the bottom plate. In cell 4, top and bottom sensor plates show similar patterns with fourteen sensors clustered tightly together at 1.7 to 3.2 volts on top and between 2.7 to 4 volts on the bottom. Two sensors each on top and bottom show values consistently around zero throughout the test period. Thus, the mean values of the continual recirculation cells are lower than the pulse cells in the early period, but are confined in a narrow range and are more consistent, as expected. Late in the test period (March 1997), the continual recirculation cells show higher mean flow values and the confidence ranges of the mean values are narrower than for the comparable pulse recirculation cells (see Table 3).

The flow patterns evolve quickly and remain consistent throughout the test. There are few shifts in the locations of channels and dry zones as indicated by the stationary locations of high and low flow sensors. The continual recirculation cells showing initially lower, but narrower ranges of flow values. Later, the continual cell values are more tightly clustered than the pulse cell values. The flow sensor results generally confirm the expected flow patterns.

The flow sensor mean and variation (as the confidence interval half width) results were subjected to a factorial analysis (2^3 with one replicate) to determine the effects of three variables (recirculation method—pulse vs. continual; sensor position—top vs. bottom; and time period—early vs. late). The estimates of effects were compared with the significance criterion of the lower limit of the 95 percent confidence interval (*t*-statistic for 8 d.f. and 95% confidence = 2.306 times the std. error for effects of 0.35 equals 0.81). Thus, recirculation at 0.22 is non- significant, position at 0.87, and time period at 1.0 are significantly above zero. Therefore, the bottom sensors show 0.87 volts higher readings than the top sensors and the mean values late in the test are 1.0 volts higher than at the beginning. Continual recirculation, however, does not significantly increase the mean sensor values.

The flow distribution was indicated by the range of sensor values (i.e., the half width of the confidence interval of the distribution of the means). These results (see Table 3) were subjected to a similar factorial analysis (with the same *t*-statistic as above = 2.306 times the std. error for effects of 0.15 equals 0.35). The effects were estimated for recirculation method at –0.46, position at –0.09, and time period at –0.14. Therefore, the recirculation method has a significant ($p < 0.01$) effect on reducing the confidence interval of mean flow values in the cross-section by about –1.0 volts.

Thus, the statistical analysis shows that the mean flow values for continual recirculation are slightly, but not significantly, higher. The range, however, is tighter and indicates a more equally distributed flow pattern from continual recirculation.

c) Leachate Quality

Leachate quality parameters were measured in bi-weekly or monthly intervals to coincide with the leachate flow measurements (see above). Total suspended solids (TSS), pH BOD/COD, and electrical conductivity (EC) were measured bi-weekly, while alkalinity, ammonia were measured monthly, and selected volatile fatty acids and metals were measured bi-monthly. The results are presented here to 1) check the consistency of the leachate characteristics with typical anaerobic degradation behavior, and 2) to test for differences between the cells that may be caused by recirculation method.

Leachate pH would be expected to drop early in the anaerobic process due to the production of volatile fatty acids (VFAs). Subsequently, with the formation of methanogenic conditions (low redox potential) and degradation of the VFAs by the methanogens, the pH normally increases back up to about 6.5 to 7.0. Starting at test begining in November 1995 with a high pH of 7.5 to 8.0 in all four cells,

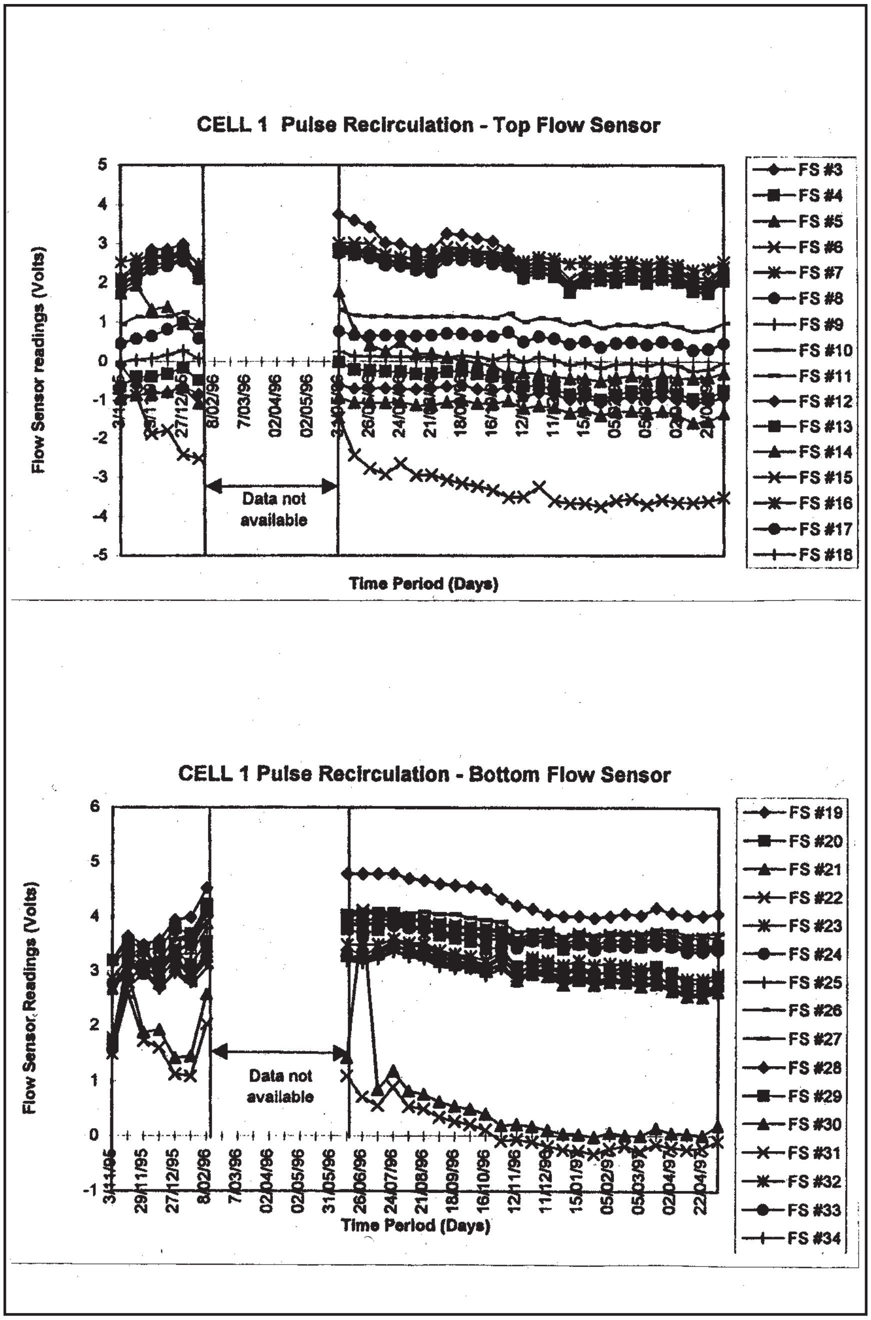


Figure 2. Pulse and continual recirculation flow sensor results.

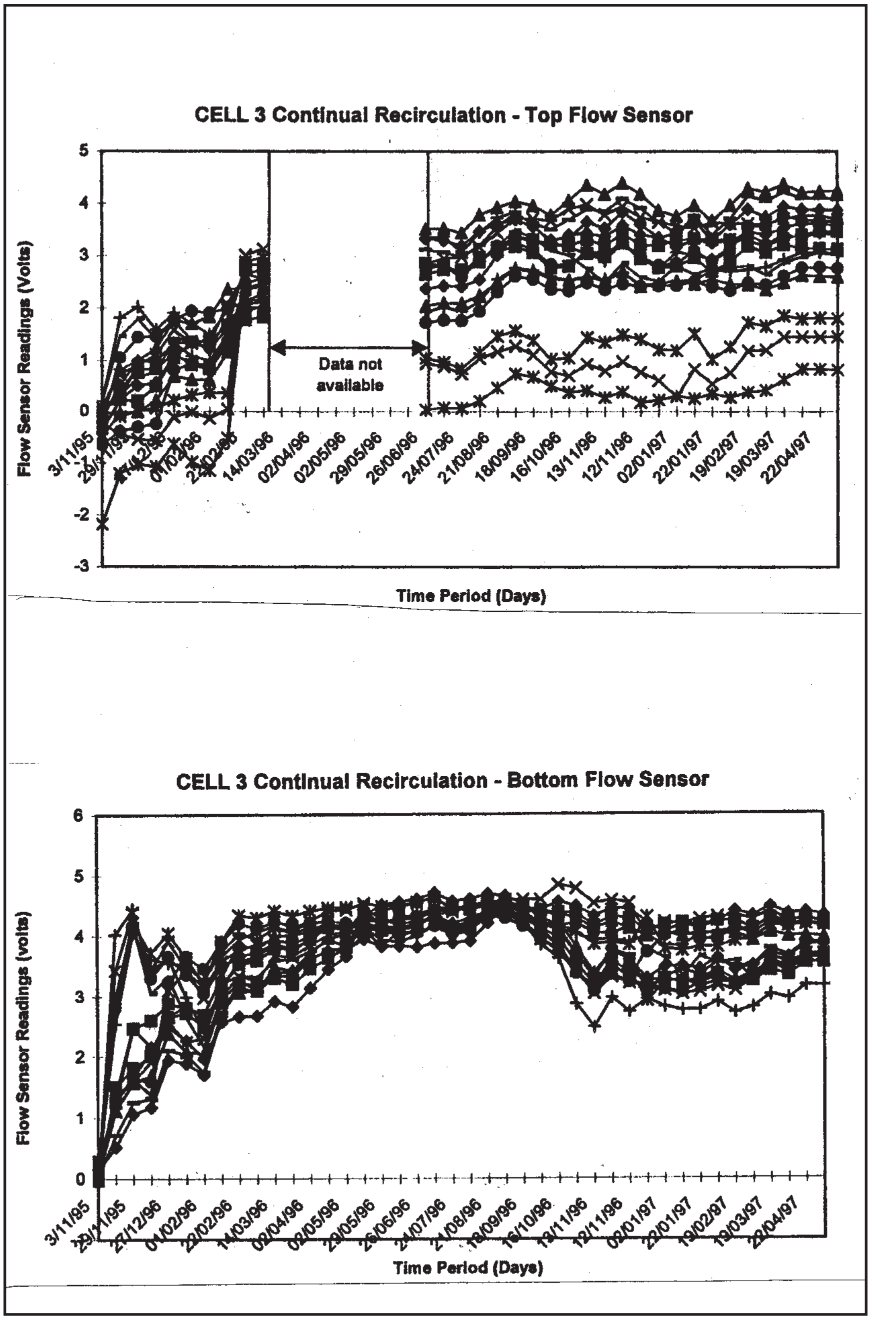


Figure 2. (Cont'd.)

Table 3. Flow Sensor Results

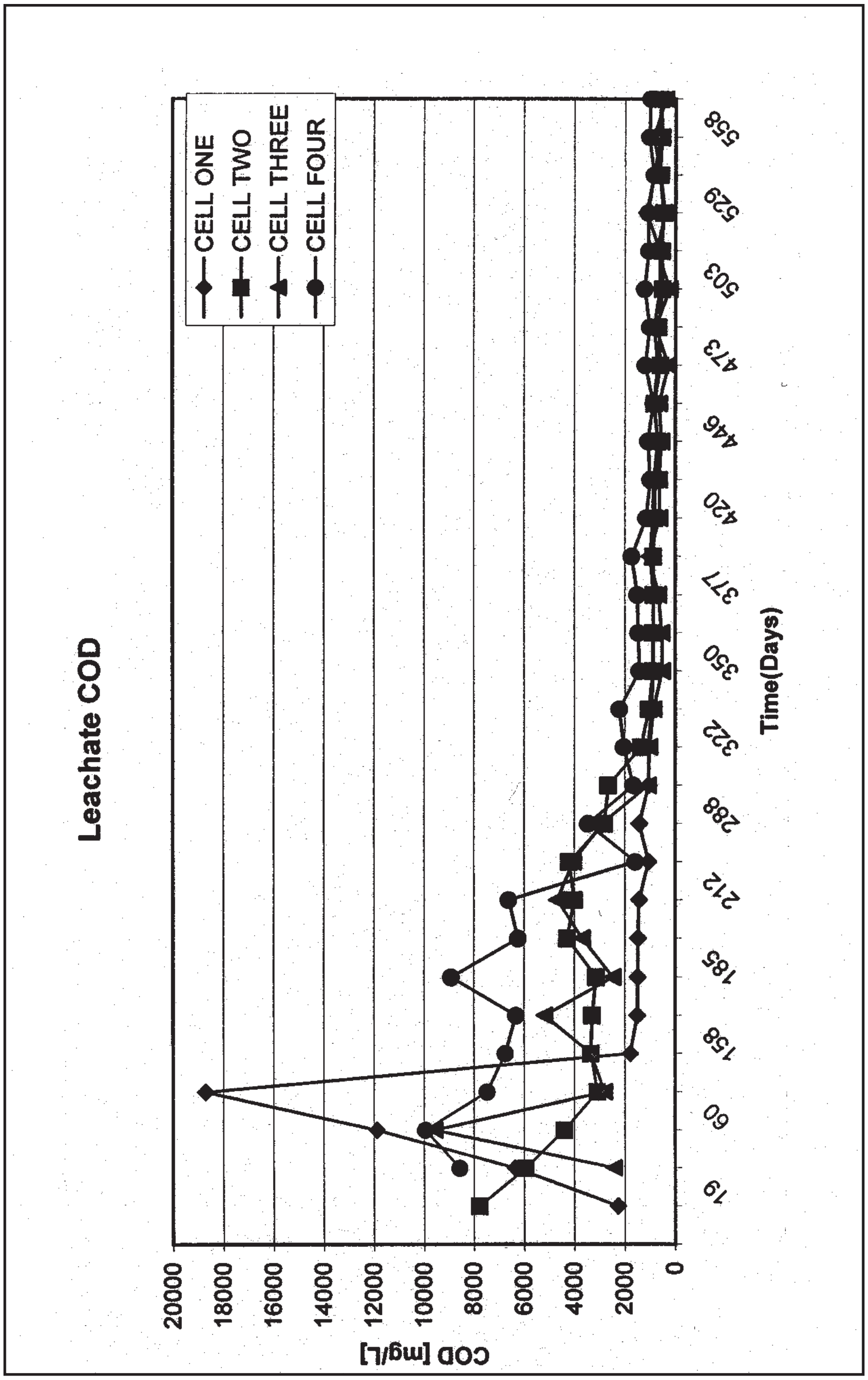
Cell	Sensor Plate	Early Period—December 1995		Late Period—March 1997	
		Mean	Half Confidence Interval $t_{16,95\%}$ * Std. Error	Mean	Half Confidence Interval $t_{16,95\%}$ * Std. Error
Cell 1 — Pulse	Top	1.55	0.61	1.22	1.04
Cell 1— Pulse	Bottom	2.87	0.83	3.09	0.16
Cell 2 — Pulse	Top	1.10	0.76	2.80	0.03
Cell 2 — Pulse	Bottom	1.17	0.25	2.40	0.39
Cell 3 — Continuous	Top	0.43	0.05	2.84	0.006
Cell 3 — Continuous	Bottom	2.09	0.21	3.55	0.006
Cell 4 — Continuous	Top	1.45	0.08	2.21	0.006
Cell 4 — Continuous	Bottom	2.42	0.02	2.96	0.032

there appears to occur a slight decrease in pH in cells 2, 3, and 4 down to about pH 6.5 by day 172. Thereafter, a slight increase occurred up to about pH 7.5 by the end of the test on day 558. Cell 1 stays high at pH 8.0 throughout. The pH does not show the marked pH decrease early in the degradation process [10], probably because the cells might have undergone some aerobic decomposition which has been shown to result in a less pronounced pH drop with the onset of anaerobic conditions [see 12]. Nonetheless, the above neutral pH values are certainly suitable for methanogenic decomposition.

The degradation of BOD and COD is one key issue in the test. The parameters were measured every two weeks for all four experimental cells. Cell 1 (pulse recirculation) shows a rapid increase to almost 6,000 mg/L BOD and 18,500 mg/L COD within two months of the test begin. Within further sixty days, both BOD and COD in cell 1 drop down to 200 mg/L BOD and 2,000 mg/L COD. Following this, the value slowly declines down to 25 mg/L BOD and 624 mg/L COD by the end of the test. The behavior of these parameters is as expected and proceeds more rapidly than expected based on results in the literature of other lysimeter test cells [8]. Cell 2 (pulse recirculation) exhibits very high initial values of up to 5,900 mg/L BOD and up to 10,000 mg/L COD on day thirty-three which then drop to 500 mg/L and 3,000 mg/L, respectively, by day sixty. Subsequently, BOD and COD rise slowly due to the conversion of solid organics by acid formers and acetogens into volatile fatty acids (see below) to secondary peak values of 2,000 mg/L BOD and 4,000 mg/L COD by day 200. Then, both decline rapidly to below 100 mg/L BOD and below 1,000 mg/L COD by day 336.

Cell 3 (continual recirculation) follows a pattern similar to cell 2, with primary concentration peaks of 2,500 mg/L BOD and nearly 10,000 mg/L COD, albeit with the BOD peak occurring on day 145 before the COD peak on day 158. Subsequently, both reach a second peak by day 199 and decrease to below 100 mg/L BOD and 2,000 mg/L COD by day 288. The final values are very low at 69 mg/L BOD and 519 mg/L Cod. Cell 4 (continual recirculation) shows the same pattern as cells 2 and 3 with primary and secondary peaks. Primary peaks consist of 3,000 mg/L BOD and 10,000 mg/L COD, but with the COD peak occurring first at day thirty-three while BOD peaks later at day 116. The second BOD peak is quite high at about 4,200 mg/L while the COD peak rises to about 9,000 mg/L COD on day 172. BOD and COD in cell 4 decline to below 300 mg/L BOD and below 2,000 mg/L COD by day 288. Thus, cell 4 behaves very similarly to cells 2 and 3.

In summary, all cells show reasonable, expected patterns of BOD/COD decay with early maxima of up to 6,000 mg/L BOD and up to 20,000 mg/L COD; both are indicative of young landfills. By the end of the test, BOD and COD values of less than 100 mg/L and less than 1,000 mg/L, respectively, are typical of a mature landfill of more than ten years of age [7, 9, 10, 13]. Cell 1 shows the highest ini-


Leachate COD
CELL ONE
CELL TWO
CELL THREE
CELL FOUR
COD [mg/L]
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
19
60
158
185
212
288
322
350
377
420
446
473
503
529
558
Time(Days)

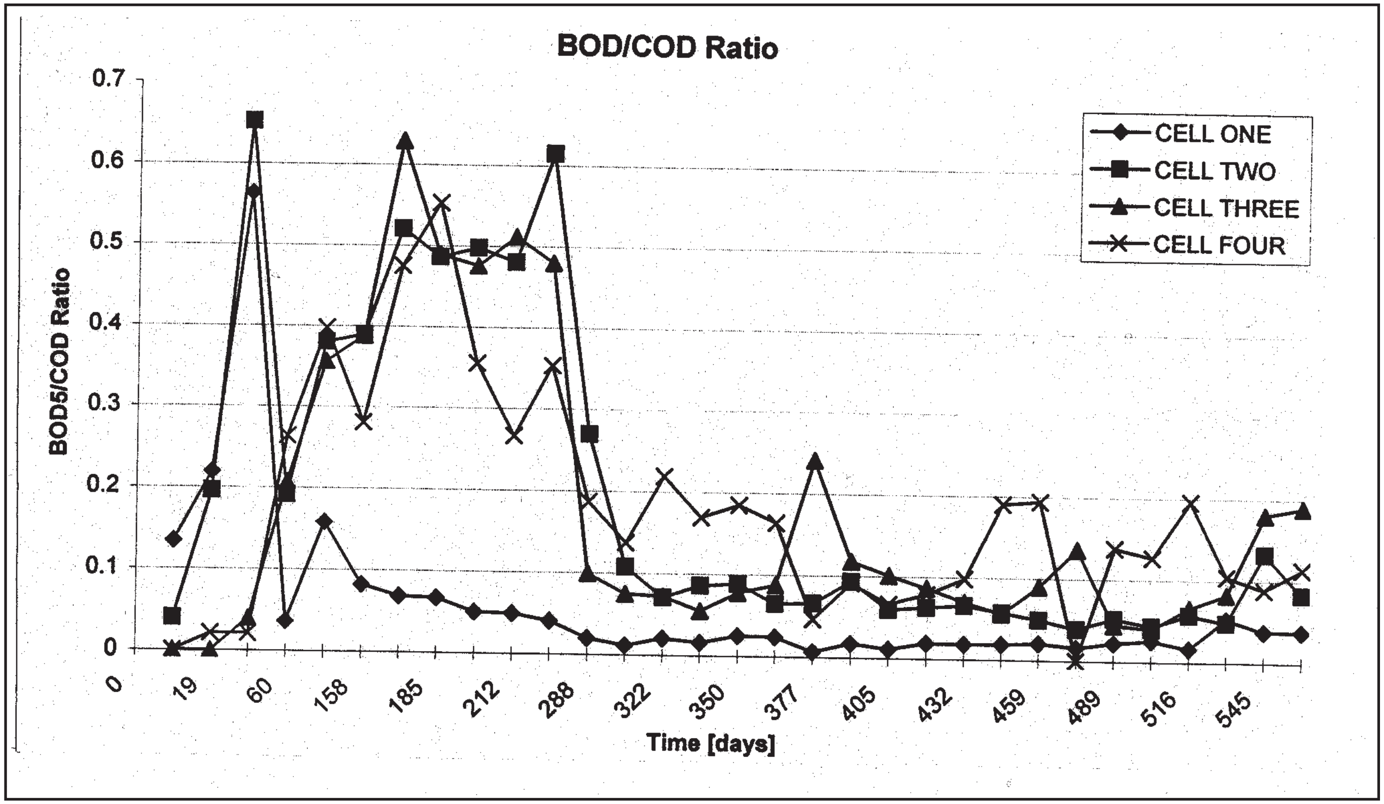


Figure 3. Leachate COD and BOD/COD ratios.

tial peaks, but also the most rapid drop in BOD/COD matter. Cells 2, 3, and 4 show very consistent patterns with an initial peak, probably from soluble organic material, and as a subsequent secondary peak value from the accumulation of VFA degradation products from the acid forming and acetogenic stages of the typical landfill degradation process.

BOD_5/COD ratios (see Figure 3), too, exhibit typical values and follow typical trends. Early ratio values of 0.4 to 0.65 decline to below 0.2 by the end of the test. The final values are consistent with old leachate equivalent to five to fifteen-year-old waste.

Negative redox potential indicates the presence of reducing conditions. Ideal redox potential values for anaerobic degradation and methanogenesis in solid waste cells should be between –200 and –300 mV early in the process. Then they should increase, crossing 0 mV at a waste age of five to ten years, and the ultimately reaching +100 mV for mature landfill cells [14, 15]. Cell 1 shows some early negative values as low as –150 mV which alternate, however, with positive values up to +175 mV. Later, an increasing trend is noted up to final values of about +200 mV, which are identical to the results for the other three cells. Cells 2, 3, and 4 show very similar behavior with early redox values in the ideal range from –200 to –310 mV up to day 288. These results coincide with rapid BOD/COD reduction in this same time period. Cells 2 and 3 then increase within thirty days to +120 mV and then gradually fluctuate up to the final values of about +150 to +200 mV. Cell 4 stays at negative redox values of about –100 mV up to day 450 and then passes into positive ranges and ends at +100 mV. Thus, all four cells exhibit the expected behavior and support the presence of anaerobic conditions for about 300 days of the test. Thereafter, the cells appear to revert to oxidizing conditions, as expected.

COD kinetic rate k mean of 1.72/yr resulted from individual cell k rates between 1.2/yr for cell one to 2.04/yr for cell 3. Cells 2 and 4 had very similar rates at, respectively, 1.86/yr and 1.79/yr. These rates are virtually identical to the reported rate constants for COD removal in other lysimeter studies [16] and slightly lower than in anaerobic digesters [17]. The factorial analysis, as a result of the narrow range of k values, showed no significant effects of recirculation method (estimate from factorial analysis of 0.38 compared with the std. error of 0.68 is non-significant) on COD degradation rates.

In summary, the factorial analysis of the results shows no significant increase in the mean values of the flow sensors, but confirms significantly narrower confidence intervals and more equal flow for continual recirculation. Moreover, the COD degradation rates for continual recirculation cells are not significantly higher than for pulse recirculation.

DISCUSSION AND CONCLUSIONS

Leachate flow cells and flow measurement instrumentation were designed and built to test the differences of pulse and continual recirculation on the flow patterns and on the COD degradation rates over a full anaerobic degradation cycle in municipal waste layers. An automated flow sensor system was installed in each of four test cells to measure flow rates by sixteen sensors spaced equally in a one-by-one meter grid at two depths in a 1.3 thick meter thick layer of waste. In two cells 128 L of leachate was recirculated once every two weeks, while in the other two the same volume was applied gradually and continually over the two-week period.

The flow sensor results showed, first, that the flow patterns evolved very quickly due to channeling (with breakthrough times from as little as 15 to 30 minutes up to 26 days) and stayed at virtually the same locations in all four cells throughout the 542-day (18-month) test period. This result supports the hypothesis that channels form early and maintain themselves over the degradation cycle. Neither method of recirculation overcomes channeling. Although continual recirculation did not produce higher mean flow readings, it did result in much narrower ranges of flow values than pulse recirculation. Thus, continual recirculation led to more consistent flow distribution in the waste layer than did pulse recirculation. If one considers that the comparison used the flow values recorded during and immediately after the pulse recirculation events, then these findings are conservative, because the flow values for pulse cells dropped off between events, while continual cells showed virtually constant flows throughout the two-week cycle.

Leachate COD degradation rates were determined and tested for effects of recirculation method. Continual recirculation, however, did not significantly increase the leachate COD degradation rates. Furthermore, the apparent degradation rates account for dilution through the addition of makeup water to achieve the desired flow rates. The differences in COD degradation might have been masked by dilution required to achieve the intensive recirculation rate applied by both methods.

For further research, a suitable method of in-situ moisture content measurement of solid waste materials should be developed and used to measure the distribution of moisture. This is not a trivial task, considering the heterogeneity of packed waste material. Neither recirculation method prevents channeling with rapid discharge, low moisture storage, and low wetted surface area for biodegradation. New approaches for recirculation to overcome these problems, which might be even more serious in full-sized landfills, must be sought. There remain challenging research issues in the theory of channeled two-phase (gas and leachate) flow as well as in the design and operation of recirculation systems that will optimize the biodegradation rate and minimize the contaminating lifespan of bioreactor landfill cells.

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