Effect of Leachate Recirculation on Landfill Gas Production and Leachate Quality: A Controlled Laboratory Study

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A national laboratory of the U.S. Department of Energy
Operated by Midwest Research Institute
for the U.S. Department of Energy
Under Contract No. XA-1-11146-1
Under Subcontract No. TAE-2-12246-01

May 1995

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EXECUTIVE SUMMARY

This report summarizes the results of a laboratory study conducted during 1992-1994 at Argonne National Laboratory. The study examined biogas production and leachate chemistry in parallel anaerobic assays run under either leachate recycle or leachate drainage regimes over a period of 400 days. A standardized synthetic refuse (paper, grass, food) was used in an experimental design which evaluated two elevated moisture contents and two added soils. All assays were conducted *in vitro* in 125 mL serum bottles. Four recycle/drainage events were completed during the 400 days of this experiment. Sufficient replicates (10 or 20) for each trial were included in the experimental design to permit destructive sampling of assay solids after each recycle/drainage event. Changes in the chemistry of solid, liquid, and gaseous phases were evaluated during the decomposition process. Analyses included major gases (CH₄, CO₂, O₂, N₂), selected chemical constituents of leachate (C1-C5 carboxylic acids, total organic carbon, Kjeldahl nitrogen, total phosphorus, iron, zinc, and chloride), leachate pH and conductivity, and selected solids analysis (gravimetric moisture content, volatile solids, total carbon, cellulose, hemicellulose, and lignin).

This study was conducted to begin to answer the following four questions pertinent to landfill decomposition :

1. Does a leachate recirculation regime result in increased methane production over a leachate drainage regime at constant starting water content? Leachate drainage is the *status quo* at landfill sites which produce leachate.
2. Can the type of soil mixed with refuse materials significantly influence leachate chemistry and biogas production?
3. Does a leachate recirculation regime result in faster, more complete carbon conversion to biogas when compared to leachate drainage ?
4. Is leachate quality improved when leachate recirculation rather than leachate drainage is practiced? That is, does leachate contain lower concentrations of major cations, anions, and carboxylic acids ?

With respect to questions 1, 3, and 4, considered together, the results indicated that there were no quantifiable benefits to leachate recirculation over leachate drainage with respect to methane production, carbon conversion, or leachate quality. Overall, through the decomposition process, the fraction of total carbon converted to biogas carbon ranged from about 0.10 (higher moisture content assays) to 0.50 (lower moisture content assays). The differences in carbon conversion were attributed to high rates of carboxylic acid production (exceeding consumption) in the higher moisture content assays. Cellulose:lignin ratios, a measure of decomposition, decreased from 4.3 (initial refuse without soil) to minimum values below 0.05 at the end of the experiment.

Leachate quality was evaluated in two ways: changes in chemical concentrations through the leachate/recycle events and overall changes in constituent loading. Loading is calculated from the product of chemical concentration and moisture content to yield the total soluble mass present in a given assay. Calculation of loads addresses simple dilution effects from increased gravimetric moisture contents through the decomposition process. Linear relationships between chloride loads and other constituent loads suggested the contribution of dilution effects to observed leachate concentrations. For the recycle assays, since these were sampled only at the time of destruction, no net changes in liquid volume or leachate chemistry were introduced due

to periodic sampling. Thus, changes in gravimetric moisture content through decomposition could be carefully observed. For recycle assays where the initial moisture: dry solids ratios had initially been 3.2 to 3.2, the final ratios were 5.6 to 9.7; for assays which had higher initial ratios of 7.0 to 7.2, the final ratios were 12.2 to 15.4.

With respect to the two soils in this study (question 2 above), they were added at small quantities to simulate the effects of soil cover and must be evaluated in parallel with refuse and leachate chemistry. For example, with respect to nitrogen, as a major nutrient, the total nitrogen content of the clay soil was higher than that of the sand soil, which might be expected to improve gas production rates from a nutritional standpoint. Nevertheless, the nitrogen contribution from the refuse (Appendix E) was high and would negate small additional nutritional benefits from the clay soil. Indeed, for gas production, the assays with added sand soil yielded slightly higher values for some assays. This may be partially attributed to better mixing in assays with added sand soil. With respect to soil influences on selected leachate metals concentrations (Fe, Zn), soil differences were apparent for iron but not for zinc. Extensive soils literature indicates that certain DTPA (diethylene triamine pentaacetic acid)-extractable metals are well-correlated to plant uptake. Since plant uptake in soil systems is mediated by bacteria and fungi in the root zone, one might start with DTPA-extractable metals to suggest metal availability to microorganisms in landfill/soil systems. For iron, the higher DTPA-extractable iron content of the clay soil (Appendix A) was apparent in higher iron concentrations in the respective leachates. This was generally true throughout the period of incubation. Iron concentrations peaked at the time of first recycle when pH values were lowest; this timing suggested that the iron was in a readily soluble form. The same relationships were not true for zinc; the DTPA-extractable zinc was uniformly low and without much contrast in the two soils studied.

The assays in this study were incubated as batch systems in serum bottles with periodic leachate manipulation, thus similar to decomposition in actual landfill settings where discrete cells are filled at given times and operate as batch reactors. The quantities of leachate extracted for recycle or drainage in this study were large relative to the mass dry solids; this was planned to focus the evaluation on the recycle/drainage alternatives. In addition, the assays were conducted at high initial moisture contents to minimize mixing limitations. Thus the assays could be considered optimized landfill batch reactors, and the results are pertinent to landfill decomposition processes.

There are, of course, major scale differences between small laboratory assays and actual landfill settings. A strength of laboratory studies of landfill decomposition is their rigorous use of both controls and replicates, which has not been accomplished in field-scale test cell studies to date. Moreover, it is rarely possible to monitor all of the variables not being controlled in a field decomposition experiment; yet knowledge of how one variable changes in relation to another is necessary for data interpretation. Thus, even though laboratory studies focus on optimized systems, they permit valid comparisons between results in these biologic systems with high natural variability. It is certain that lower rates will be observed at field scale. However, in field decomposition studies to date, the natural variability within a given field test cell may preclude obtaining gas and leachate data across various test cells which exhibit statistically significant differences. In addition, even at well-controlled field test cells, opportunities exist for external gas and liquid exchange that are excluded in an *in vitro* laboratory study.

Further laboratory studies are needed to rigorously examine controlling variables in landfill systems, particularly with respect to organic carbon and nitrogen cycling. These should be followed by innovative design of landfill cells to optimize decomposition rates within current management and regulatory guidelines. Laboratory studies with adequate control of physical and biochemical variables should be used to guide conceptual design of landfill cells, with later scale-up to field sites to test only the most promising alternatives. To a large extent, this has not been done in past studies. For example, very little is known about major nutrient (N,P,K) cycling in landfills or the role of interbedded soils. Existing anaerobic digestion literature lacks comment on these topics since soils and nitrogen limitations are both absent in conventional digesters. Very little is known about carbon cycling in landfill systems, as well. Existing literature on landfill carbon conversion (summarized in Bogner, 1992) indicates that, at best,

only 0.25-0.40 of organic carbon deposited in landfills is eventually converted to biogas carbon (methane and carbon dioxide). Thus, complete "stabilization" of refuse would appear to be an unrealistic goal. Rather, we must examine the solid and liquid form of remaining carbon with respect to valid transformations over very long time frames. To a large extent, cellulose and hemicellulose can be anerobically degraded while lignin is recalcitrant and remains in landfill storage.

Our specific recommendations for future studies stress both the chemical and physical aspects of landfill decomposition at various scales. As mentioned above, there are, realistically, very few studies in landfill/soil systems which address the important issues of water balance dynamics, nutrient cycling, or carbon balance. The first focus, as in any process engineering problem, should be on laboratory studies with detailed chemistry of solid, liquid, and gaseous phases to evaluate critical variables relative to design goals (more methane, faster stabilization to a selected end point, leachate quality goals). Laboratory studies have the advantage of a high level of process control, routine use of replicates and controls in experimental designs, and low cost. The combination of laboratory studies and realistic process modeling should form the basis for careful scale-up to field studies. At field scale, the physical aspects of leachate recirculation and control of landfill liquids also become very important. Thus, the following detailed recommendations are made:

1. In studies at various scales, the physical increase in water content through the process of decomposition should be monitored to separate simple dilution effects in leachate chemistry from the effects of leachate recirculation or drainage *per se*. To some extent, dilution effects can be evaluated by comparison of selected ion concentrations with conservative ions (e.g., chloride). For field settings, a dynamic water balance is needed which includes increases in observed water content through time due to internal biodegradation reactions plus any external contributions (net infiltration, groundwater leakage). The results of this study indicate that it is especially critical to monitor leachate concentrations with respect to overall moisture contents.

2. Soils are an important element in virtually all landfill systems where soils are used as daily, intermediate, and final cover materials. Soil chemistry must be taken into consideration in this complex system and may be expected to be a major influence on certain aspects of leachate chemistry.

3. Physical aspects of liquid redistribution and mixing in landfill systems must be considered, even at small laboratory scale. We observed that extraction of leachates from sandy soil/refuse assays was easier than from clay soil/refuse assays. Such physical constraints become increasingly more important at larger scales. In the field, the complexities of unsaturated zone flow over much of the internal volume of the landfill suggest that innovative designs are necessary to promote more uniform downward infiltration of recirculating liquids. The complexities of aqueous movement further complicate questions of microorganism distribution and movement.; this was recently addressed by Wan et al. (1994).

4. More standardized methods to study and characterize landfill decomposition processes are needed, particularly in regard to leachate recirculation. These methods should be appropriate to the scale of a given study and, include solid, liquid, and gaseous phases. Simple and robust field and laboratory methods should be developed that can implemented at specific sites to guide site design and management.

Finally, leachate recirculation should continue to be encouraged at sites where it is permitted under existing Federal and state regulations. It must be emphasized that there are many landfill sites where leachate recirculation is economically attractive to offset or reduce the need for leachate treatment. Since the process of leachate recycle rather than leachate drainage in field settings will tend to increase the net moisture content of the refuse, the recirculation process could be beneficial to biodegradation if distribution of the leachate is uniform. A reasonable approach is to practice leachate recirculation if it offsets or reduces the need for external leachate treatment and is not too costly when site-specific issues are taken into account.

1.0 Introduction

Leachate recirculation as a landfill management technique has been considered since the early 1970's (Pohland and Kang, 1974). Numerous published reports of laboratory studies, most conducted without independent control of moisture content, have suggested that leachate recirculation accelerates landfill stabilization, increases rates of biogas production, improves leachate quality, and decreases temporal variability of leachate quality (Pohland, 1975, 1980; Klink and Ham, 1982; Tittlebaum, 1982; Pohland et al., 1983; Pohland, Cross and Gould, 1987). In operating landfills, however, leachate recirculation has been rarely practiced or, where practiced, lacks complementary monitoring data collected in a controlled manner to quantitatively document tangible benefits.

Recently, leachate recirculation has been given increased emphasis as a result of Federal landfilling regulations under Subtitle D of the Resource Conservation and Recovery Act (RCRA). These regulations contain minimum Federal requirements for nonhazardous waste landfills, with individual approved state programs free to establish more stringent regulations. Under Subtitle D, the introduction of liquids or liquid wastes into landfills is prohibited, but leachate recirculation may be practiced at lined sites with leachate collection systems. Thus, leachate recirculation has now become the only means of increasing landfill moisture content to promote faster decomposition.

In addition, leachate recirculation is viewed as a potential means of eliminating or reducing the need for separate leachate treatment facilities at a given landfill site. Both on-site leachate treatment or transport of leachate to off-site wastewater treatment result in high costs to landfill operators. To date, many of the questions pertaining to the absorption capacity of landfills at field-scale, under a regime of continuous leachate recycle, are unaddressed. This is particularly true with respect to their ability to degrade low molecular weight carboxylic acids, adsorb or complex metals, and anaerobically degrade chlorinated organic compounds of environmental concern.

To some extent, field test cell projects in progress in the U.S., Sweden, the U.K., and Austria are addressing these issues at well-monitored sites. However, existing projects have rarely monitored the biodegradable organic carbon content or nutrient content of input refuse, negating a reasonably precise understanding of input variability with which to compare output gas production and leachate chemistry. Moreover, at field scale, it is virtually impossible to control all the variables that are not being monitored. Thus, costly field-scale experiments conducted without duplicate trials may not observe significant differences as a result of leachate recirculation. This is due to the natural variability of anaerobic refuse decomposition under conditions of overall moisture limitation, the *status quo* for current landfill design practice. In addition, the expense and long time frames required for field test cell studies — a 10-yr minimum is probably a necessity — argue for focused laboratory studies followed by a careful scale-up where physical limitations to moisture and nutrient transport can potentially be overcome using innovative designs. The present study was undertaken at small laboratory scale to address 1) relative methane yields under leachate recirculation and leachate drainage regimes; 2) the influence of interbedded soils on leachate chemistry and gas production; 3) carbon conversion under leachate recirculation and leachate drainage regimes; and 4) dynamic variations in leachate quality under leachate recirculation and drainage regimes.

This study was conducted at Argonne National Laboratory during 1992-1993 to compare gas production and leachate quality in parallel anaerobic assays run *in vitro* either with or without leachate recirculation. For the assays without leachate recirculation, the same volume of leachate was drained and replaced by distilled water. This simulates standard practice at most landfills producing leachate; that is, the leachate is drained via bottom gravity-drainage systems and either treated on site or transported to public wastewater treatment facilities. This study focused on biogas production and major changes in leachate chemistry during decomposition; we did not address physical aspects of leachate recirculation nor questions related to degradation of chlorinated compounds in leachate.

Laboratory procedures were similar to those used in previous studies of anaerobic decomposition of landfill samples (Bogner, Rose, and Piorkowski, 1989; Bogner, 1990), which were based on the biochemical methane potential (BMP) assay (Shelton and Tiedje, 1984; Owen et al., 1979). In this study, a synthetic refuse mixture (grass/food/paper) was used to standardize the starting materials. Samples were incubated anaerobically in 125 mL gas-tight serum bottles. Solids contents were chosen to optimize moisture contents and simulate either high or low solids anaerobic digestion. Either a sand or clay soil was added to each assay; both soils have been well-characterized physically and chemically for use as internal laboratory standards at Argonne. Samples were incubated for 400 days at 40°C. Ten to twenty replicates were used for each trial, depending on the treatment. The variables examined were moisture content and soil type under both leachate drainage and leachate recirculation modes. Four leachate recycle/leachate drainage events were completed during the period of incubation. Leachate neutralization and addition of a methanogenic seed were each completed two times during this period. Gas production and selected leachate variables were compared for the four events.

Although this study was initiated to answer specific questions related to leachate recirculation in the context of optimized landfill decomposition, there are several associated issues which were also addressed. First, even though it is well-known that landfills function as moisture-deficient anaerobic digesters, there are virtually no studies which address the details of anaerobic decomposition in refuse/soil systems. Many of the decomposition studies to date did not include added soils, which can contribute organic matter, microorganisms, and nutrients to landfill microbial processes. Recent literature has emphasized the potential contribution of soil organic matter to production of intermediates such as acetate in anaerobic settings (Kusel and Drake, 1994). Secondly, the dynamics of carbon and nitrogen cycling in refuse/soil systems are also virtually unstudied; such major element cycles are extremely important to considerations of long-term stabilization of refuse and greenhouse gas emissions (methane, carbon dioxide, nitrous oxide). Third, laboratory studies permit study of well-mixed optimized systems using multiple replicates so that rates can be quantitatively compared among various treatments. Even though field rates will be less, the value of a given management technique relative to a competing technique can nevertheless be determined under controlled conditions. Fourth, by examining the literature, it is apparent that there is a lack of standardized procedures to examine refuse decomposition; studies to date were conducted using a wide variety of containers and experimental conditions, making it difficult to interpolate among their respective results. This current study supplements a relatively small number of existing studies discussed below where some of these issues were addressed.

2.0 Background

Landfills produce leachate when sufficient water is present in a free phase to move through refuse under unsaturated or saturated flow conditions. Traditionally, the production of leachate has implied refuse at or above field capacity. However, channeling and horizontal flowpaths, particularly under unsaturated conditions, appear to be common in landfills and may thus result in observable leachate at overall moisture conditions below field capacity.

Recognition of groundwater and surface-water contamination due to leachate migration resulted in numerous studies of landfill leachates during the late 1960's and 1970's. Most of these studies were more concerned with offsite migration than with leachate chemistry in the landfill. Migrating leachates are affected by changing redox conditions and interactions with offsite strata with variable chemistries. For example, Baedecker and Back (1979) showed increasingly oxidized groundwater with greater distance downgradient from an Ohio landfill, starting with a highly anaerobic zone adjacent to the landfill proper. Field studies by Hughes et al. (1971), focusing on several northeastern Illinois landfills, suggested cation exchange in surrounding clays affecting changing groundwater compositions with distance from the landfill.

Johnson and Cartwright (1980) showed that leachate migration may be more rapid in the unsaturated zone than below the top of the zone of saturation. More recently, Johnson et al. (1989) showed that saturated zone diffusion may be an important mechanism for leachate migration at the base of a landfill.

Leachate composition is highly variable. Halvadakis et al. (1983) summarized observed chemical characteristics of leachates from a number of studies (Table 1). Note that ranges of three to four orders of magnitude for a given variable are common. More recently, Levine and Rear (1989) statistically analyzed leachate monitoring data from 58 landfill sites and contrasted compositions between 26 conventional municipal solid waste (MSW) landfills, 24 co-disposal sites containing MSW and hazardous waste, and 8 hazardous waste landfills. In all, 1560 samples from 1984-1987 were analyzed; ranges and geometric means are shown in Tables 2a and 2b. Again, wide ranges of values are apparent in the data shown. In general, values for the co-disposal sites were intermediate between the MSW and hazardous waste sites for many variables shown in Table 2a. BOD₅ was highest for the MSW sites while specific conductivity was highest for the hazardous waste sites. Many, but not all, metals tended to be higher at the hazardous waste sites. Among the many sources of the observed variability in these data are differing analytical methods and analysts, analytical accuracy, and unknown groundwater contributions to observed leachate concentrations. In another study, recent analyses by WMNA (1991) examined concentrations of a wide variety of metals, conventional parameters, and organic compounds at six landfill sites, concentrating on listed EPA Priority Pollutants. Results are shown in Table 3. Again, note the wide variety of results obtained.

Table 1 Ranges for selected leachate parameters from reported values (from Halvadakis et al., 1983).

Parameter	Number of Observations	Absolute Values		Mean Values ^b	
		Minimum	Maximum	Minimum	Maximum
pH	16	3.00	8.50	5.35	6.82
Specific Conductance, μ mhos/cm	4	1,080	12,180	4,420	7,945
Total Dissolved Solids, mg/l	8	0	42,276	5,370	18,880
Alkalinity, mg/l as CaCO_3	12	0	20,850	1,539	8,058
BOD ₅ , mg/l	12	0.6	50,000	4,008	25,017
COD, mg/l	12	0	89,520	5,511	38,872
Organic Nitrogen, mg/l	8	0	1,000	36	512
Total Organic Carbon, mg/l	2	332	15,000	1,666	7,985
Total Volatile Acids, mg/l as HAc	4	0	19,000	3,500	15,214
Ammonia Nitrogen, mg/l	8	0.12	1,000	83	649
Nitrate Nitrogen, mg/l	5	0.10	9.80	2.04	6.06
Phosphate, mg/l	14	0.01	154	3.13	50
Sulfate, mg/l	12	0	1,826	93	775
Sodium, mg/l	13	0	7,700	177	1,904
Potassium, mg/l	11	0.16	3,770	174	1,272
Calcium, mg/l	12	5.00	4,080	479	1,912
Magnesium, mg/l	12	13	15,600	151	1,708
Iron, total, mg/l	15	0.07	5,500	141	1,220
Cadmium, mg/l	3	0	0.5	0.15	0.32
Chromium, mg/l	2	0.05	0.5	0.18	0.35
Copper, mg/l	10	0	9.9	1.24	1.72
Lead, mg/l	7	0	5.0	0.33	1.79
Manganese, mg/l	5	0.05	1,400	25	333
Chloride, mg/l	16	5.84	2,800	282	1,429

^aCompiled from the following sources: California State WPCB, 1954, 1961; Andersen and Dornbush, 1967; Qasim and Burchinal, 1970; Furgaroli, 1971; Hughes, et al., 1971; Mao and Pohland, 1973; EMCON, 1975; USEPA, 1977; Pohland, 1980. See Halvadakis et al., 1983 for complete citations.

^bReported values have been presented as ranges. Minimum and maximum mean values were determined by averaging corresponding values of the reported ranges.

Table 2a Summary of nonspecific parameters and selected inorganic and organic constituents of landfill leachate (from Levine and Lear, 1989)

Type of Facility	Co-Disposal				Hazardous				Sanitary			
Parameter, units	n	Range	Geom Mean	Coef ^a Var	n	Range	Geom Mean	Coef ^a Var	n	Range	Geom Mean	Coef ^a Var
Nonspecific parameters												
Alkalinity/mg/L	198	5-110,000	2702	19	0	-	-	-	64	753-19,800	2972	10
Hardness, mg/L	208	6-40,000	1906	16	0	-	-	-	91	460-114,300	1845	13
pH	321	3.3-12.5	6.7	6	415	2.6-12.9	7.5	15	172	4.9-7.9	6.6	4
Solids, mg/L												
Total Dissolved (TDS)	40	71-50,380	4143	15	9	2,670-33,100	8159	8	65	390-19,731	3799	9
Total Suspended (TSS)	48	15-135,000	289	33	5	4-2,300	117	50	94	11-89,840	451	26
Specific Conductance, Field μ mhos/cm	292	108-111,000	6852	13	402	30-100,000	11,955	13	139	350-20,000	4852	9
Temperature, C	268	0.6-58	15.8	17	342	6.1-33	22	8	161	1.7-37.1	13.8	15
Inorganic ions												
Chloride, mg/L	204	1-17,000	1051	24	70	6.9-33,000	766	30	161	11-4,700	498	16
Cyanide, mg/L	201	0.01-7.3	0.16	***b	128	0.02-82	0.4	***	73	0.008-1,200	0.03	48
Fluoride, mg/L	92	0.1-166	0.79	***	61	0.4-424	1.5	***	55	0.1-3.8	0.45	***
Nitrogen as N, mg/L												
Ammonia	89	0.1-2,200	75	60	17	0.08-5,600	318	43	54	0.1-1,800	78	50
Nitrate	85	0.01-100	0.33	***	66	0.05-150	0.3	***	63	0.01-15	0.23	***
Nitrite	21	0.01-0.25	0.07	40	0	-	-	-	3	0.01-2.3	0.06	91
Total Kjeldahl	64	0.2-3,600	195	44	0	-	-	-	5	51-298	113	14
Sulfate, mg/L	205	0.1-9,815	72.9	43	64	2-4,000	331	30	43	5-1,714	52	38
Nonspecific organic parameters												
Oil and Grease	22	2-3,400	29.3	66	8	1-132	26	45	27	1-1,000	33	55
BOD, mg/L	143	2-66,200	1002	36	7	28-3,768	426	24	93	9-38,000	1555	26
COD, mg/L	177	5-180,00	1744	29	7	1,100-8,220	2350	8	120	20-32,498	2570	19
Phenolics, mg/L	236	0.004-98	0.74	***	148	<0.001-1,500	4	***	92	0.01-12	1.1	***
TOC, mg/L	196	3-128,128	871	30	238	1-17,300	861	38	59	9-14,500	611	28
TOX, μ g/L	68	<0.001-256	0.9	***	74	0.008-440	1.8	***	26	0.05-7	0.8	***

^acoef. var. = [log (Std. Dev.)/log (Geom. Mean.)] 100.

^bcoef. var. was greater than 100%.

Table 2b Summary of metals found in landfill leachate (from Levine and Lear, 1989)

Metal	n	Co-Disposal			n	Hazardous			n	Sanitary		
		Maximum Value (µg/L)	Geom Mean (µg/L)	Coef ^a Var		Maximum Value (µg/L)	Geom Mean (µg/L)	Coef ^a Var		Maximum Value (µg/L)	Geom Mean (µg/L)	Coef ^a Var
Aluminum	15	2,140	353	15	58	6.0E + 05	2,911	27	18	2.6E + 05	3,517	25
Antimony	171	2,600	249	25	95	2,400	403	15	16	900	76	44
Arsenic	221	51,600	33	50	228	1.6E + 06	507	51	75	2,130	14	54
Barium	68	10,000	365	16	111	6,100	273	24	63	5,560	455	16
Beryllium	166	702	2	***	101	102	4	***	16	143	4	***
Boron	18	45,800	887	32	54	2.2E + 05	4,954	23	19	1.8E + 05	5,723	13
Cadmium	239	396	10	57	223	8.0E + 05	107	67	109	370	11	50
Chromium	238	6,500	138	29	219	4.3E + 05	215	44	109	1,500	57	28
Hexavalent	15	5,200	104	50	5	2,000	303	26	13	8,000	149	36
Cobalt	-	-	-	-	105	4.5E + 04	2,074	27	-	-	-	-
Copper	216	2,530	46	25	163	3.1E + 05	268	40	91	2,800	35	28
Iron	268	3.9E + 06	47,700	21	174	1.3E + 07	12,900	29	164	1.0E + 07	76,800	16
Lead	244	9,100	76	32	157	7.2E + 04	79	49	109	4,280	48	32
Magnesium	-	-	-	-	42	6.8E + 05	71,480	11	-	-	-	-
Manganese	183	81,000	1,501	31	167	6.5E + 05	3,391	30	95	5.0E + 04	2,328	24
Mercury	228	50	1	***	220	2,300	3	***	101	1,200	1	****
Molybdenum	-	-	-	-	42	1.2E + 04	5	***	-	-	-	-
Nickel	213	9.7E + 05	272	28	168	6.9E + 04	1,264	25	75	1,700	137	18
Selenium	223	680	6	67	214	5,200	46	45	75	5,000	4	***
Silver	215	540	20	40	153	101	16	35	75	421	20	37
Sodium	58	8.9E + 06	31,300	18	104	1.8E + 07	1.1E + 06	10	47	4.7E + 06	2.9E + 05	17
Thallium	165	8,830	226	26	56	350	244	19	16	300	207	8
Tin	10	10,000	86	54	42	580	131	16	26	1.0E + 04	166	44
Titanium	-	-	-	-	45	2,500	47	5	-	-	-	-
Vanadium	-	-	-	-	46	2,700	83	40	-	-	-	-
Zinc	218	5.5E + 05	1,202	30	170	3.5E + 05	1,085	36	90	4.2E + 04	791	24

^acoef. var. = [log (Std. Dev.)/log (Geom. Mean.)] 100.^bcoef. var. was greater than 100%.

Table 3 Detected constituents in landfill leachate at six sites (from WMNA, 1991)

Parameter in (µg/l)	1	2	3	4	5	6
Acetone	3000	5200	540	4900	6700	ND
Acetophenone	ND	ND	ND	12	ND	ND
Antimony *	ND	9.3	ND	ND	ND	9.1
Arsenic *	ND	16	12	23	11	4.4
Barium	910	1400	250	110	940	260
Benzene *	15	ND	ND	ND	ND	ND
Beryllium *	ND	2.8	ND	ND	ND	2
Carbon disulfide	ND	ND	7	ND	ND	ND
Chlorobenzene *	10	ND	ND	ND	ND	ND
Chloroethane; Ethyl chloride *	30	ND	20	ND	ND	ND
Chloroform *	ND	ND	10	ND	ND	ND
Chromium *	26	68	ND	ND	75	35
Cobalt	23	52	ND	37	51	120
Copper *	52	87	ND	44	23	20
m-Cresol	1100	1500	110	720	900	ND
p-Cresol	1100	1500	110	720	900	1300
Cyanide *	18	12	98	ND	10	47
2,4-D	ND	ND	ND	ND	69	ND
p-Dichlorobenzene *	ND	ND	ND	14	ND	ND
1,1-Dichloroethane *	50	ND	12	200	100	ND
1,2-Dichloroethane *	87	ND	ND	ND	ND	ND
o,o-Diethyl o-2-pyrazinyl	ND	8.2	ND	ND	ND	ND
Dimethoate	12	9.6	ND	3.6	5.7	ND
Ethylbenzene *	13	ND	17	ND	ND	ND
2-Hezanone	73	ND	ND	ND	ND	ND
Lead *	24	23	ND	7.5	ND	83
Methyl chloride; Chloromethane *	14	ND	13	ND	ND	ND
Methylene chloride; Dichloromethane *	140	460	46	ND	590	ND
Methyl ethyl ketone; MEK	2900	6700	840	2000	13000	ND
Methyl parathion; Parathion methyl	0.38	ND	1.9	ND	ND	ND
4-Methyl-2-pentanone	420	ND	ND	ND	ND	ND
Nickel *	120	250	ND	23	94	370
Hexachlorodibenzofuran	0.028	ND	ND	ND	ND	ND
Pentachlorodibenzofuran	0.0016	ND	ND	ND	ND	ND
Phenol *	440	210	ND	82	200	110
Phorate	3.5	1.9	ND	ND	ND	ND
Silver *	41	34	15	27	24	21
Sulfide	ND	4600	1400	4000	ND	1400
Tetraethyl dithiopyrophosphate	ND	1.4	ND	ND	ND	ND
Toluene *	180	560	150	500	470	ND
Trichloroethylene; Trichloroethene *	12	ND	ND	ND	ND	ND
Vanadium	ND	43	ND	ND	ND	ND
Vinyl chloride *	20	ND	55	ND	ND	ND
Xylene (total)	44	ND	55	ND	ND	ND
Zinc *	650	890	780	350	640	600

*Indicates priority pollutant compound.

Published reviews on landfill decomposition processes which include some discussion of leachate chemistry include Pohland (1975); Halvadakis et al. (1983); and Barlaz, Ham, and Schaefer (1990). In controlled laboratory studies, the evolution of leachate chemistry can be linked to successive biochemical reactions during refuse decomposition. Barlaz, Schaefer, and Ham (1989), for example, studied chemical and microbiological processes of refuse decomposition in 2 liter containers. Also, in laboratory studies conducted in Germany over the last 10 years, a contrast in chemical composition is suggested between young leachates and those from fully methanogenic systems (Ehrig, 1991 and papers cited therein). Younger leachates are characterized by low pH, high TOC (total organic carbon), and high metals due to the production of intermediate decomposition products that accumulate in advance of significant methanogenic population development. These intermediate decomposition products include low molecular weight carboxylic acids, particularly acetic acid. Once methanogenesis is established, since acids are typically consumed at rates close to their rates of production, the pH is close to neutrality, TOC concentrations are reduced, and metals concentrations are low. Chloride, as a conservative ion, tends to remain at concentrations of a few hundred mg/L in all leachates.

The existing literature on leachate recirculation yields contradictory results with respect to the benefits of the practice. The water balance of a given test container (at laboratory scale) or test cell (at field scale) is often not considered, thus confounding the task of data evaluation by including any dilution effects. Barlaz, Ham, and Schaefer (1990) surveyed the literature prior to 1990 and concluded that leachate recycle plus neutralization was usually stimulatory for methanogenesis from fresh refuse. Barlaz, Ham, and Schaefer (1989; 1992) achieved very rapid rates of refuse stabilization by leachate recycle and neutralization in laboratory studies. A recent French study (Clement et al., 1992) also observed faster and more substantial biodegradation with leachate recycle plus pH control. Recent German studies at laboratory scale, in field cells, and full-scale landfill trials concluded that (1) recirculation stimulated a decrease in leachate COD and BOD; (2) it could not be proven that recirculation positively enhanced either gas production rates or landfill stabilization rates; (3) leachate recirculation could be an economic means of leachate treatment or pre-treatment, depending on leachate quantity and quality at a given site; and (4) gas condensates and leachate treatment sludges should also be considered candidates for landfill recirculation (Doedens and Cord-Landwehr, 1989). The reductions in BOD and COD with leachate recycle were also observed in an earlier field test cell study in Sonoma County, California (Leckie et al., 1979). As mentioned above, however, dilution effects may have contributed to the observed reductions in a number of these studies.

Other potentially important factors are maintenance of surface vegetation and physical transport processes during leachate recirculation. The former must be considered where leachate recirculation takes place by surface spraying or by shallow infiltration techniques in the root zone. The effect of recirculating leachate on vegetation was reviewed by Cureton et al. (1991) in reference to their own work with various candidate species, the most successful being reed canarygrass (*Phalaris arundinacea* L.). Previously, Ettala (1988) had investigated maximizing evapotranspiration as a means of reducing leachate volume during the recirculation process. Important issues with respect to vegetative growth on landfills with leachate recirculation include species selected for rapid establishment and wide tolerance of moisture/nutrient regimes, the need for relatively high infiltration rates, and both physical and chemical leachate/soil interactions. Finally, with respect to physical transport processes, leachate recirculation systems must promote uniform downward infiltration. However, throughout the unsaturated zone, due to horizontal discontinuities and nonuniform infiltration fronts, this is extremely difficult to achieve and has not been addressed in previous studies. Creative engineering solutions are needed to address physical aspects of maintaining efficient recirculation systems.

3.0 Methods

A standardized refuse mixture was incubated under controlled anaerobic conditions in new 125 mL glass serum bottles (Wheaton). The refuse mixture consisted of:

- paper — homogenized white Xerox stock, shredded;
- grass — fresh clippings with a few leaves (without recent fertilizer/herbicide application);
- food — mixture of bread, raw hamburger, apples, banana, lettuce, collard greens.

The relative quantities of each component are given in Table 4 for the base control samples with added sand or clay soil. In all, a target quantity of 15-16 g (dry weight) of the composite refuse sample plus 1 mL of high fructose corn syrup were added to each bottle. The purpose of the corn syrup addition was to include a small quantity of an easily degradable initial substrate. In addition a standard clay or sand soil was added to each assay. The soils had been well-characterized in previous work and functioned as internal laboratory standards at Argonne for various soil analyses. The clay had relatively high Kjeldahl nitrogen content and alkaline pH in contrast to the sand which was low in major nutrients (N,P) and more acid. In addition, the clay had higher DTPA extractable iron than the sand. Background chemical and physical data for the two soils are given in Appendix A.

Initial gravimetric moisture contents for the assays were in the range of 70-80 % (dry weight basis). Corresponding wet weight moisture contents would be 41-44%. In this report, we will consistently use gravimetric moisture contents calculated on a dry basis as these give more information with respect to the mass of water relative to the mass of dry solids in a given assay at a given time.

Table 4. Assay control quantities, included added sand and clay soils.

Assays with added sand soil:			
	<u>g /assay</u>	<u>% total solids (component)</u>	<u>mass dry solids (g) added</u>
Paper	2.00	94.3	1.9
Grass	3.00	66.5	2.0
Food	15.00	31.2	4.7
Sand	7.00	99.3	7.0
Corn Syrup	0.70	71.7	0.5
Total	27.70		
Water present	11.69		
Initial Water Content (% , dry weight basis) = 73.0			
Assays with added clay soil:			
	<u>g /assay</u>	<u>% total solids (component)</u>	<u>mass dry solids (g) added</u>
Paper	2.00	94.3	1.9
Grass	3.00	66.5	2.0
Food	15.00	31.2	4.7
Clay	6.65	97.8	6.5
Corn Syrup	0.70	71.7	0.5
Total	27.35		
Water present	11.78		
Initial Water Content (% , dry weight basis) = 75.7			

The various trials for this experiment included three moisture contents with two added soils run under either leachate drainage or leachate recycle regimes. The target moisture contents given below refer to weight water/dry weight soil, as commonly expressed in the engineering literature. The target moisture contents replicate either high solids (the 350% moisture content) or low solids (the 750% moisture) anaerobic digestion regimes. The high moisture contents were chosen so that moisture would not be limiting in the various trials in order to optimize decomposition under either the leachate drainage or leachate recycle modes. The trials were:

- a) 80% Moisture Content- Controls: no additional water added to starting refuse mixture, including
 - 10 replicates with clay soil addition (80C)
 - 10 replicates with sand soil addition (80S)
- b) 350% Moisture - Leachate Drainage Mode, including
 - 10 replicates with sand soil addition (350SD)
 - 10 replicates with clay soil addition (350CD)
- c) 350% Moisture - Leachate Recycle Mode, including
 - 20 replicates with sand soil addition (350SR)
 - 20 replicates with clay soil addition (350SD)
- d) 750% Moisture - Leachate Drainage Mode, including
 - 10 replicates with sand soil addition (750SD)
 - 10 replicates with clay soil addition (750CD)
- e) 750% Moisture - Leachate Recycle Mode, including
 - 20 replicates with sand soil addition (750SR)
 - 20 replicates with clay soil addition (750CR)

The larger numbers of replicates for the leachate recycle trials were for the purpose of providing sufficient assays for periodic tear-down and sampling of residual solids during the decomposition process. Four leachate recycle/leachate drainage events were planned for this experiment. For all assays except the controls (no moisture addition), the elevated moisture contents were achieved with the addition of a sodium sulfide (0.5 g/L) and resazurin (1.8 mL/L) solution using distilled water. Table 5 summarizes the initial moisture additions for the various assays. Note that the initial moisture contents differed slightly from the target moisture contents of 80%, 350%, and 750%.

Table 5. Initial moisture content and moisture additions for assays. All moisture contents expressed on a dry weight basis.

	Sand	Clay
Initial Water Content (Controls)	73.0	75.7
Moisture Addition for 350% (mL)	41	41
Moisture Addition for 750% (mL)	101	101
Resulting Moisture Content for 350%	329.3	339.0
Resulting Moisture Content for 750%	703.6	724.4

All assays were degassed with nitrogen for 45 minutes prior to sealing with a standard aluminum crimped seal over a butyl rubber stopper. Bottles were incubated at 40°C. The total gas produced in the assays was quantified using a glass water-lubricated syringe (Popper) — the syringe was inserted through the butyl rubber stopper; internal pressure was equilibrated to atmospheric pressure; and the gas production volume was recorded. Assays were de-gassed daily or as needed.

Gases were periodically analyzed on a Hewlett Packard 5890-Series II gas chromatograph (GC) equipped with a thermal conductivity detector (TCD) and a flame ionization detector (FID). Porapak Q columns (6 ft. x 1/8" SS, Alltech) were used on each injection port. The TCD detector was used for analysis of carbon dioxide and methane (>0.1%), and the FID was utilized for low methane concentrations (<0.1%). The GC was calibrated using a series of standards (AGA and Scott) over the entire analytical range (1 ppm - 50% methane and 0.03%-50% carbon dioxide).

For purposes of this experiment, a conservative approach was applied so that the need for assay neutralization and sludge addition to aid decomposition were determined during the course of the experiment. Periodic testing and analysis of gas, liquid, and solid fractions were used to scale the periodic additions.

The first leachate drainage and leachate recycle event occurred 24 days after the start of the experiment on August 17, 1992. Initial gas production (CO_2) was starting to subside by this time. For the 350% moisture leachate recirculation trials, leachate was extracted using 1 mL plastic disposable syringes (B-D). To avoid cross sample contamination each syringe was used only once. The leachate was withdrawn using the following procedure: the assay bottle was removed from incubator, bottle was shaken by hand and placed upside down for 10 minutes (after shaking the solids remained at the bottom of bottle allowing the liquid to drain to the top of the bottle when bottle was inverted for easier removal), the "free" liquid was then extracted with the 1 mL plastic syringes. This procedure was repeated for a total of 3 extractions with a 1-2 hour delay between sampling times. It was not possible to extract more than about 2 mL of leachate from any of the 350% moisture trials. Leachate quantities that were withdrawn were recorded and then temporarily stored in nitrogen purged 5-15 mL serum bottles (Wheaton). After the three extractions, leachate was then replaced back into the original serum bottle for the recycle trials. Four of the recycle assays (350%) from each of the sand and clay trials were destructively sampled (bottles 17, 18, 19, and 20). Bottle 17 was used for total solids and volatile solids analysis, along with being dried for future solid analyses. Bottles 18 and 19 were used for pH and conductivity analysis; also, the leachate was composited and prepared for future chemical analyses by following the procedure outlined in Appendix B. The remaining solids from bottles 18 and 19 were dried for later analysis. Bottle 20 of both the sand and clay recycle assays was used for a titration experiment to determine the required molarity of a potassium hydroxide/calcium hydroxide neutralizing solution for the 350% moisture assays. From this experiment, a strong 18M solution was determined to be required to neutralize the assays to promote the development of methanogenic populations. Thus 1 mL of an 18M solution of potassium hydroxide and calcium hydroxide (101 g KOH and 0.1g $\text{Ca}(\text{OH})_2$ per 100 mL) was injected into each 350% moisture recycle assay. The neutralizing solution was prepared with oxygen-free distilled water which was, in turn, prepared by bubbling nitrogen through the water for 30 minutes. After neutralization, the bottles were returned to the incubator.

Leachate samples from the 350% moisture content leachate drainage assays were extracted using the same technique. However, the leachate that was withdrawn from all of the 350% sand drainage assays was composited like the leachate recirculation trials due to low leachate volumes. The same procedure was followed for the 350% clay drainage assays. The leachate samples for the 350% sand and clay drainage trials were prepared for chemical analyses by the procedures outlined in Appendix B. Leachate quantities were recorded for individual assays, and the removed leachate in each assay was replaced by an equal volume of oxygen-free distilled water. Finally 1 mL of the neutralization solution (determined from the 350% recycle sand and clay titrations) was added to each of the drainage assays and then they were returned to the incubator. It should be noted that up to the point of the first recycle event, there was no difference between the drainage and recycle assays.

The 750% moisture content trials were extracted using the same technique as the 350% moisture trials. However, a standard volume of 30 mL of leachate was withdrawn from each of the trials (recycle and drainage) using individual 5 mL disposable syringes (B-D). For the 750% moisture drainage trials the withdrawn volume was again replaced with oxygen free distilled

water. Leachate from Bottles 1, 5, and 10 (leachate drainage) were kept as individual samples, with the remainder (bottles 2, 3, 4, 6, 7, 8, and 9) composited, and prepared for chemical analyses as described in Appendix B. Four of the leachate recycle assays were destructively sampled as described above for the 350% recycle assays. The leachate from bottles 18 and 19 for the sand and clay trials were prepared for analysis as described in Appendix B. Finally, 1 mL of the neutralization solution (101g KOH and 0.1g Ca (OH)₂ per 100 mL) was added to each of the 750% assays (recycle and drainage) that remained, and all were returned to the incubator.

The second recycle/drainage event occurred on October 12, 1992, day 83 since the start of the experiment. Leachate from the bottles were extracted using the same procedure as the first recycle and drainage event. However, for the 350% drainage trials, a constant 1 mL of leachate was removed. Leachate samples were composited to form three master samples based on leachate production quantities during the previous recycle event. The composited leachate samples were then prepared for chemical analysis following the procedure outlined in Appendix B. Bottle 10 from both the sand and clay drainage trials was used for a titration experiment to determine the necessary molarity of a second neutralizing solution.

For the 350% moisture recycle trials, bottles 1-12 also had 1 mL of leachate removed and then re-injected, using a new syringe for each withdrawal or injection. Bottles 13-16 were destructively sampled in a fashion similar to the first recycle/drainage event. Bottle 13 was opened and sampled for total solids and volatile solids, and the remainder dried for solids analysis. Bottles 14 and 15 were sampled and prepared as outlined in Appendix B, with the remainder of solids dried for future analyses. Bottle 16 was used for the titration experiment.

For the 750% moisture drainage trials, 5 mL of leachate was removed from each of the bottles 1-9 and composited into three master samples. The composited leachate samples were then prepared for further chemical analysis following the procedure outlined in Appendix B. Then 5 mL of oxygen-free make-up water was added to each bottle. Bottle 10 of both the sand and clay series was used for the titration experiment.

For the 750% moisture recycle trials, bottles 1-12 each had 5 mL of leachate removed and then re-injected using a new syringe for each withdrawal or injection. Bottles 13-16 were destructively sampled as described above for the first recycle/drainage event. Bottle 13 was opened and sampled for total solids and volatile solids, and the remainder dried for additional solids analysis. Bottles 14 and 15 were sampled and prepared as outlined in Appendix B, with the remainder of solids dried for future analyses. Bottle 16 was used for the titration experiment.

At this point in the experiment, at day 83, a methanogenic seed was added via an injection of 0.2 mL of wastewater treatment sludge to each assay. It should be noted that, based on median leachate pH values of approximately 6 at the time of second recycle/drainage event, the results of the titration experiments, and the anticipated sludge addition, there was no sample neutralization at this time. The sludge consisted of fresh bottom sludge obtained from the second (methanogenic) stage of a two-stage anaerobic digester located at the DuPage County Woodridge Treatment Plant, Woodridge, IL. The sludge was added to each assay (except controls) using a disposable 1 mL syringe. After this addition, all bottles were returned to the incubator.

The third recycle/drainage event occurred on December 7, 1992, day 139 since the start of the experiment. The bottles again were extracted using the same procedure as before. For the 350% drainage trials, 2 mL of leachate was removed and composited as before. The composited leachate samples were then prepared for chemical analysis following the procedure outlined in Appendix B.

For the 350% moisture recycle trials bottles 1-8 each had 2 mL of leachate removed and then re-injected using a new syringe for each withdrawal or injection. Bottles 9-12 were destructively sampled as had been done for previous events. Bottle 9 was opened and sampled for total solids and volatile solids, and the remainder dried for solids analysis. Bottles 10 and 11 were sampled and prepared as outlined in Appendix B, with the remainder of solids dried for future analyses. Bottle 12 was used for the titration experiment.

For the 750% moisture drainage trials, 20 mL of leachate was removed and composited into three master samples. The composited leachate samples were then prepared for chemical analysis following the procedure outlined in Appendix B. 20 mL of oxygen-free make-up water was added to each of the 750% moisture drainage assays.

For the 750% moisture recycle trials, bottles 1-8 had 20 mL of leachate removed and then re-injected using a new syringe for each withdrawal or injection. Bottles 9-12 were destructively sampled as had been done for previous events. Bottle 9 was opened and sampled for total solids and volatile solids, and the remainder dried for future analysis. Bottles 10 and 11 were sampled and prepared as outlined in Appendix B, with the remainder of solids dried for future analyses. Bottle 12 was used for the titration experiment.

From the titration experiments performed on the leachate recycle bottles, it was determined that a 10 M potassium hydroxide solution (56.11 g KOH / 100 mL) would be used for neutralization. Then 1 mL of this solution was added to each assay (except the controls), and all bottles were returned to the incubator.

On February 10, 1993, day 204 since the start of the experiment, in an effort to further stimulate methane production, the bottles were each inoculated with 3 mL sludge. The fresh sludge was again obtained from the second (methanogenic) stage of a two-stage anaerobic digester located at the DuPage County Woodridge Treatment Plant. To add the sludge, each butyl rubber stopper was removed, the sludge was injected directly into a given serum bottle using a disposable 5 mL syringe, and the stopper was replaced. The opened serum bottles were purged continuously with nitrogen while the stopper was removed. After the sludge addition, the serum bottles were purged for an additional 10 minutes and new butyl rubber stoppers were placed in the bottles, the bottles were re-crimped with aluminum seals, shaken by hand, and returned to the incubator. This procedure was followed for all the 350% moisture and the 750% moisture trials remaining — the controls had no sludge addition.

The fourth and final recycle/drainage event occurred on June 7, 1993, day 321 of the experiment. Leachate was again extracted as before, using disposable syringes. A total of 1 mL of leachate was extracted from each of the 350% moisture assays and 10 mL from each of the 750% moisture assays. The leachates were composited and then prepared for chemical analysis by the procedure outlined in Appendix B. Leachate samples were composited according to historic gas production (low, medium, high). The remaining solids were sampled (for total solids and volatile solids), and the assays were set aside to dry for additional solids analyses. The assays with low and intermediate gas production were torn down at the end of the fourth event.

The remaining bottles (high gas production) were treated in the same fashion as the other three recycle and drainage events but were not immediately torn down as with the low and intermediate producers. The 350% moisture assays had 1 mL extracted from them which was then re-injected or replaced with oxygen free water. The 750% moisture assays had 10 mL of leachate extracted, and likewise this was either replaced with oxygen free water or re-injected. Samples were not composited. The leachate was prepared for chemical analysis by following the procedure in Appendix B. The remaining bottles were then returned to the incubator. Incubation continued to approximately 400 days to determine an optimum methane potential for the high producers.

All filtered liquid samples were analyzed for C1-C5 carboxylic acids (volatile fatty acids) using gas chromatography by the Argonne Analytical Chemistry Laboratory. The technique consisted of hot on-column injection to a DB-FFAP column (30m, 0.53 μ m) (J & W Scientific) connected to a flame ionization detector (FID) on an HP 5890A gas chromatograph. The injector temperature was 225 °C; the column temperature was ramped over a 10 min run from 125 °C to 150 °C; and the FID temperature was 275 °C. Column flow rate was 3.0 mL/min using He as a carrier. The total carboxylic acids reported represent the sum of the individual acids quantitated. The filtered leachate samples were also analyzed for total organic carbon, iron, zinc, Kjeldahl nitrogen, total phosphorus, and chloride using methods described in Appendix C. Standard methods were used for total solids and volatile solids analysis (Standard Methods, 1992). Total carbon, nitrogen, and hydrogen of solids were analyzed by the Argonne ACL using a LECO 900

CHN analyzer at a temperature of 1000° C. Cellulose and lignin were determined by the U.S. Dept. of Agriculture Forest Products Laboratory in Madison, Wisconsin, using standard techniques as described in Appendix D. With the exception of the cellulose and lignin analyses, all analytical work was completed at Argonne National Laboratory.

4.0 Results and Discussion

The following sections of this report will discuss the results of this laboratory study with respect to gaseous, liquid, and solid phases, thus addressing gas production, leachate chemistry, and a comparison of initial to final solids analysis. In all cases, the mean of replicates for a given treatment will form the basis for discussion. Some anaerobic digester literature that discusses selected aspects of the chemistry of refuse degradation includes Bjorndal and Moore (1988); Magruder et al. (1988); and Perot et al. (1988). However, there is little guidance in the literature regarding the anaerobic degradation of refuse/soil systems, with an emphasis on the dynamics of carbon and nitrogen.

4.1 Gas Production and Carbon Conversion

Summary plots of cumulative gas production are given in Figures 1a through 1e. Results and standard deviations for the various trials are given in Table 6. Also given in Table 6 are the specific results for methane production. Note that the differences in gas production between the leachate recycle and the leachate drainage assays do not suggest any benefit resulting from leachate recycle.

Figure 1. Cumulative gas production (mL) during 400 days incubation.

Figure 1. Cumulative gas production (mL) during 400 days incubation.

Table 6. Summary of Gas Production.

Assay	Total Gas Production (mL)	std.dev.	Total Methane (mL)
80C	228	68	<0.01
80S	187	34	<0.01
350C-DRAIN	5618	86	2842
350C-RECYCLE	3877	2223	1469
350S-DRAIN	5420	151	2753
350S-RECYCLE	4828	159	2298
750C-DRAIN	959	56	297
750C-RECYCLE	1068	112	264
750S-DRAIN	1124	77	430
750S-RECYCLE	1160	42	336

The high standard deviation associated with the 350C recycle assays reflects the wide range of gas production for this particular set of assays. There were no indications of leakage or lower pH for the low producers, nor were there any differences in original set-up of these assays; thus, at present, we can only attribute these results to natural variability within microbially-controlled systems. Barlaz (1988) discussed possible causes for inhibition among refuse assays. There was insufficient leachate sample from individual assays for further investigation.

If one examines methane production alone, note that it was always higher for the leachate drainage as opposed to the leachate recycle assays. With respect to total gas production, for the 350% moisture content assays, the production was higher for the drainage than for the recycle assays; total gas production was slightly higher for the recycle assays at 750% moisture content.

Drastically different gas production results were achieved at the moisture contents studied, resulting in greater cumulative gas production for the lower water content assays. Averaging the above results across the two moisture contents, the methane production for the 350% assays is 2341 mL with a standard deviation of 544 as opposed to 332 with a standard deviation of 62 for the 750% assays. Even though all the assays were periodically neutralized, as discussed above, rapid hydrolysis and carboxylic acid production in the higher water content assays apparently exceeded the ability of acetogenic and methanogenic populations to utilize these acids, resulting in lower overall gas production. This will be discussed further in the next section of this report dealing with aqueous chemistry of the assays.

In addition, one can examine the gas production results with respect to the type of soil added (sand vs. clay). Averaging the above results across soil types without respect to mode of operation, the assays with the added sand soil were characterized by higher overall methane production at both moisture contents. We attribute these results to better mixing of liquids and solids within the assays with added sand soil. We might add parenthetically that draining leachate from the assays with added clay soil was difficult using the syringe technique discussed above, also suggesting freer mixing in the assays with added sand soil.

Table 7 indicates carbon conversion for the various assays. The carbon conversion is expressed as the fraction of original carbon converted to biogas carbon (methane plus carbon dioxide). As shown in the table, the 350% moisture content assays generally showed better than 40% carbon conversion while the 750% moisture content assays were in the range of 7-10%. As noted above for the gas production data, the 350CR (clay recycle) assays lagged behind the other 350% moisture assays. Figure 2 shows the relationship between biogas production and carbon conversion for these particular assays.

Table 7. Carbon conversion. Fraction of total carbon converted to biogas C (methane plus carbon dioxide) after four recycle events.

Assay	Total C converted to biogas C (fraction)
80C	0.0042
80S	0.0032
350C-DRAIN	0.47
350C-RECYCLE	0.27
350S-DRAIN	0.47
350S-RECYCLE	0.41
750C-DRAIN	0.07
750C-RECYCLE	0.07
750S-DRAIN	0.10
750S-RECYCLE	0.08

Figure 2. Relationship between cumulative gas production and carbon conversion for this study. Included is fractional conversion of original carbon to biogas carbon (methane and carbon dioxide).

A compilation of data from the literature on carbon conversion during laboratory decomposition of refuse suggests that, at best, 25-45% conversion is observed (Bogner and Spokas, 1994). As has been pointed out by Barlaz et al. (1989), more than 90% of the methane potential of a typical U.S. refuse (Madison, WI) can be attributed to cellulose and hemicellulose with minor contributions from other degradable fractions. Thus the carbon conversion figures, to a large extent, reflect the preferential degradation of cellulose over lignin during anaerobic burial. It should be noted that organic carbon is also sequestered in microbial biomass in these settings. In general, these low rates of carbon conversion (less than 50% at best) have implications for large quantities of carbon entering long term carbon storage in landfill environments (Bogner, 1992; Bogner and Spokas, 1994). Issues related to cellulose conversion will be addressed in more detail below with reference to the solids analysis.

4.2 Leachate Chemistry

Table 8 summarizes leachate chemistry during decomposition with respect to the four leachate recycle/leachate drainage events. Additional data, including individual carboxylic acids for the various leachates, are given in Appendix E--Supporting Data. Included in the table are total carboxylic acids (VFA, volatile fatty acids), acetic acid (HAc), total organic carbon (TOC), selected major nutrients including Kjeldahl nitrogen (TKN) and total phosphorus (TP), selected metals (Fe and Zn), chloride (Cl), pH, and conductivity. Also included are the final gravimetric moisture contents for comparison with the initial moisture contents given above in Table 5. This section will focus on the leachate data with reference to Table 8 and some accompanying figures.

In general, as shown in Table 8, the total carboxylic acids consistently increase through the third recycle/drainage event and decline thereafter. The only exceptions are the 750% moisture recycle assays where total acids reach a maximum at the time of the fourth recycle/drainage event. For the 350% moisture assays, particularly for the leachate drainage assays with sand soil added, the total acids decrease dramatically between the third and fourth recycle/drainage events.

Table 8. Summary of leachate chemistry during the four recycle/drainage events. All units mg/L except pH, conductivity (umohs/cm), and final gravimetric moisture content (W%). The latter reflects the final moisture content (dry weight basis) at the end of 400 days incubation.

Trial	TOC	VFA	HAC	TKN	TP	Fe	Zn	Cl	pH/cond	W%end
350CD-1	26100	5360	5160	1070	130	2220	56	700	3.55/330	
350CD-2	27300	45100	24400	786	14	1350	103	789	6.06/589	
350CD-3	46400	95300	21400	836	11	930	146	1080	5.51/494	
350CD-4	22500	12000	800	931	37	13	32	734	8.05/552	643
350CR-1	25900	3140	3140	455	72	5190	88	834	3.55/331	
350CR-2	25800	68900	28000	813	15	1056	341	700	5.55/489	
350CR-3	38500	106000	27600	901	19	1050	180	1400	5.44/534	
350CR-4	38600	83700	12800	937	13	8	18	696	7.41/553	559
350SD-1	27700	3790	3790	688	91	319	135	888	3.48/313	
350SD-2	25300	50700	25800	889	34	143	103	565	5.86/476	
350SD-3	46200	126000	37500	1140	29	152	160	1110	5.48/484	
350SD-4	24100	50300	2100	978	47	17	42	593	7.85/512	1025
350SR-1	20280	6600	6600	1070	153	306	262	767	3.48/333	
350SR-2	27300	46400	28200	943	46	232	79	700	5.32/537	
350SR-3	36100	137000	34300	721	30	137	169	1130	5.6/509	
350SR-4	40500	82400	1500	940	57	12	27	1310	7.27/549	973
750CD-1	12000	4020	3880	568	62	610	77	68	3.77/66	
750CD-2	10600	32500	15300	448	13	422	76	53	5.35/231	
750CD-3	20100	86200	32200	524	21	367	203	435	5.01/218	
750CD-4	23300	67000	22800	523	13	245	46	247	4.99/310	1673
750CR-1	13200	5580	5100	625	47	555	109	138	3.69/727	
750CR-2	12700	36300	16000	561	6	572	113	91	5.44/281	
750CR-3	25800	62100	22700	702	13	585	168	504	5.13/271	
750CR-4	33200	99400	39800	643	12	450	30	386	5.32/630	1216
750SD-1	8610	176	163	609	57	139	56	16	3.36/730	
750SD-2	10500	28900	13100	433	15	35	99	30	6.45/236	
750SD-3	21500	69200	26300	731	24	77	203	425	5.05/236	
750SD-4	22900	55200	21800	536	47	48	34	237	4.99/280	1929
750SR-1	6830	0	0	568	70	156	115	91	3.36/726	
750SR-2	13100	37500	19000	423	16	80	161	213	5.86/275	
750SR-3	23400	98300	33700	505	47	119	137	584	5.11/301	
750SR-4	16100	105000	41600	573	57	93	33	396	5.16/379	1544

1,2,3,4 refer to the four leachate recycle events

350,750 = W % initial, nominal (dry weight basis)

C,S, = Clay or Sand soil added

R,D = Recycled leachate (R) or leachate drained (D) with make-up water added.

The dynamics of individual acids differed through the decomposition process. Figure 3 summarizes the content of the most abundant carboxylic acids through the various leachate recycle/drainage events in separate plots for the two moisture contents. Figure 4 gives parallel data for pH for the four events while Figure 5 contains a plot of pH vs. total carboxylic acids concentration, which peaked at about pH 6.0. Typically, pH was 3.0-4.0 for the first event, rising to 5.0-6.0 for the second and third events, and reaching 7.0-8.0 by the fourth event for the 350% moisture assays. For the 750% moisture assays, pH's for both the third and fourth events were both in the range of 5.0 to 5.5, suggesting that the batch neutralization after the third recycle was rapidly outstripped by acid production. For the 750SD assays, the neutralization after the first recycle/drainage event was sufficient to maintain pH above 6.0 through the second event, while, for the other 750% moisture assays, pH's were in the range of 5.0-6.0 at the time of the second event.

For the various events, early acid production was mainly acetate with the share of acid production attributed to acetate declining for the later recycle/drainage events. By the fourth event, the ratio of acetate concentration to the sum of the acetate, butyrate, and n-propionate concentration was always less than one third for the 350% moisture assays and less than one half for the 750% moisture assays. There are several possibilities for this observed proportion: 1) the efficiency of conversion of the other acids to acetate (acetogenesis) was low, resulting in the observed build-up of other acids relative to acetate during the later recycle/drainage events; 2) the conversion of acetate to methane (via acetate cleavage) has become more efficient with longer incubation times, resulting in lower observed acetate concentrations by the fourth recycle/drainage event; and 3) sequential degradation of various substrates within the synthetic refuse mixture is contributing to the observed differences.

The higher acetate concentrations for the fourth event were characteristic of the 750% moisture assays rather than the 350% moisture assays. This suggests more rapid acidogenesis due to the higher moisture content but lower than desirable rates of acetate conversion to methane, consistent with the lower gas production data cited in the previous section. Comparing the assays at the two moisture contents with respect to the various carboxylic acids shown in Figure 3, the propionate concentration increases through the fourth recycle event while the butyrate is typically highest for the third recycle event. The literature emphasizes that acetogenesis, or conversion of higher carboxylic acids to acetate, is strongly linked to methanogenesis by hydrogen reduction through hydrogen partial pressures in a given anaerobic system. That is, the conversion of propionate to acetate, for example, is only energetically favorable at extremely low hydrogen partial pressures (McCarty, 1981). The hydrogen-utilizing methanogens, via this syntrophic relationship, thus encourage acetogenesis. The accumulation of propionate in the assays suggests that this relationship was not functioning efficiently. Propionate buildup in a mixed soil/cellulose system has been recently observed by Kotsyurbenko et al. (1994). There was also high propionate relative to acetate reported at one site in an earlier landfill study (Johannsen and Carlson, 1976).

Figure 3 Concentrations of major carboxylic acids in leachate through the four recycle/drainage events.

Figure 4. Observed changes in leachate pH through the four recycle/drainage events.

Other aspects of the aqueous chemistry of the leachates are also shown on Table 8. Since filtered samples were analyzed, total organic carbon (TOC) should be related to total carboxylic acids as the major component of the aqueous organic carbon in these systems; for example, see Figure 5 for the 350% moisture assays. Although these data exhibit some variability, if one compares the measured TOC to the calculated carbon content of the carboxylic acids, the slope of the fitted regression lines shown in Figure 5 suggest that the TOC technique could adequately quantify the organic carbon content of these assays. Figure 6 compares the total carboxylic acids (total VFA's) to pH, suggesting a peak pH value of about 6.0. Harmsen (1983) previously quantified the major components of the TOC in acid and methanogenic leachates; he concluded that over 95% of the high TOC in acid leachates was attributable to volatile acids while the low TOC in the older leachate was dominated by higher molecular weight organic compounds.

With respect to major nutrients during the four leachate recycle/drainage events, nitrogen and phosphorus concentrations are compared in Figures 7 and 8, respectively. The nitrogen data (total Kjeldahl nitrogen) are highly variable, as evidenced by a comparison of values between the first recycle and drainage events for a given moisture content and soil addition. Since the assays were run identically up to the first event, the average concentrations should compare more favorably. Thus, these numbers should perhaps be used as an indication of the general range of values for nitrogen. Taken as whole, these data suggest that these assays were not nitrogen-limited, assuming that nitrogen would be present in reduced forms within the serum bottles. There were no obvious differences between the assays with the added clay soil (with higher indigenous nitrogen than the sand soil); however, the contribution of nitrogen from the various food fractions also contributed to the total observed nitrogen in these assays. This will be addressed more in the next section with discussion of the solids data. In general, the 750% moisture assays had lower observed nitrogen for any given assay type, suggesting simple dilution effects.

Figure 5. Relationship between total carboxylic acid concentrations (Total VFA) and total organic carbon. All units mg/L.

Figure 6. Relationship between total carboxylic acid concentrations (Total VFA) and pH.

Figure 7. Comparison of observed (Kjeldahl) nitrogen concentrations in leachate through the four recycle/drainage events.

Figure 8. Comparison of observed phosphorus concentrations in leachate through the four recycle/drainage events.

The phosphorus data (Fig. 8) indicate phosphorus concentrations were highest at the time of the first recycle event for all assays. For later events, for assays with added clay soil, concentrations were always less than about 1/3 of the observed concentration after the first event. However, for the 750% moisture content assays with added sand soil, the phosphorus concentrations peaked at the first event, dropped very low at the time of the second event, and then rose steadily from the second through the fourth event. The reasons for this are unclear; however, two possible causes are lower phosphorus utilization and secondary contributions of phosphorus from the sandy soil. The literature suggests that where sufficient nitrogen is available, the phosphorus requirement for anaerobic digestion of complex organic substrates should be about 15% of the nitrogen. (see discussion in Speece, 1983) In all cases, this criterion is met in the assays included in this study.

A major consideration for the assays studied is the issue of simple dilution with respect to observed concentrations during the various recycle/drainage events. One way to examine dilution is to compare the changes in assay moisture content during decomposition. Figure 9 compares initial (as fabricated) and final moisture contents for the various assays. Note that, on a gravimetric dry weight basis, there are substantial increases between the initial and final values for all assays except the controls. In addition, for the nominal 350% (starting) moisture content assays, there are also substantial differences related to the added clay or sand soil, with the higher final moisture contents for assays with added sand soil. For the nominal 750% (starting) moisture content assays, the differences were related more to the recycle vs. drainage comparison, with the drainage assays exhibiting the higher values.

One can also compare concentrations of chloride, as a conservative ion in aqueous systems, to changes in moisture content during decomposition. Figure 10 compares chloride concentrations for the 350% and 750% moisture assays during the four events. Note that chloride concentrations are typically low for the first two events and peak at the third event. This trend is similar to the trend for the total carboxylic acids, suggesting that decomposition had not reached any sort of steady state since leachate concentrations were increasing as moisture contents were increasing. However, at the third event, chloride concentrations for the 350% moisture assays were roughly half those of the 750% moisture assays, suggesting some dilution effects. If chloride is plotted against gravimetric moisture content for all the leachate events, there is a possible inverse relationship (Fig. 11) which would have been better except for the very low chlorides in the initial event for the 750% moisture assays. The dilution effect is strongly suggested in this figure with the higher moisture contents associated with the lower chlorides.

Examining selected metals, namely iron and zinc, there were some differences in the behavior and concentrations of these metals in the systems studied. Figures 12 and 13 show plots of zinc and iron concentrations, respectively, during the four recycle/drainage events. Note that zinc concentrations typically peaked at the time of the third event with two exceptions, the 350SR and the 750SR assays. Peak concentrations for both the 350% and 750% moisture content assays were in the range of 150-350 mg/L. Some pH dependence of zinc concentrations is suggested in Figure 14 which included data from the first and fourth events to maximize the range of pH data. Iron concentrations, on the other hand, typically were highest at the time of the first event. Moreover, iron concentrations in the leachates studied were higher for the assays with added clay soil, which has higher indigenous iron concentrations than the sand soil (see Appendix A). The peak concentrations of iron in the 750% moisture assays with added clay soil were less than 30% of the concentrations for the 350% moisture assays, suggesting some influence of dilution effects. The rapid release of iron by the time of the first event suggests that the iron in the clay soil was in a readily soluble form. Thus, the dynamics of individual metals may be quite different, depending on their original form and aqueous chemical processes influencing their dissolution.

Finally, with respect to dilution effects, we calculated the load of various constituents within the assay bottles as the product of the constituent concentration and the gravimetric moisture content (dry weight basis) expressed as a fraction. This calculation, in effect,

normalizes the concentration with respect to the amount of moisture relative to dry solids in a given bottle at a given time. Then we compared the resulting datasets for selected variables vs. chloride, the conservative ion in aqueous systems. In all cases, a positive relationship was observed, as plotted in Figure 15 for carboxylic acids for the two starting moisture contents. Similar plots were obtained for other major variables such as total organic carbon, acetate, and kjeldahl nitrogen (plots not shown). The direct linear relationship between these other constituents and chloride, whose concentration is dependent on simple dissolution, strongly indicates that the observed concentrations are moisture-content dependent.

Figure 9. Comparison of observed gravimetric moisture contents (dry weight basis) for assays at beginning and end of incubation period. Starting moisture contents = St; first leachate recirculation = 1; and final moisture content = F.

Figure 10. Comparison of observed chloride concentrations in leachate through the four recycle/drainage events.

Figure 11. Relationship between chloride concentration and gravimetric moisture content (dry weight basis) during the four recycle/drainage events.

Figure 12. Comparison of observed zinc concentrations in leachate through the four recycle/drainage events.

Figure 13. Comparison of observed iron concentrations in leachate through the four recycle/drainage events

Figure 14. Relationship between observed zinc concentration and leachate pH during the four recycle/drainage events.

Figure 15. Relationship between chloride loading and carboxylic acid (VFA) loading in 350% and 750% moisture assays. Data points were calculated from the product of the gravimetric moisture content expressed as a fraction and the variable value.

4.3 Chemistry of Solids

As discussed above, most of the methane potential for anaerobic degradation of refuse is derived from the cellulose + hemicellulose fractions. This is due to the large paper content of refuse plus contributions from cellulosic materials contained in food and garden wastes. Lignin is recalcitrant to anaerobic digestion and sometimes retards degradation of cellulose due to its presence as a surficial sheath in combination with various cellulosic plant materials. With this in mind, it is useful to examine the cellulose, hemicellulose, and lignin contents of the various assays at the beginning and end of incubation. Figure 16 summarizes the cellulose and hemicellulose content of the various assays. The starting values for the sand and clay controls will be the same values for all of the assays, since these are calculated on a dry weight basis. For the 350% and 750% moisture assays, the values given in the figure are for the first leachate recycle and the final value at the end of incubation (after the fourth leachate recycle). It is interesting to note that considerable cellulose degradation occurred in the controls, with final values similar to the values obtained at the first leachate recycle for the 350% moisture assays. There were no benefits to the leachate recycle mode of operation over the leachate drainage mode in this experiment with respect to loss of cellulose + hemicellulose; indeed, in most cases, the final cellulose + hemicellulose for the leachate recycle assays were higher than for the leachate drainage assays.

Figure 16. Comparison of cellulose and hemicellulose contents of assay solids at beginning of incubation (Clay control; Sand control); after the first recycle/drainage event (1); and at the end of 400 days incubation (F).

The cellulose/lignin ratios for the same data are plotted in Figure 17. This figure supports the same trends discussed in the previous figure with the addition of the cellulose/lignin ratio values for comparison to others presented in the literature. Bookter and Ham (1982) presented values ranging from about 4.0 to <1.0 for fresh vs. degraded refuse. The starting values shown in this figure are much less than 4.0, approximate 0.6, due to the large contribution of the clay or sand soil added, which is here quantified with the "lignin" fraction. If a recalculation is made for the standardized refuse without the soil, the starting value is 4.3 for this ratio. When using actual landfill samples, one must use caution in interpretation of results since the lignin is quantified as the insoluble residue after acid hydrolysis (see appendix D for method). Thus, any insoluble materials retained in the bulk dried sample will be included in the lignin fraction. To some extent, this error can be minimized by sample pretreatment to remove nonorganic fractions. The declining cellulose/lignin ratio through the process of decomposition is shown in Figure 18. Here, cellulose/lignin is plotted gravimetric moisture content, which increased through the experiment in the various assays.

The individual hemicelluloses are plotted separately in Figure 19. The major changes between the fresh refuse (C control, S control) and the first recycle/drainage event involves the loss of the xylan. Between the first and fourth events, both the xylan and mannan are affected more than the other fractions. Ghosh et al. (1985) discuss anaerobic digestion of the hemicellulose fraction as a whole but do not discuss the dynamics of individual sugars during anaerobic decay.

Figure 17. Comparison of cellulose/lignin ratios for assay solids at beginning of incubation (Clay control; Sand control); after the first recycle/drainage event (1); and at the end of 400 days incubation (F).

Figure 18. Relationship of cellulose/lignin ratio to gravimetric moisture content (dry weight basis).

Figure 19. Comparison of hemicellulose contents of assay solids at beginning of incubation (Clay control; Sand control); after the first recycle/drainage event (1); and at the end of 400 days incubation (F).

Finally, examining total carbon, total nitrogen, and carbon/nitrogen ratios for the dry solids before (St), during (1 for first event), and at the end of the incubation period (F), as shown in Figures 20-22, some general trends are apparent. With respect to carbon, one can see that carbon contents for the controls, with negligible carbon conversion to biogas, were relatively constant. The small amount of variation shown in Fig. 20, from about 23-25%, was within sampling and experimental error. For all the other assays, a decrease in total carbon was noted consistent with the carbon conversion data discussed above. The fractional conversion of total carbon to biogas carbon between the first recycle/drainage event and the end of the experiment ranged from about 0.10 to 0.50. This is reasonably consistent with previous literature on optimized refuse decomposition where carbon conversion ranges between 0.25 and 0.40. The lower values around 0.10 were characteristic of the 750% moisture assays and were attributed to high rates of production of intermediate carboxylic acids, retarding development of methanogenic populations. It should be noted that, in Figure 20, "increases" in total carbon in some assays between the controls and the first recycle event are an artifact of early losses of other soluble constituents relative to carbon.

With respect to nitrogen (Fig. 21), the controls tended to show increases in the % nitrogen between the initial and final samples. There was no sludge addition to the controls and, certainly, some of this increase could be attributed to sampling/experimental error. However, since all of the bottles were degassed with nitrogen, denitrification and retention of reduced nitrogen within the solid phase is also possible, perhaps as ammonium ions not utilized by microbial systems. It should be noted that, due to the low biogas production in the controls, there was quantifiable nitrogen in the headspace gas. For all of the rest of the assays, there was a net decrease in nitrogen in the solid phase, which is consistent with microbial utilization of nitrogen. Examining the carbon/nitrogen ratios (Fig. 22), the values for all the assays shown range from about 12 to 30. The controls and most of the 350% moisture assays show a decrease from initial to final values. However, the 350CR and all of the 750% moisture assays show an increase. This can be attributed to microbial utilization of nitrogen in the assays combined with lower overall rates of biogas production and lower carbon conversion, as given above in Tables 6 and 7. Thus, the solids data in large part supports the gas production and carbon conversion data.

Figure 20. Comparison of total carbon content of assay solids at beginning of incubation (Clay control; Sand control); after the first recycle/drainage event (1); and at the end of 400 days incubation (F).

Figure 21. Comparison of total nitrogen content of assay solids at beginning of incubation (C; Clay control; Sand control); after the first recycle/drainage event (1); and at the end of 400 days incubation (F).

Figure 22. Comparison of carbon/nitrogen ratios for assay solids at beginning of incubation (C; Clay control; Sand control); after the first recycle/drainage event (1); and at the end of 400 days incubation (F).

5.0 Conclusions and Recommendations

This study was undertaken at small laboratory scale to address technical questions relating to the net effects of leachate recirculation with respect to methane production, rate of stabilization, and leachate chemistry. In addition, two types of soil were included in the experimental design to indicate whether their physical and chemical properties influenced leachate chemistry. At constant starting moisture contents, there were no quantifiable benefits to leachate recirculation over leachate drainage with respect to methane production, carbon conversion, or leachate quality. The assays in this study were incubated as batch systems in serum bottles with periodic leachate manipulation, thus similar to decomposition in actual landfill settings where discrete cells are filled at given times and operate as batch reactors. The assays were conducted at high initial moisture contents to minimize mixing limitations and could be considered optimized landfill batch reactors, with results that are useful in the general context of landfill decomposition processes. The added soils chosen for this experiment had small but recognizable effects on leachate chemistry, especially with regard to iron. However, better mixing and easier extraction of leachates were characteristic of the assays with the added sand soil.

In future studies, in both laboratory and field batch reactors, a careful evaluation of the dynamics of the water balance during decomposition is needed. This would serve the purpose of better separating the effects of simple moisture addition on gas production and simple dilution on leachate chemistry from the effects of leachate recirculation or drainage *per se*. In effect, a dynamic water balance is needed which includes water content changes due to internal processes of biodegradation as well as any external contributions. It is especially critical to view leachate concentrations with respect to overall moisture contents in order to evaluate dilution effects.

The results of this study suggest the need for additional studies of the chemical aspects of leachate recirculation in well-controlled experiments at various scales. There are, realistically, very few studies which address leachate recycle in landfill/soil systems which address the important issues of water balance dynamics, nutrient cycling, carbon balance, or the dynamics of the various carboxylic acids. Laboratory studies have the advantage of a high level of process control, routine use of replicates and multiple controls in experimental designs, and low cost. The combination of laboratory studies and realistic process modeling should form the basis for careful scale-up to field studies. Thus, the following recommendations are made:

1. In studies at various scales, the water balance should be carefully evaluated to separate dilution effects from overall changes in leachate chemistry.
2. Soils are an important element in virtually all landfill systems where soils are used as daily, intermediate, and final cover materials. Soil chemistry must be taken into consideration in this complex system and may be expected to be a major influence on certain aspects of leachate chemistry.
3. Physical aspects of liquid redistribution and mixing in landfill systems must be considered, even at small laboratory scale. Such physical constraints become increasingly more important at larger scales. In the field, the complexities of unsaturated zone flow over much of the internal volume of the landfill suggest that innovative designs are necessary to promote more uniform downward infiltration of recirculating liquids. The complexities of aqueous movement further complicate questions of microorganism distribution and movement.; this was recently addressed by Wan et al. (1994).

4. More standardized methods to study and characterize landfill decomposition processes are needed, particularly in regard to leachate recirculation. These methods should be appropriate to the scale of a given study and, include solid, liquid, and gaseous phases. Simple, useful, field and laboratory methods should be developed that can be implemented at specific sites to guide site design and management.

Finally, there are many existing sites where leachate recirculation is economically justified to offset the need for separate leachate treatment. At such sites, leachate recirculation should continue to be encouraged where it is permitted under existing Federal and state regulations. Leachate recycle will tend to increase the net moisture content of the refuse, which is beneficial to biodegradation if liquids can be uniformly distributed. A reasonable approach is to practice leachate recirculation if it offsets or reduces the need for external leachate treatment and is not too costly when site-specific issues are taken into account.

6.0 Acknowledgements

The authors gratefully acknowledge the support and encouragement of the following sponsors: 1) the National Renewable Energy Laboratory, especially C. Wiles, B. Gupta, and P. Shepherd; 2) the U.S. Dept. of Energy, especially S. Friedrich; and 3) Rust Environment and Infrastructure (formerly Waste Management of North America), especially P. Gagnard and J. Rohr. In addition, analytical support for this project was provided by the following individuals whose valuable contribution we acknowledge here:

- J. Taylor of the Energy Systems Division at Argonne--chloride, metals, and nutrients in leachates;
- I. Fox of the Argonne ACL (Analytical Chemistry Laboratory)--C,H,N analysis of solids;
- K. Parish of the ACL--carboxylic acids (C1-C5) in leachates, and
- R. Pettersen and V. Schwandt of the U.S. Dept. of Agriculture Forest Products Laboratory, Madison, Wisconsin--cellulose, hemicellulose, lignin.

We would also like to thank the personnel of the DuPage County Wastewater Treatment Plant in Woodridge, IL, for the anaerobic inoculum used in this study.

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**APPENDIX A.
SUMMARY OF SOIL PROPERTIES.**

**Sand Soil: Argonne Energy Systems Division Soil Laboratory
Quality Control Sample #5 (QC# 5)**

Location: Wheeler County, TX, cotton field near blowout site

Color: 5YR 4/4 (Reddish Brown)

Analyses:

Method Parameter Units	Date	Walkley-Black Organic C %	Date	Kjeldahl Total N ug/g	Date	Digestion Total P ug/g
	02-89	0.198	02-89	129.2	02-89	27.4
	02-89	0.218	03-90	179.2	03-90	116
					05-90	128
			10-89	298.1	05-89	107
			05-89	207.5	05-89	98.6
			10-89	276.6	06-90	99.6
			11-90	221.8		

Method Parameter Units	Date	Bray P ug P/g	Date	Olsen P ug P/g	Date	1:1 H ₂ O pH	Date	NaAc CEC meq/100g
	08-90	27.46	05-89	20.20	07-88	8.04	02-89	18.89
	08-90	26.36	05-89	20.22	10-88	8.01		
			12-89	18.42	12-88	7.85		
			02-90	18.74	06-90	7.74		
			03-90	20.14				
			01-91	18.09				
			01-91	16.93				

Method Parameter Units	Date	Saturated EC mmhos/cm
	10-88	600
	06-90	770
	03-91	700

QC# 5 (continued)

Method Parameter Units	Date	Hydrometer Analysis				Pressure Plates				
		Sand %	Silt %	Clay %	Texture Class	Date	1/3 Bar % Moist.	5 Bar >	7 Bar >	15 Bar >
	12-88	84	6	10	Lo Sand	01-89				3.11
	06-91	78	10	12	Sa Loam	01-89				3.42
						08-90				3.57
						08-90				3.93
						08-90	5.82			
						01-91	5.86			

Method Parameter Units	Date	NH ₄ AC Extraction (Ex. Bases)				Date	DTPA Extraction			
		Ca ug/g	Mg ----->	Na ----->	K ----->		Zn ug/g	Cu ----->	Ni ----->	Fe ----->
	11-88				127.65	06-89	0.10	0.17	0.40	4.31
	02-89	780	123							
	06-89	875	152	7.23	129.76					
	06-89	856		6.31	142.60					
	02-89		130		125.7					
	06-89				128.24					
	02-90	951			218.1					
	02-90				118.00					
	03-90		137							
	03-90		138							
Ft. Riley Ext.	04-90	831			232.36					
Ft. Riley	04-90				229.97					
Mid.Ext.89	11-89	705	118							
Mid.Ext.89	11-89		113		124.50					
Mid.Ext.89	11-89				129.06					
Mid.Ext.89	01-91			3.84						
	03-91		123							

**Clay Soil: Argonne Energy Systems Division Soil Laboratory
Quality Control Sample #9 (QC# 9)**

Location: Montgomery County, OH, soybean field at Intersection of Rts. 49 and 70.
Miami-Celina, mostly gently sloping to moderately steep, light-colored, well and moderately drained upland soils.

Color: 10YR 5/3 (Brown)

Analyses:

Method Parameter Units	Date	Walkley-Black Organic C %	Date	Kjeldahl Total N ug/g	Date	Digestion Total P ug/g
	10-88	1.89	03-89	2090	03-89	718
	10-88	1.86	10-89	1928	15-89	537
	10-88	1.80	05-90	1835	06-90	573
	10-88	1.86	11-90	1678	10-90	609
	02-89	1.75				
	02-89	1.77				
	02-89	1.77				
	12-89	1.85				
	12-89	1.60				

Method Parameter Units	Date	Bray P ug P/g	Date	Olsen P ug P/g	NH ₄ Ac CEC meq/100g
	05-89	7.05	07-88	5.8	18.89
	02-90	7.60	10-99	5.71	
	01-90	6.37	10-88	5.64	
	01-91	7.37	06-90	5.49	
	01-91	6.34	01-91	5.44	

Method Parameter Units	Date	Saturated EC mmhos/cm	1:1 H ₂ O pH
	10-88	649	5.71
	01-91		5.44

Method Parameter Units	Date	Hydrometer Analysis				Pressure Plates				
		Sand %	Silt %	Clay %	Texture Class	Date	1/3 Bar % Moist.	5 Bar >	7 Bar >	15 Bar >
	06-91	12	46	42	Si Clay	01-89	28.71			17.07
						01-89	27.95			
						08-90	26.57			
						08-90	26.99			
						01-91	26.52			
						08-90	26.00			

QC# 9 (continued).

Method Parameter Units	NH4Ac Extraction (Ex. Bases)					DTPA Extraction				
	Date	Ca ug/g	Mg	Na	K	Date	Zn ug/g	Cu	Ni	Fe
	11-88			11.2	114.55	06-89	0.87	1.58	0.95	58.40
	06-89	2281		27.9	138.87	106-89	0.84	1.54	1.26	55.40
	02-89		464			12-89	1.34	1.94	0.96	54.60
	02-90	2114								
	02-90				125.7					
	03-90		529							
	10-89				218.1					
Ft. Riley Ext.	05-90	1848	329		233.8					
Ft. Riley	05-90			14.4						
Ft. Riley	05-90				167.8					
	06-90	2122	454	14.6	119.1					
Ft.Sill	11-90	1914	375		162.8					
Mid.Ext.89	11-90	1572	369		121.9					
Mid.Ext.89	11-90	1491								
Mid.Ext.89	01-91			16.9						
Mid.Ext.89	01-91			15.7						
Ft.SillExt.	02-91	2092		19.9	203.6					

APPENDIX B.

PREPARATION OF LEACHATE SUBSAMPLES FOR CHEMICAL ANALYSIS.

Initial subsamples (undiluted and untreated) were taken from each of the bulk leachate sample for pH and conductivity determinations. Then a 1 mL subsample was diluted 1:100 with distilled water and filtered to 0.45 microns using a syringe filter (Nalgene). Five 5 mL subsamples were prepared for the various analyses described below and stored refrigerated (4° C.) in 5 ml serum bottles (Wheaton). The subsamples for total organic carbon analysis were frozen. All serum bottles were sealed with butyl rubber stoppers and an aluminum crimp.

Chloride Analysis	No preservative required.
Metals Analysis	Subsamples were preserved by adding 0.1 mL of ultrapure nitric acid to each subsample (1 mL Nitric Acid/ 250 mL sample).
Nitrogen and Phosphorus Analysis	Subsamples were preserved by adding mercuric (II) chloride solution (0.5 g HgCl ₂ /100 mL). Added 50 microliters solution per 15 mL sample.
Volatile Fatty Acid Analysis	Subsamples were preserved by adding phosphoric acid to the sample (1 mL per 10 mL sample, to lower pH to 2 to 2.3).
Total Organic Carbon (TOC) Analysis	Subsamples were preserved by adding phosphoric acid to the sample (1 mL per 10 mL sample, this lowered pH to 2 -2.3). The TOC subsamples were stored frozen at -5 °C until the time of analysis.

APPENDIX C. **METHODS FOR AQUEOUS CHEMICAL ANALYSES.**

Analysis	Reference
TOC	UV-persulfate oxidation using a Dohrmann™ DC-180 Carbon Analyzer, infrared detection of CO ₂ product, Dohrmann™ Instrument manual.
Cl	"Chloride in Water and Wastewater", Industrial Method No. 99-70W/B, Technicon™ Industrial Systems
TP and TKN	"Individual/Simutaneous Detection of Nitrogen and/or Phosphorus in BD Acid Digests", Industrial Method No. 329-74W/B, Technicon™ Industrial Systems
Fe, Zn	DTPA extracton with filtrate analized by atomic absorption, <u>Methods of Soil Analysis, Part II</u> , Ed. A.L. Page, No. 9, pp. 331-332, Soil Science of America, Inc, Madison.

APPENDIX D. METHODS FOR CELLULOSE, HEMICELLULOSE, AND LIGNIN ANALYSIS.

(Analysis by Forest Products Laboratory, Madison, WI)

Air-dried ground samples were used for all analyses. The basic method is described in Pettersen, R., and Schwandt, V., 1991, Wood Sugar Analysis by Anion Chromatography, J. of Wood Chemistry and Technology, 11(4), 495-501.

Samples are milled to pass a 40-mesh screen and vacuum-dried at 45°C. Approximately 200 mg are hydrolyzed with 2.00 mL 72% (W/W) H₂SO₄ for 1 hr at 30°C. Samples are diluted to 4% (W/W) H₂SO₄ with distilled water, fucose added as an internal standard, and a secondary hydrolysis performed for 1 hr at 121°C. Following secondary hydrolysis samples are immediately filtered through tared crucibles containing glass fiber filters. The filtrate and three washes with 5 mL distilled water are collected in 100 mL volumetric flasks. The acid-insoluble residue (Klason lignin) is washed an additional six times with 10 mL hot distilled water and quantitated gravimetrically.

Sugar content of the hydrolysates are determined by anion exchange high performance liquid chromatography using pulsed amperometric detection. The chromatographic system consists of a 738 autosampler (Alcott), a GPM-1 quaternary gradient high pressure pump (Dionex), and a pulsed amperometric detector (Dionex). Sugar separation is achieved with Barbo-Pak PA1 guard and analytical columns (Dionex) connected in series. Hydrophobic interferences are removed by on-line solid phase extraction employing a NG1 Ion Pak guard column (Dionex). Sugars are eluted with distilled water at a flow rate of 1.2 mL/min. For detection, 300 mM NaOH is added as a post-column reagent at a flow rate of 0.5 mL/min. Prior to each injection, the anion exchange columns are conditioned with 500 mM NaOH + 100 mM CH₃CO₂Na for 10 min., then equilibrated with distilled water for 10 min. Sugars are quantitated using an internal standard method.

APPENDIX E.
SUPPORTING CHEMICAL DATA.

	Lignin			Cellulose					cellulose/lignin	Total Hemi-
Description	K. Lignin	Arabinan	Galactan	Glucan	Xylan	Mannan	Rhamnan	Total	ratio	Celluloses
Food	7.5%	0.60%	0.68%	44.67%	0.86%	0.33%	0.04%	54.7%	5.980	2.51%
Grass	40.2%	2.23%	1.52%	15.00%	7.09%	0.71%	0.63%	67.4%	0.373	12.19%
Paper	0.9%	0.13%	0.00%	66.06%	14.41%	1.44%	0.03%	83.0%	74.465	16.00%
Soil Sand	97.9%	0.01%	0.02%	0.02%	0.04%	0.01%	0.00%	98.1%	0.000	0.09%
Soil Clay	88.1%	0.07%	0.08%	0.21%	0.10%	0.08%	0.06%	88.6%	0.002	0.37%
Without Soil	11.62 %	0.73 %	0.51 %	50.04 %	9.83 %	1.04 %	0.17 %	73.94 %	4.307	12.28 %
** Expressed as percent dry weight of the sample.										
** Note : In the above calculations the corn syrup addition was omitted.										
Description	AVG C	AVG H	AVG N							
Food	45.70	8.98	2.84							
Grass	46.14	5.97	2.81							
Paper	36.37	5.46	0.04							
Soil Sand	0.20	0.12	0.04							
Soil Clay	1.37	0.52	0.20							
Without Soil	41.18	6.43	1.32							
** Expressed as percent dry weight of the sample.										
** Note : In the above calculations the corn syrup addition was omitted.										

Final Chem.

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Final Chem.

	Lignin	Arabinan	Galactan	Cellulose	Xylan	Mannan	Rhamnan	Total	Cell/Lign	Sum Hemi	AVG C	AVG H	AVG N	C/N	TotalC/Cel	Cel/TotalC	gravim W%	VS%
																	329	
350SR-1	61.5%	0.38%	0.47%	12.68%	2.54%	1.03%	0.22%	78.8%	0.21	4.65%	29.6	4.47	1.55	19.10	233.51	0.00	358	50.1
350SR-2	45.1%	0.46%	0.43%	16.32%	4.01%	0.53%	0.19%	67.0%	0.36	5.61%	25.1	3.71	1.14	22.02	153.78	0.01	368	39.1
350SR-3	63.2%	0.37%	0.34%	10.10%	2.67%	0.36%	0.14%	77.1%	0.16	3.88%	14.1	1.88	0.7	20.14	139.55	0.01	362	38.7
350SR-4	77.5%	0.14%	0.16%	1.39%	0.50%	0.07%	0.08%	79.8%	0.02	0.94%	14.4	1.94	0.74	19.46	1033.96	0.00	891	
350SR-F	71.7%	0.15%	0.17%	1.07%	0.43%	0.07%	0.11%	73.8%	0.01	0.95%	18.8	2.56	1.2	15.67	1750.23	0.00	973	35.4
																	724	
750CD-1	60.3%	0.37%	0.32%	8.83%	2.36%	0.28%	0.13%	72.6%	0.15	3.46%					0.00		875	
750CD-2	48.7%	0.38%	0.34%	12.51%	2.85%	0.38%	0.15%	65.3%	0.26	4.10%	19.4	2.75	0.86	22.56	155.14	0.01		
750CD-3																		
750CD-4	56.7%	0.43%	0.39%	5.34%	1.67%	0.24%	0.20%	65.0%	0.09	2.93%	26.57	3.93	1.23	21.60	497.30	0.00	2575	61
750CD-F	68.0%	0.38%	0.37%	2.65%	1.10%	0.17%	0.22%	72.8%	0.04	2.23%	18.2	2.55	0.86	21.16	686.20	0.00	1673	49.2
																	724	
750CR-1	60.3%	0.37%	0.32%	8.83%	2.36%	0.28%	0.13%	72.6%	0.15	3.46%	24.1	3.5	1.53	15.75	272.79	0.00	875	
750CR-2	57.2%	0.35%	0.38%	3.19%	1.26%	0.18%	0.18%	62.7%	0.06	2.35%	24.2	3.39	1.14	21.23	758.66	0.00	943	45.5
750CR-3	58.2%	0.41%	0.41%	3.58%	1.29%	0.21%	0.19%	64.3%	0.06	2.51%	25.9	3.66	1.41	18.37	724.22	0.00	1136	45.4
750CR-4	48.5%	0.53%	0.47%	15.38%	4.04%	0.52%	0.19%	69.7%	0.32	5.76%	24.6	3.57	1.02	24.12	159.95	0.01	959	39.4
750CR-F	56.6%	0.47%	0.47%	4.93%	1.57%	0.27%	0.20%	64.5%	0.09	2.98%	23	3.255	1.03	22.33	466.78	0.00	1216	50.5
																	704	
750SD-1	63.2%	0.40%	0.42%	9.75%	2.30%	0.40%	0.14%	76.6%	0.15	3.66%					0.00		825	
750SD-2	56.3%	0.44%	0.38%	11.52%	2.72%	0.37%	0.16%	71.9%	0.20	4.09%	15.3	2.1	0.66	23.18	132.81	0.01		
750SD-3																		
750SD-4	65.3%	0.38%	0.33%	2.69%	1.20%	0.12%	0.17%	70.2%	0.04	2.20%	12.6	1.67	0.85	14.82	468.82	0.00	2104	54.9
750SD-F	75.5%	0.25%	0.21%	1.85%	0.77%	0.09%	0.11%	78.8%	0.02	1.43%	20.9	2.93	0.79	26.46	1132.75	0.00	1929	51.9

Final Chem.

	Lignin	Arabinan	Galactan	Cellulose	Xylan	Mannan	Rhamnan	Total	Cell/Lign	Sum Hemi	AVG C	AVG H	AVG N	C/N	TotalC/Cel	Cel/TotalC	gravim W%	VS%
																	704	
750SR-1	63.2%	0.40%	0.42%	9.75%	2.30%	0.40%	0.14%	76.6%	0.15	3.66%	35.5	5.76	1.94	18.30	364.17	0.00	825	
750SR-2	65.0%	0.36%	0.31%	10.41%	2.70%	0.35%	0.13%	79.3%	0.16	3.85%	34.5	5.24	1.385	24.91	331.44	0.00	998	43.7
750SR-3	73.5%	0.26%	0.22%	7.51%	2.76%	0.25%	0.10%	84.6%	0.10	3.59%	19.6	2.72	0.72	27.22	260.95	0.00	837	42.2
750SR-4	64.8%	0.27%	0.29%	2.49%	1.30%	0.13%	0.14%	69.4%	0.04	2.12%	21.1	2.99	0.9	23.44	846.43	0.00	896	61.2
750SR-F	66.1%	0.27%	0.32%	3.05%	1.01%	0.14%	0.16%	71.0%	0.05	1.89%	23.7	3.31	0.87	27.24	777.65	0.00	1544	51.37
Food	7.5%	0.60%	0.68%	44.67%	0.86%	0.33%	0.04%	54.7%	5.98	2.51%	45.7	8.98	2.84	16.09	102.30	0.01		
Grass	40.2%	2.23%	1.52%	15.00%	7.09%	0.71%	0.63%	67.4%	0.37	12.19%	46.14	5.97	2.81	16.42	307.64	0.00		
Paper	0.9%	0.13%	0.00%	66.06%	14.41%	1.44%	0.03%	83.0%	74.46	16.00%	36.4	5.46	0.035	1040.00	55.10	0.02		
Sludge 1	32.6%	0.68%	0.75%	3.41%	0.88%	0.76%	0.95%	40.0%	0.10	4.01%	31.4	5.64	5.45	5.76	922.00	0.00		
Sludge 2	33.5%	0.71%	0.76%	2.85%	0.82%	0.71%	0.92%	40.2%	0.09	3.92%	31.05	5.75	5.23	5.94	1088.02	0.00		
Sand	97.9%	0.01%	0.02%	0.02%	0.04%	0.01%	0.00%	98.1%	0.00	0.09%	0.2	0.12	0.035	5.71	891.25	0.00		
Clay	88.1%	0.07%	0.08%	0.21%	0.10%	0.08%	0.06%	88.6%	0.00	0.37%	1.4	0.52	0.2	7.00	661.88	0.00		
350CD-7	61.2%	0.29%	0.37%	2.20%	0.78%	0.15%	0.15%	65.2%	0.04	1.74%	16.5	2.18	1.31	12.60	748.98	0.00		

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Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
80-C-1	11.542	19.899	16.205	14.457	55.80	37.49	53.63	42.77	0.79	0.87
	8.043	14.813	11.527	9.853	51.46	48.05			0.94	
80-C-2	54.174	62.580	58.271	56.214	48.74	50.21	52.34	46.50	1.05	0.92
	8.310	11.472	10.079	9.322	55.95	42.79			0.79	
80-C-3	30.253	35.478	33.013	31.498	52.82	54.89	51.16	60.36	0.89	0.96
	11.302	13.785	12.531	11.722	49.50	65.83			1.02	
80-C-4	11.795	16.603	14.036	12.721	46.61	58.68	50.49	49.89	1.15	0.99
	12.098	20.447	16.638	14.772	54.38	41.10			0.84	
80-C-5	30.243	39.765	35.042	32.296	50.40	57.22	52.92	51.88	0.98	0.89
	8.296	12.095	10.402	9.422	55.44	46.53			0.80	
80-C-6	29.626	39.625	35.018	32.537	53.93	46.01	51.55	51.85	0.85	0.94
	10.923	15.115	12.984	11.795	49.17	57.69			1.03	
80-C-7	31.590	36.611	34.174	32.749	51.46	55.15	47.56	63.91	0.94	1.12
	8.025	10.222	8.984	8.287	43.65	72.68			1.29	
80-C-8	30.048	35.415	32.750	31.104	50.34	60.92	48.85	67.75	0.99	1.05
	11.784	13.163	12.437	11.950	47.35	74.58			1.11	
80-C-9	28.661	37.674	33.093	30.605	49.17	56.14	49.86	57.51	1.03	1.01
	11.213	13.263	12.249	11.639	50.54	58.88			0.98	
80-C-10	21.662	28.790	25.424	23.530	52.78	50.35	52.34	51.70	0.89	0.91
	8.213	11.369	9.851	8.982	51.90	53.05			0.93	
80-S-1	29.121	35.082	32.206	30.470	51.75	56.27	51.64	56.21	0.93	0.94
	11.291	14.150	12.764	11.937	51.52	56.14			0.94	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
80-S-2	54.671	62.108	58.409	56.241	50.26	58.00	55.40	49.22	0.99	0.82
	11.585	15.997	14.256	13.176	60.54	40.43			0.65	
80-S-3	54.174	56.612	55.442	54.695	52.01	58.91	52.77	57.26	0.92	0.90
	11.070	15.337	13.354	12.084	53.53	55.60			0.87	
80-S-4	21.648	25.022	23.400	22.348	51.93	60.05	52.42	57.83	0.93	0.91
	11.531	14.460	13.081	12.219	52.92	55.61			0.89	
80-S-5	28.699	33.739	31.336	29.806	52.32	58.02	52.62	56.82	0.91	0.90
	11.531	14.460	13.081	12.219	52.92	55.61			0.89	
80-S-6	40.184	47.261	43.953	41.851	53.26	55.77	52.12	58.33	0.88	0.92
	12.087	15.512	13.833	12.770	50.98	60.88			0.96	
80-S-7	43.849	47.426	45.588	44.442	48.62	65.90	49.23	65.02	1.06	1.03
	11.180	14.800	12.984	11.827	49.83	64.14			1.01	
80-S-8	65.332	70.675	68.398	66.938	57.38	47.62	56.55	51.70	0.74	0.77
	10.622	12.794	11.832	11.157	55.71	55.79			0.80	
80-S-9	83.732	87.807	85.797	84.453	50.67	65.08	50.85	65.93	0.97	0.97
	20.456	24.143	22.337	21.081	51.02	66.77			0.96	
80-S-10	58.141	65.661	61.987	59.562	51.14	63.05	52.10	60.70	0.96	0.92
	61.650	66.773	64.368	62.782	53.05	58.35			0.88	
350-CD-1	29.088	48.297	32.010	31.168	15.21	28.82	14.42	28.20	5.57	5.95
	10.597	15.394	11.283	11.092	14.30	27.84			5.99	
	11.283	16.544	12.006	11.804	13.74	27.94			6.28	
350-CD-2	30.025	37.558	30.888	30.673	11.46	24.91	11.81	-6.41	7.73	7.47
	28.654	34.184	29.327	29.581	12.17	-37.74			7.22	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
350-CD-3	8.209	12.119	8.710	8.599	12.81	22.16	13.00	22.79	6.80	6.69
	8.023	12.003	8.548	8.425	13.19	23.43			6.58	
350-CD-4	10.611	18.503	11.649	11.396	13.15	24.37	12.74	25.15	6.60	6.86
	11.299	15.210	11.781	11.656	12.32	25.93			7.11	
350-CD-5	11.202	16.125	11.901	11.690	14.20	30.19	14.07	30.08	6.04	6.11
	11.173	15.166	11.730	11.563	13.95	29.98			6.17	
350-CD-6	29.637	37.169	30.709	30.433	14.23	25.75	13.96	24.27	6.03	6.17
	29.117	34.727	29.885	29.710	13.69	22.79			6.30	
350-CD-7	28.779	35.486	29.594	29.371	12.15	27.36	12.30	27.64	7.23	7.13
	21.651	27.089	22.328	22.139	12.45	27.92			7.03	
350-CD-8	30.039	39.044	31.258	30.948	13.54	25.43	13.62	24.37	6.39	6.34
	31.570	38.897	32.574	32.340	13.70	23.31			6.30	
350-CD-9	10.915	17.555	11.856	11.623	14.17	24.76	14.10	24.00	6.06	6.09
	12.041	19.060	13.026	12.797	14.03	23.25			6.13	
350-CD-10										
350-SD-1										
350-SD-2	28.664	33.440	29.792	28.956	23.62	74.11	16.72	58.60	3.23	6.21
	31.579	36.515	32.064	31.855	9.83	43.09			9.18	
350-SD-3	11.182	17.687	11.948	11.799	11.78	19.45	9.47	26.77	7.49	10.23
	8.283	13.155	8.632	8.513	7.16	34.10			12.96	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
350-SD-4	11.782	17.855	12.263	12.124	7.92	28.90	7.58	29.10	11.63	12.21
	11.206	15.772	11.537	11.440	7.25	29.31			12.79	
350-SD-5	11.538	18.267	12.147	11.993	9.05	25.29	8.85	26.60	10.05	10.30
	11.573	18.116	12.139	11.981	8.65	27.92			10.56	
350-SD-6	12.101	17.198	12.439	12.328	6.63	32.84	7.66	27.29	14.08	12.30
	11.070	16.795	11.567	11.459	8.68	21.73			10.52	
350-SD-7	28.714	34.259	29.215	29.088	9.04	25.35	8.94	28.57	10.07	10.18
	21.688	29.505	22.380	22.160	8.85	31.79			10.30	
350-SD-8	31.554	36.245	32.048	31.890	10.53	31.98	10.07	34.94	8.50	8.96
	30.237	37.081	30.894	30.645	9.60	37.90			9.42	
350-SD-9	8.283	12.286	8.613	8.502	8.24	33.64	9.32	29.94	11.13	9.87
	8.018	12.488	8.483	8.361	10.40	26.24			8.61	
350-SD-10										
350-CR-1	29.102	33.809	29.580	29.435	10.16	30.33	10.44	31.23	8.85	8.59
	28.672	34.360	29.282	29.086	10.72	32.13			8.32	
350-CR-2	31.576	39.032	32.561	32.337	13.21	22.74	13.19	23.56	6.57	6.58
	30.258	36.051	31.021	30.835	13.17	24.38			6.59	
350-CR-3	12.030	17.368	13.160	12.663	21.17	43.98	20.29	43.45	3.72	3.94
	10.895	20.272	12.715	11.934	19.41	42.91			4.15	
350-CR-4	11.793	17.709	12.951	12.486	19.57	40.16	19.56	39.40	4.11	4.11
	11.210	17.287	12.398	11.939	19.55	38.64			4.12	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
350-CR-5	10.622	14.963	11.992	11.515	31.56	34.82	23.51	34.98	2.17	3.82
	11.533	17.240	12.415	12.105	15.45	35.15			5.47	
350-CR-6	8.207	12.848	8.962	8.686	16.27	36.56	16.18	36.50	5.15	5.18
	8.293	12.030	8.894	8.675	16.08	36.44			5.22	
350-CR-7	10.622	15.751	11.308	11.141	13.37	24.34	13.36	24.07	6.48	6.48
	8.027	12.056	8.565	8.437	13.35	23.79			6.49	
350-CR-8	12.090	20.670	13.032	12.777	10.98	27.07	11.28	26.64	8.11	7.87
	11.786	19.862	12.721	12.476	11.58	26.20			7.64	
350-CR-9 12/16/92	28.815	52.761	33.665	31.717	20.25	40.16	20.24	42.07	3.94	3.94
	11.902	20.192	13.589	12.882	20.35	41.91			3.91	
	11.551	19.932	13.237	12.493	20.12	44.13			3.97	
350-CR-10 12/22/92	31.753	52.006	35.972	34.267	20.83	40.41	20.53	41.33	3.80	3.87
	30.387	45.424	33.421	32.168	20.18	41.30			3.96	
	10.950	18.242	12.450	11.816	20.57	42.27			3.86	
350-CR-11 12/22/92	29.950	49.935	34.053	32.317	20.53	42.31	20.53	43.11	3.87	3.87
	29.010	45.721	32.474	30.958	20.73	43.76			3.82	
	11.275	18.544	12.752	12.113	20.32	43.26			3.92	
350-CR-12										
350-CR-13	29.808	44.623	32.739	31.502	19.78	42.20	19.94	43.73	4.05	4.02
	30.319	44.685	33.225	31.964	20.23	43.39			3.94	
	12.189	18.610	13.461	12.881	19.81	45.60			4.05	
350-CR-14 12/1/92	28.662	43.930	31.690	30.387	19.83	43.03	19.67	41.95	4.04	4.08
	31.551	49.423	35.072	33.603	19.70	41.72			4.08	
	21.648	32.382	23.740	22.880	19.49	41.11			4.13	
350-CR-15 12/1/92	29.084	49.174	33.139	31.384	20.18	43.28	20.00	42.16	3.95	4.00
	21.652	31.827	23.664	22.827	19.77	41.60			4.06	
	29.620	42.359	32.172	31.110	20.03	41.61			3.99	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
350-CR-16										
350-CR-17	28.923	40.583	31.516	30.098	22.24	54.69	22.29	54.12	3.50	3.49
	30.309	39.920	32.423	31.278	22.00	54.16			3.55	
	10.752	15.829	11.901	11.286	22.63	53.52			3.42	
350-CR-18										
350-CR-19										
350-CR-20										
350-SR-1	11.579	16.853	12.038	11.849	8.70	41.18	8.59	41.92	10.49	10.64
	21.665	29.629	22.340	22.052	8.48	42.67			10.80	
350-SR-2	28.695	34.612	29.235	28.969	9.13	49.26	9.51	48.38	9.96	9.54
	29.625	35.098	30.166	29.909	9.88	47.50			9.12	
350-SR-3	29.631	39.345	30.719	30.327	11.20	36.03	10.03	39.77	7.93	9.11
	28.702	36.979	29.435	29.116	8.86	43.52			10.29	
350-SR-4	11.530	16.085	11.913	11.752	8.41	42.04	9.42	45.22	10.89	9.74
	10.610	15.705	11.141	10.884	10.42	48.40			8.60	
350-SR-5	11.076	17.838	11.683	11.506	8.98	29.16	9.03	27.28	10.14	10.07
	11.541	16.911	12.029	11.905	9.09	25.41			10.00	
350-SR-6	10.921	17.186	11.574	11.342	10.42	35.53	8.62	38.87	8.59	11.13
	11.303	18.738	11.810	11.596	6.82	42.21			13.66	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
350-SR-7	11.179	18.385	11.927	11.686	10.38	32.22	11.63	28.90	8.63	7.70
	12.051	17.452	12.747	12.569	12.89	25.57			6.76	
350-SR-8	11.322	15.119	11.717	11.507	10.40	53.16	11.07	57.35	8.61	8.07
	11.583	16.943	12.212	11.825	11.74	61.53			7.52	
350-SR-9	29.241	50.936	33.740	31.977	20.74	39.19	21.13	38.26	3.82	3.73
12/16/92	12.060	21.237	14.002	13.278	21.16	37.28			3.73	
	11.592	21.081	13.631	12.850	21.49	38.30			3.65	
350-SR-10	28.761	49.474	33.251	31.546	21.68	37.97	21.77	38.70	3.61	3.59
12/22/92	30.207	44.863	33.386	32.158	21.69	38.63			3.61	
	12.101	18.182	13.435	12.908	21.94	39.51			3.56	
350-SR-11	29.276	48.152	33.492	31.837	22.34	39.26	22.03	39.08	3.48	3.54
12/22/92	12.146	18.663	13.566	13.010	21.79	39.15			3.59	
	21.781	31.736	23.968	23.119	21.97	38.82			3.55	
350-SR-12										
350-SR-13	30.366	43.461	33.229	32.053	21.86	41.08	21.28	43.16	3.57	3.70
	31.219	41.592	33.393	32.402	20.96	45.58			3.77	
	11.092	17.887	12.521	11.909	21.03	42.83			3.76	
350-SR-14	30.857	48.503	34.405	33.095	20.11	36.92	21.32	35.05	3.97	3.70
12/1/92	8.203	17.956	10.422	9.680	22.75	33.44			3.40	
	11.204	22.386	13.564	12.743	21.11	34.79			3.74	
350-SR-15	30.031	39.197	31.916	31.148	20.57	40.74	21.56	39.04	3.86	3.64
11/30/92	11.557	18.301	13.077	12.500	22.54	37.96			3.44	
	12.086	19.116	13.603	13.020	21.58	38.43			3.63	
350-SR-16										
350-SR-17	12.183	16.393	13.062	12.613	20.88	51.08	21.89	50.90	3.79	3.58
	21.744	33.991	24.583	23.183	23.18	49.31			3.31	
	29.793	43.705	32.800	31.227	21.61	52.31			3.63	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
350-SR-18										
350-SR-19										
350-SR-20										
750-CD-1	65.321	79.228	68.211	65.764	20.78	84.67	13.02	61.13	3.81	10.90
	40.163	51.630	40.767	40.540	5.27	37.58			17.99	
750-CD-2	11.196	19.326	12.050	11.643	10.50	47.66	10.50	45.61	8.52	8.52
	11.198	20.005	12.123	11.720	10.50	43.57			8.52	
750-CD-3	10.907	15.790	11.091	11.002	3.77	48.37	3.64	49.54	25.54	26.51
	12.033	18.101	12.246	12.138	3.51	50.70			27.49	
750-CD-4	29.637	35.936	29.879	29.733	3.84	60.33	3.74	60.97	25.03	25.75
	28.707	35.575	28.957	28.803	3.64	61.60			26.47	
750-CD-5	30.255	38.803	30.719	30.520	5.43	42.89	5.69	40.38	17.42	16.62
	28.667	37.811	29.211	29.005	5.95	37.87			15.81	
750-CD-6	12.090	21.061	12.618	12.391	5.89	42.99	6.05	41.82	15.99	15.54
	21.652	28.699	22.090	21.912	6.22	40.64			15.09	
750-CD-7	61.642	71.626	61.950	61.780	3.08	55.19	4.94	53.14	31.42	22.57
	58.134	64.878	58.592	58.358	6.79	51.09			13.72	
750-CD-8										

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
750-CD-9	54.150	69.242	54.914	54.586	5.06	42.93	5.67	42.19	18.75	16.85
	43.840	55.496	44.571	44.268	6.27	41.45			14.95	
750-CD-10										
750-SD-1	83.708	100.115	84.360	83.985	3.97	57.52	4.72	49.40	24.16	20.72
	54.628	69.196	55.425	55.096	5.47	41.28			17.28	
750-SD-2	11.188	19.738	11.660	11.427	5.52	49.36	4.83	54.96	17.11	20.14
	11.541	17.606	11.792	11.640	4.14	60.56			23.16	
750-SD-3	29.611	51.553	30.798	30.214	5.41	49.20	4.75	55.52	17.49	20.24
	11.562	19.337	11.905	11.682	4.42	64.94			21.64	
	11.167	19.146	11.520	11.335	4.42	52.41			21.60	
750-SD-4	8.296	14.673	8.943	8.391	10.15	85.32	6.55	67.66	8.86	20.86
	11.216	17.448	11.400	11.308	2.95	50.00			32.87	
750-SD-5	11.797	20.282	12.258	12.078	5.43	39.05	6.35	35.27	17.41	15.07
	12.046	17.804	12.465	12.333	7.28	31.50			12.74	
750-SD-6	8.206	12.722	8.401	8.280	4.32	62.05	5.90	44.39	22.16	17.26
	8.031	13.630	8.450	8.338	7.48	26.73			12.36	
750-SD-7	10.916	18.529	11.244	11.047	4.31	60.06	4.42	59.97	22.21	21.65
	11.583	19.185	11.927	11.721	4.53	59.88			21.10	
750-SD-8	11.775	18.186	12.044	11.895	4.20	55.39	4.39	54.19	22.83	21.84
	12.077	21.232	12.496	12.274	4.58	52.98			20.85	
750-SD-9	30.255	39.800	30.571	30.439	3.31	41.77	3.54	48.65	29.21	27.34
	30.035	38.429	30.352	30.176	3.78	55.52			25.48	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
750-SD-10										
750-CR-1										
750-CR-2	31.600	58.720	34.124	33.183	9.31	37.28	9.91	37.85	9.74	9.12
	10.920	22.030	12.089	11.640	10.52	38.41			8.50	
750-CR-3	28.663	68.192	31.832	30.470	8.02	42.98	8.10	43.67	11.47	11.36
	11.558	24.599	12.654	12.181	8.40	43.16			10.90	
	11.056	24.435	12.110	11.637	7.88	44.88			11.69	
750-CR-4	11.068	17.803	11.531	11.319	6.87	45.79	5.95	45.17	13.55	16.22
	12.042	20.435	12.464	12.276	5.03	44.55			18.89	
750-CR-5	30.082	47.957	31.731	31.101	9.23	38.20	9.06	39.32	9.84	10.04
	12.052	22.555	12.987	12.609	8.90	40.43			10.23	
750-CR-6	21.723	38.720	23.226	22.672	8.84	36.86	8.60	37.34	10.31	10.64
	8.217	12.838	8.603	8.457	8.35	37.82			10.97	
750-CR-7	29.134	63.431	32.382	31.008	9.47	42.30	9.07	40.95	9.56	10.05
	11.072	23.482	12.148	11.722	8.67	39.59			10.53	
750-CR-8	8.205	13.548	8.913	8.419	13.25	69.77	10.71	62.77	6.55	8.89
	29.136	39.431	29.977	29.508	8.17	55.77			11.24	
750-CR-9	28.707	55.075	30.865	29.872	8.18	46.01	7.27	45.14	11.22	12.98
12/9/92	11.785	23.443	12.526	12.198	6.36	44.26			14.73	
750-CR-10	29.787	57.932	32.702	31.380	10.36	45.35	10.06	43.88	8.66	9.34
12/16/92	31.651	48.911	32.961	32.311	7.59	49.62			12.18	
	11.071	18.834	12.020	11.672	12.22	36.67			7.18	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
750-CR-11	30.298	51.649	31.841	31.006	7.23	54.12	7.89	47.17	12.84	11.75
12/16/92	21.747	35.093	22.770	22.291	7.67	46.82			12.05	
	11.189	19.039	11.879	11.599	8.79	40.58			10.38	
750-CR-12										
750-CR-13	21.735	55.918	24.524	23.210	8.16	47.11	8.17	47.03	11.26	11.25
	8.221	15.861	8.826	8.545	7.92	46.45			11.63	
	11.287	18.747	11.916	11.617	8.43	47.54			10.86	
750-CR-14	30.070	60.044	33.226	31.751	10.53	46.74	10.68	43.86	8.50	8.36
12/9/92	21.693	42.516	23.960	22.950	10.89	44.55			8.19	
	12.102	22.333	13.189	12.751	10.62	40.29			8.41	
750-CR-15	29.675	62.927	33.142	31.569	10.43	45.37	10.34	45.74	8.59	8.67
12/9/92	10.906	19.857	11.804	11.377	10.03	47.55			8.97	
	11.227	20.876	12.247	11.795	10.57	44.31			8.46	
750-CR-16										
750-CR-17	11.378	16.190	11.910		11.06		10.29		8.05	8.75
	30.943	47.092	32.579		10.13				8.87	
	10.991	19.209	11.787		9.69				9.32	
750-CR-18										
750-CR-19										
750-CR-20										
750-SR-1	28.681	41.968	29.478	29.088	6.00	48.93	5.98	50.99	15.67	15.73
	12.111	17.903	12.456	12.273	5.96	53.04			15.79	

Final Solids Data

Final Solids Analysis of Leachate Recycle					PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Crucible and			TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample	110	550	SOLIDS	SOLIDS	TS	VS		WATER CONTENT
750-SR-2	30.248	47.917	31.563	30.967	7.44	45.32	6.65	50.73	12.44	14.26
	10.640	22.058	11.308	10.933	5.85	56.14			16.09	
750-SR-3	29.652	44.974	30.562	30.064	5.94	54.73	5.78	54.67	15.84	16.32
	11.797	17.209	12.101	11.935	5.62	54.61			16.80	
750-SR-4	11.189	21.655	11.775	11.454	5.60	54.78	5.58	53.58	16.86	16.93
	11.311	21.550	11.880	11.582	5.56	52.37			16.99	
750-SR-5	11.073	18.667	11.442	11.236	4.86	55.83	4.94	56.31	19.58	19.26
	8.200	12.309	8.406	8.289	5.01	56.80			18.95	
750-SR-6	28.694	41.920	29.616	29.224	6.97	42.52	6.69	46.83	13.34	13.97
	11.222	18.722	11.703	11.457	6.41	51.14			14.59	
750-SR-7	10.907	16.495	11.179	11.034	4.87	53.31	5.48	60.51	19.54	17.49
	11.792	17.036	12.111	11.895	6.08	67.71			15.44	
750-SR-8	29.691	35.604	29.992	29.800	5.09	63.79	5.29	66.18	18.64	17.92
?	29.175	35.255	29.509	29.280	5.49	68.56			17.20	
750-SR-9	31.605	57.399	34.023	32.872	9.37	47.60	9.23	45.36	9.67	9.84
12/9/92	30.266	55.285	32.588	31.544	9.28	44.96			9.77	
	11.525	20.937	12.375	12.005	9.03	43.53			10.07	
750-SR-10	21.750	45.219	24.891	23.652	13.38	39.45	12.99	40.85	6.47	6.71
12/16/92	28.814	53.891	31.887	30.582	12.25	42.47			7.16	
	11.314	20.607	12.552	12.049	13.32	40.63			6.51	
750-SR-11	28.683	55.544	31.545	30.356	10.65	41.54	10.47	40.52	8.39	8.56
12/9/92	11.290	18.849	12.053	11.736	10.09	41.55			8.91	
	11.169	20.870	12.204	11.806	10.67	38.45			8.37	
750-SR-12										

Final Solids Data

Final Solids Analysis of Leachate Recycle										
		Crucible and			PERCENT	PERCENT	AVERAGE	AVERAGE	Gravimetric	AVERAGE
		Sample	110	550	TOTAL	VOLATILE	PERCENT	PERCENT	Water Content	GRAVIMETRIC
Sample	Crucible	Sample			SOLIDS	SOLIDS	TS	VS		WATER CONTENT
750-SR-13	28.926	48.138	30.643	29.918	8.94	42.22	9.00	40.53	10.19	10.14
	11.921	23.216	13.003	12.583	9.58	38.82			9.44	
	8.367	14.414	8.880	8.672	8.48	40.55			10.79	
750-SR-14	21.698	49.101	24.718	23.483	11.02	40.89	9.52	43.56	8.07	9.85
12/9/92	30.898	60.123	33.894	32.659	10.25	41.22			8.75	
	10.605	21.091	11.369	10.998	7.29	48.56			12.73	
750-SR-15	29.196	64.105	32.870	31.280	10.52	43.28	9.26	47.28	8.50	9.95
12/9/92	11.578	21.595	12.515	12.082	9.35	46.21			9.69	
	12.031	22.248	12.839	12.416	7.91	52.35			11.64	
750-SR-16										
750-SR-17	31.624	60.429	35.031		11.83		10.86		7.45	8.25
	11.229	20.178	12.127		10.03				8.97	
	11.158	21.692	12.288		10.73				8.32	
750-SR-18										
750-SR-19										
750-SR-20										

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE May 1995	3. REPORT TYPE AND DATES COVERED Final subcontract report	
4. TITLE AND SUBTITLE Effect of Leachate Recirculation on Landfill Gas Production and Leachate Quality: A controlled laboratory Study Final Report		5. FUNDING NUMBERS (C)XA-1-11146-1 (TA)WM51.1010	
6. AUTHOR(S) J. Bogner and K. Spokas, Argonne National Laboratory			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Argonne National Laboratory 9700 South Cass Avenue Argonne, Illinois 60439		8. PERFORMING ORGANIZATION REPORT NUMBER DE95009215	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 617 Cole Boulevard Golden, CO 80401-3393		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/TP-430-7973	
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 285 Port Royal Road Springfield, VA 22161		12b. DISTRIBUTION CODE UC-1414	
13. ABSTRACT (Maximum 200 words) This study summarizes the results of a laboratory study conducted during 1992-1994 at Argonne National Laboratory. The study examined biogas production and leachate chemistry in parallel anaerobic assays run under either leachate recycle or leachate or leachate drainage regimes for 400 days. In respect to landfill decomposition, the results indicated that there were no quantifiable benefits to leachate recirculation or leachate drainage with respect to methane production, carbon conversion, or leachate quality.			
14. SUBJECT TERMS landfill decomposition, biogas production, methane, leachate drainage, leachate chemistry, landfill carbon conversion.		15. NUMBER OF PAGES 86 pages	
		16. PRICE CODE A04	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT