[illegible]

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: July 30, 1973

Project Title: Sanitary Landfill Stabilization with Leachate Recycle and Residual Treatment

Project No: E-20-642

Principal Investigator Dr. Frederick G. Pohland

Sponsor: Environmental Protection Agency; Washington, D.C.

Agreement Period: From 6/25/73 Until 6/24/74

Type Agreement: Grant No. R-801397

Amount:	$23,626 EPA Funds (E-20-642)
	$ 8,515 GIT Contribution (E-20-320)
	$32,141 TOTAL

Reports Required:

Quarterly Progress Reports; Final Report

Sponsor Contact Person (s):

Technical Matters	Contractual Matters
Mr. Dirk R. Brunner	Grants Officer (thru ORA)
Project Manager	Environmental Protection Agenc
Nat'l Environ. Research Center	Grants Administration Div.
EPA	401 M Street, S.W.
Cincinnati, Ohio 45268	Washington, D.C. 20460
Phone (513) 684-4491	

NOTE: Follow-on project to E-20-616 (6-1-71 thru 6-24-73).

Assigned to: School of Civil Engineering

COPIES TO:

- Principal Investigator
- School Director
- Dean of the College
- Director, Research Administration
- Director, Financial Affairs (2)
- Security-Reports-Property Office
- Patent Coordinator
- Library
- Rich Electronic Computer Center
- Photographic Laboratory
- Project File
- Other ____________________

RA-3 (6-71)

Posted 8

GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT TERMINATION

Date: April 2, 1975

Project Title Sanitary Landfill Stabilization with Leachate Recycle and Residual Treatment

Project No: E-20-642

Principal Investigator: Dr. Frederick G. Pohland 2265 2223

Sponsor: Environmental Protection Agency; Washington, D. C.

Effective Termination Date: 12/24/74

Clearance of Accounting Charges: 12/31/74

Grant/~~Contract~~ Closeout Actions Remaining:

1. Final Invoice
2. Closing Documents
3. Final Report of Inventions
4. Gov't. Property Inventory & Related Cert.
5. Classified Material Certificate

Assigned to School of Civil Engineering

COPIES TO:

Principal Investigator

School Director

Dean of the College

Director of Research Administration

Office of Financial Affairs (2)

Security - Reports - Property Office

Patent and Inventions Coordinator

Library, Technical Reports Section

Computer Sciences

Photographic Laboratory

Terminated Project File No. ____________

Other ____________

E-20-642

QUARTERLY PROGRESS REPORT (1 & 2)

Research Project No. R-801397

"Sanitary Landfill Stabilization With Leachate
Recycle And Residual Treatment"

June 25, 1973 - December 31, 1973

Georgia Institute of Technology
Atlanta, Georgia

In accordance with the objectives and research schedule provided in the grant application the operation of four 14-ft simulated landfill has been continued to further substantiate the effect of leachate collection, recycle and seeding on the rate and degree of solid waste stabilization within the fills together with the feasibility of using the landfill as a treatment process for the leachate. In addition, studies have been initiated to determined the nature of leachate residuals after biological stabilization and to evaluate the application of physical-chemical methods for removal of these residuals.

Data collection on the original two landfill columns has entered itsthird year and is nearing two years for the last two columns. These data continue to indicate the beneficial effect of recycle and pH control on the initiation of rapid decomposition and stabilization as measured by such parameters as BOD, TOC, COD, volatile acids, alkalinity, acidity, pH and selected ions. Most of these data are presented in detail in the research report submitted to EPA in September 1973 covering the initial two years of the project period.

The changes in test parameters with time continue to follow a trend predictable by the recognized requirement for effective acid and methane fermentation processes with the initial production of volatile acids and their subsequent utilization and conversion to methane and carbon dioxide. Seeding with raw sludge although initially accelerating the decomposition process and somewhat retarding methane fermentation by excessive volatile acid production, also provided for effective removal of pollutants from the refuse and leachate. Whereas the three recycle units have decreased the pollutants to low concentrations without an upsurge due to possible attack on the more resistant organics, the control unit without recycle yet contains unsatisfactory pollutant concentrations.

Studies on the separate biological and/or physical-chemical treatment of leachate alone or in sequence have also been initiated. Preliminary results with both aerobic and anaerobic batch and continuous culture studies as well as residual treatment with activated carbon and ion exchange resins have indicated that organics and inorganic pollutants may be removed from leachate to an extent to where the leachate is acceptable for ultimate disposal. Moreover, any degree of treatment may be met by sequencing the processes beginning with biological treatment for removal of readily available organics either by recycle or separate treatment and following with carbon adsorption and ion exchange as required.

Studies on recycle and separate treatment are continuing in order to further establish trends and alternative practices. A partial account of these efforts have been presented at the WPCF meeting in Cleveland in October and at a special seminar at the University of Florida in November. In addition, a paper will be presented at the AIChE meeting in Tulsa in March 1974.

Frederick G. Pohland
Project Director

E-20-642

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
CIVIL ENGINEERING

TELEPHONE
(404) 894-2265

April 8, 1974

Mr. Dirk Brunner, Project Manager
SWRD,ORM,EPA
National Environmental Research Center
Cincinnati, Ohio 45268

Dear Dirk:

Enclosed find five copies of a report of progress on my research project R-801397, "Sanitary Landfill Stabilization with Leachate Recycle and Residual Treatment" covering the period January through March, 1974.

As per my letter of March 27, 1974, we are hoping to extend the project through the summer for completion in September and trust that this no-cost extension will meet with your approval. We appreciate your interest in our research efforts and hope that the results merit your continued support.

Best regards.

Sincerely,

Frederick G. Pohland,
Professor of Civil Engineering

cc: Mr. A. A. Camp.
Encl.

FGP:ja

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
CIVIL ENGINEERING

TELEPHONE:
(404) 894-

QUARTERLY PROGRESS REPORT No. 3

Research Project No. R-801397

"Sanitary Landfill Stabilization with Leachate
Recycle and Residual Treatment"

January 1, 1974 March 31, 1974

Georgia Institute of Technology
Atlanta, Georgia 30332

In accordance with the objectives and research schedule provided in the grant application, the operation of four 14-ft. simulated landfills has continued to further substantiate the effect of leachate collection, recycle and seeding on the rate and degree of solid waste stabilization within the fills together with the feasibility of using the landfill as a treatment process for the leachate. In addition, adjunct studies on leachate residuals by biological and physical-chemical treatment have continued.

The analytical results continue to indicate the beneficial effect of recycle and pH control on the extent of decomposition and stabilization as measured by such parameters as BOD, TOC, COD, volatile acids, alkalinity, acidity, pH and selected ions. The changes in test parameters with time have followed the predicted trend as consequenced by initial production of volatile acids and subsequent conversion to methane and carbon dioxide Pollutants in the leachate from the units with recycle have been dramatically reduced as compared to the control.

Separate studies on aerobic and anaerobic biological treatment with and without physical-chemical treatment of residuals in the effluent have indicated that organic and inorganic pollutants may be removed to whatever extent is required for ultimate discharge. Continuing studies will concentrate on confirmation of preliminary results and development of possible landfill design and operation alternatives. A portion of these results have been presented at the AIChE Meeting in Tulsa in March 1974; additional reports will be presented at the ASCE Specialty Conference at Penn State in July 1974 and at the International Water Pollution Research Conference in Paris in September 1974.

Frederick G. Pohland
Project Director

FGP:ja

File: E-20-642

QUARTERLY PROGRESS REPORT No. 4

Research Project No. R-801397

"Sanitary Landfill Stabilization and Leachate
Recycle and Residual Treatment"

April 1, 1974 through June 30, 1974

Georgia Institute of Technology
Atlanta, Georgia 30332

In accordance with the schedule of activities provided in the grant application as extended, the operation of the four simulated landfills has been continued with monthly monitoring to ascertain terminal characteristics. The major effort now is the analysis of the accumulated data and preparation of the final project report.

The analytical results have confirmed the benefits of recycle and pH control on the extent of decomposition and stabilization of the simulated refuse as measured by such parameters as BOD, TOC, COD, volatile acids, alkalinity, acidity, pH and selected ions. Pollutants in the leachate from the columns with recycle have been dramatically reduced in a period of time much less than usually required during conventional landfill operations.

The recycle studies have been complemented with separate and continuing biological and physical-chemical treatment of leachate residuals and a proposed treatment scheme has been developed. These results together with the studies on leachate recycle have been presented at the ASCE Specialty Conference at Penn State and will also be presented at the International Water Pollution Research Conference in Paris in September 1974.

Frederick G. Pohland
Project Director

SANITARY LANDFILL STABILIZATION WITH LEACHATE RECYCLE AND RESIDUAL TREATMENT

By

Frederick G. Pohland
School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

Grant No. R-801397

Project Officer

Mr. Dirk Brunner, Sanitary Engineer
Solids and Hazardous Waste Research Laboratory
National Environmental Research Center
Cincinnati, Ohio 45268

Prepared for
OFFICE OF RESEARCH AND MONITORING
U. S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D. C. 20460

ABSTRACT

This report presents the results of studies with an experimental system which was developed to simulate landfill disposal of domestic-type refuse but with opportunities for comparison of the characteristics of normal leachate production with leachate collected, adjusted and recirculated back through the refuse in a manner analogous to the operation of an anaerobic trickling filter. The basic experimental system consisted of four 3-foot diameter columns containing 10 feet of compacted refuse covered with 2.5 feet of soil. The system was equipped to permit collection and analysis of changes in characteristics of the refuse, gas produced and leachate generated in response to intercepted rainfall. Of particular interest were the effects of initial sludge seeding and pH control on the rate of biological stabilization of the refuse and leachate constituents.

Since decisions on the acceptability of the leachate for ultimate disposal into some receptor, and hence the time when leachate recycle would no longer be needed, were considered functions of environmental and/or regulatory requirements, the basic leachate recycle investigations were complemented by separate physical-chemical as well as biological treatment studies.

Results of analyses, procured over an experimental period of about three years, indicated that leachate recycle was very beneficial in accelerating the removal of at least the readily available organics from the refuse and leachate. Compared to the leachate emanating from a control unit which contained significant concentrations of pollutants even at the end of the experimental period, the leachate subjected to recirculation through the refuse exhibited rapid decreases in organic pollutant concentrations in a matter of months. This rate of decrease in organic leachate pollutants was further enhanced by the initial addition of sewage sludge and/or by pH control.

Results from the separate leachate treatment studies indicated that leachate could be successfully treated by either aerobic or anaerobic biological processes and that the effluent residuals could be polished by activated carbon adsorption and/or ion exchange either separately or in combination. The degree of residual treatment is predictable and therefore responsive to whatever effluent requirement may be imposed.

This report was submitted in fulfillment of Project Number E-20-642 under the sponsorship of the U. S. Environmental Protection Agency.

CONTENTS

		Page
Abstract		ii
List of Figures		iv
List of Tables		vi
Acknowledgements		viii

Sections

I	Conclusions	1
II	Recommendations	2
III	Review of Literature	3
IV	Materials and Methods	11
V	Presentation of the Data	20
VI	Discussion	66
VII	Separate Treatment of Leachate and Leachate Residuals	80
VIII	References	100

FIGURES

No.		Page
1	Simulated Landfill Columns	12
2	Leachate Distribution System	14
3	Results of Cover Soil Leaching Study	23
4	Internal Temperature Fluctuations of the Simulated Landfills	25
5	Biochemical Oxygen Demand of Leachate	46
6	Chemical Oxygen Demand of Leachate	47
7	Total Organic Carbon Concentration of Leachate	48
8	Valeric Acid Concentration of Leachate	49
9	Butyric Acid Concentration of Leachate	50
10	Propionic Acid Concentration of Leachate	51
11	Acetic Acid Concentration of Leachate	52
12	pH and Total Volatile Acid Concentration of Leachate	53
13	Acidity of Leachate	54
14	Alkalinity of Leachate	55
15	Concentrations of Organic and Ammonia Nitrogen in Leachate	56
16	Phosphate and Chloride Concentrations of Leachate	57
17	Iron and Sodium Concentrations of Leachate	58
18	Manganese, Magnesium and Calcium Concentrations of Leachate	59
19	Total Hardness of Leachate	60
20	Solids Concentration of Leachate	61
21	Addition of Neutralizing Agent, Sodium Hydroxide, During Phase II	62

FIGURES (continued)

No.		Page
22	Completely Mixed Continuous Flow Reactor System	82
23	Anaerobic Biological Treatment of Leachate in Continuous Culture	85
24	Aerobic Biological Treatment of Leachate in Continuous Culture	87
25	Removal of Metals from Aerobic Biological Leachate Treatment Effluent by Cation Exchange	89
26	Effect of Cation Exchange on pH and Acidity of Effluents from Aerobic Biological Treatment of Leachate	91
27	Effect of Cation Exchange on Total Dissolved Solids and Specific Conductance of Effluent from Aerobic Biological Treatment of Leachate	92
28	Mixed Resin Ion Exchange Treatment of Effluent from Aerobic Biological Treatment of Leachate	93
29	Effect of Mixed Resin Ion Exchange on Dissolved Solids and Specific Conductance of Effluent from Aerobic Biological Treatment of Leachate	94
30	The Freundlich Isotherm of Carbon Adsorption on Effluent of Aerobic Biological Treatment of Leachate	96
31	Possible Scheme for On-Site Treatment of Non-Recycled Leachate	99

TABLES

No.		Page
1	Variations in Leachate Composition	7
2	Stimulating and Inhibitory Concentrations of Alkali and Alkaline-Earth Cations to the Digestion of Sewage Sludge	9
3	Composition of Simulated Refuse	13
4	Initial Composition of the Organic Fraction of the Simulated Refuse Used During Phase I and Phase II	20
5	Changes in Composition of the Organic Fraction of the Simulated Refuse for Each Test Unit During Phase I and Phase II	21
6	Results of Cover Soil Leaching Experiments	24
7	Cumulative Surface Settlement of the Simulated Landfills	27
8	Moisture and Precipitation Intercepted by Simulated Landfills During Phase I	29
9	Moisture and Precipitation Intercepted by Simulated Landfills During Phase II	34
10	Concentrations of Extracted Materials in Leachate Obtained from Control Landfill (Fill 1)	38
11	Concentrations of Extracted Materials in Leachate Obtained from Recirculated Landfill (Fill 2)	40
12	Concentration of Extracted Materials in Leachate Obtained from Fill 3	42
13	Concentration of Extracted Materials in Leachate Obtained from Fill 4	44
14	Composition of Gas Produced During Phase II	64
15	Analysis of Raw Primary Sludge Added to Fill 4 in Phase II	65
16	Estimated Incremental and Total Mass of Materials Extracted from Fill 1 During Phase I	77

TABLES (continued)

No.		Page
17	Characteristics of Leachate Used During Separate Biological Treatment	80
18	Results of Separate Anaerobic Biological Leachate Treatment in Continuous Culture Without Solids Recycle	84
19	Results of Separate Aerobic Biological Leachate Treatment in Continuous Culture Without Solids Recycle	86
20	Cation Exchange Treatment of Leachate Residuals	88
21	Mixed Resin Treatment of Leachate Residuals	90
22	Carbon Treatment of Leachate Residuals	95
23	Combined Mixed Resin Ion Exchange and Carbon Treatment of Leachate Residuals	97

ACKNOWLEDGEMENTS

The participation and efforts of Messrs. W. F. Armentrout, L. L. Bortner, P. R. Maye, P. R. Karr, C. G. Breland, M. Mao, F. C. Mingledorff, R. R. Bouton, C. L. Simmons and P. J. Pujals in the conduct of the research detailed in this report, and the able assistance of Messrs. E. E. Ozburn, R. A. Wiscovitch, and J. W. Hudson of the Sanitary Engineering Program at the Georgia Institute of Technology are gratefully acknowledged.

Appreciation is also extended to the administrative and financial support provided in part by the School of Civil Engineering at the Georgia Institute of Technology and by the Environmental Protection Agency through its Solid Waste Training Program.

Finally, to Mr. Dirk Brunner, EPA Project Officer, a special recognition and thanks for agency support and personal interest in the successful completion of the project.

SECTION I

CONCLUSIONS

The results of experimental studies on the treatment of leachate by recycle and/or separate biological and physical-chemical methods have indicated that a combination of these methods may be necessary to reduce the pollutional potential of leachate from refuse disposal sites to a concentration acceptable for ultimate disposal.

Recirculation of leachate through a landfill promotes a more rapid development of an active anaerobic bacterial population of methane formers, increases the rate and predictability of biological stabilization of the readily available organic pollutants in the refuse and leachate,dramatically decreases the time required for stabilization, and reduces the potential for environmental impairment.

Leachate recirculation with pH control and initial sludge seeding may further enhance treatment efficiency so that the time required for biological stabilization of the readily available organic pollutants in the leachate can be reduced to a matter of months rather than years with the opportunity for controlled final discharge and/or treatment of residuals as may be required.

Separate aerobic or anaerobic biological processes have proven satisfactory for treatment of leachate; residual organics and inorganics in the effluent are best removed by carbon adsorption followed by mixed resin ion exchange. The degree of residual treatment is predictable and therefore responsive to whatever effluent requirement may be imposed.

Based upon the concept of leachate containment, collection and treatment either by recycle through a landfill and/or by separate biological and physical-chemical methods, the landfill of the future may well be conceived as a controlled process conducive to accelerated stabilization, environmental protection, and rapid realization of potentials for land reclamation and/or ultimate use.

SECTION II

RECOMMENDATIONS

The studies reported herein have formed the basis for introduction of a relatively new and innovative method for management and control of solid waste disposal sites. However, the studies were somewhat limited in scope and application since they were conducted on a laboratory scale essentially as a research investigation.

Sufficient data have been accumulated to justify an extension of the studies to pilot- or full-scale landfill operations. In addition to the development of some test cells, simultaneous investigations of alternatives for leachate containment, recycle, and residual treatment should be conducted together with studies on: the predictability of refuse and leachate stabilization with respect to rate and time required for eventual use of the site; the potentials for possible energy recovery either from gas (methane) produced during rapid biological stabilization or from the stabilized refuse as a raw material for resource recovery; the variance between leachate problems, control procedures and requisite treatment accountable to refuse characteristics, environmental stresses, and operational procedures; and the economic and design factors necessary to support the development and acceptability of a viable system. Such information would also support the decision process necessary to determine applicability and potential environmental hazard and would therefore contribute to the state of the art and possible development of guidelines for landfill disposal of solid waste.

SECTION III

REVIEW OF THE LITERATURE

Whenever refuse is deposited on land, some of its organic and inorganic constituents are subject to leaching as water percolating through the refuse carries these materials into aquifers, surface streams or impoundments. Such leaching of pollutants may seriously impair water quality and endanger the health and welfare of the community.

The leachate formed by such action has been defined as the contaminated liquid which is discharged from a landfill to either surface or subsurface receptors[1]. For pollution of ground water to occur, three conditions are required: (1) the refuse must be located over, adjacent to, or in an aquifer; (2) supersaturation must exist in the fill due mainly to the movement of ground water into the fill and the percolation of precipitation and surface water runoff; and (3) leached fluids must be produced and this leachate must be capable of entering an aquifer[2].

EFFECT OF LANDFILLS ON WATER QUALITY

Based on the study of an existing landfill in an abandoned gravel pit, Anderson and Dornbush[3] reported that ground water in the immediate vicinity of the landfill and in direct contact with the fill exhibited an increase in ionic strength and that the impairment of water quality by excess ions decreased with distance from the fill area. Analyses on samples obtained at various depths from 22 wells located around the landfill indicated that the chloride and sodium concentrations and specific conductance were the most appropriate chemical parameters of those employed to measure leachate pollution. It was also reported that the pond downstream from the fill area served to reduce the hardness and alkalinity during the summer months.

Hughes, et al.[4-8] investigated the characteristics of four active landfills of varying ages in northeastern Illinois. Piezometers were installed at various points in the landfills and core samples were obtained at the piezometer locations. The results indicated that ground water mounds had formed under each fill and that leachate moved away from the fill area through springs in the superficial sand layer around the fills and vertically downward into the subgrade. Analyses of samples revealed that ground water quality increased with age of the fill material and with distance from the fill area. Ground water quality also varied greatly over short vertical and horizontal distances within the fill.

Coe[9] reported from studies at the University of Southern California that the ground water under the Riverside Landfill contained BOD, chloride, sodium, and sulfate increases of 26, 10, 9 and 8 times, respectively over the concentrations found in the natural and uncontaminated ground water. In general, the ground water at all points sampled downstream of the fill showed significant increases in mineral constituents, hardness, and alkalinity; however, the effects were considerably less than those found in ground water under the fill.

Calvert[10] reported an increase in hardness, calcium, magnesium, total solids and carbon dioxide in a well 500 feet from a refuse storage pit at a garbage reduction plant. Carpenter and Setter[11] sampled water at the bottom of a refuse fill and obtained average BOD, alkalinity and chloride concentrations of 1,987, 3,867, and 3,506 mg/l, respectively. Lang[11] reported the pollution of well water 2,000 feet from a fill.

Davison[12] studied the characteristics of refuse tips in England and concluded that such effluents could promote the growth of bacterial slimes or fungus in groundwater supplies and lead to taste and odor problems.

The pollution of the surface water supply of Kansas City, Mo. reported by Hopkins and Papalisky[13] was attributed to the reactivation of an industrial waste landfill with the subsequent leaching of organic compounds directly into the Missouri River one mile above the city's water intake. A review of German experiences[14] has indicated the detection of pollution in surface waters 2.5 miles downstream from a solid waste disposal area.

QUANTITIES OF LEACHATE PRODUCED BY LANDFILLS

Remson, et al.[15] have developed a moisture routing model based on the equation of continuity to predict the quantity of leachate which would be produced by a landfill for a given refuse, soil, and precipitation pattern. Sample calculations for a hypothetical landfill composed of eight feet of compacted refuse and two feet of soil cover were provided together with characteristics of a municipal refuse. Calculations were simplified by assuming: (1) a fully vegetated fill surface with plants whose roots draw water from all parts of the soil cover but not the underlying fill; (2) no moisture removed by diffusing gases; (3) infiltration of all rainfall; (4) a soil cover and refuse with uniform hydraulic characteristics in all directions; and (5) a freely draining landfill and substrata. The examples assumed instantaneous placement of a refuse of various moisture contents and at various times of the year. The average rainfall was superimposed and the amounts of leachate produced calculated.

A graphical phase relationship presented by Fungaroli[1] showed a definite lag between initial addition of water and the production of leachate as well as a correlation between water added and leachate produced. The relationships between field capacity and dry density of the refuse and the effect of cover soil type on infiltration into the fill indicated that denser refuse yielded higher field capacity and therefore a longer time to saturate the landfill and produce leachate. A light clay loam proved to be the best cover material because of the longer time required to bring a given thickness to field capacity and allow percolation into the fill. It was concluded that leachate production could be attributed to refuse composition and placement, channeling and/or type of wetting front.

Experiments by Merz and Stone[14] with landfill cells of approximately 20 feet in depth and covered with two feet of earth indicated that little leachate percolated into the subgrade beneath the landfills. Water was applied in sufficient quantities to the refuse cells by a sprinkler system so as to augment the natural rainfall and match the yearly rainfall of Seattle, Wash. for one cell and to provide enough water to allow the growth of a thick turf on the other. The moisture content of the soil cover, refuse and subgrade was obtained from core samples taken at various points in the cells. Differences in moisture content at different levels (bands) in the cells were noted. Except for the soil cover, the top band of the cell simulating rainfall patterns of Seattle, was always drier than the other bands. During the final year of the project, the middle band maintained a higher moisture content than the bottom band thereby indicating that the fill material had a high holding capacity. The adobe-shale subgrade beneath the cell maintained a moisture content only seven percent greater than native soils taken from the same depth. The earth cover of the other cell had a lower moisture content than the three bands at all times except for two core samples. There was no relatioship between the moisture content of the top and middle bands and the subgrade averaged about the same water content as observed before for the other cell until it was accidently flooded. After flooding, the moisture content of the subgrade increased 38 percent.

CHARACTERISTICS OF LEACHATE PRODUCED BY LANDFILLS

Theoretically, any time the amount of water entering a landfill exceeds the field capacity of the deposited refuse, leachate will be produced and discharged. Leachate characteristics may vary widely and no general method has been developed to forecast the exact composition of leachate which may be associated with a particular fill at a particular time. Leachate characteristics are influenced not only by the materials placed in the fill but also by the stage of decomposition and the physical characteristics of the percolating water and the soil adjacent to the fill or used for cover. Therefore, leachate will be composed of various concentrations of pollutants in the form of dissolved and finely suspended organic and inorganic materials as well as products of microbial activity.

Several studies have been performed to ascertain the characteristics of leachate. Coe[9] reported that the color of leachate ranged from green to brown, and that odors were similar to those of garbage (decomposing food stuffs) and oil and grease (hydrocarbons). Qasim[16] noted that fresh leachate samples were dark green and became darker and septic soon after collection.

Qasim and Burchinal[16, 17] reported experimental results obtained from examination of leachate produced from simulated landfills consisting of 36-inch concrete cylinders containing municipal refuse and covered to exclude precipitation. Water was applied by an internal sprinkling system and leachate samples were collected and analyzed for alkalinity, acidity, pH, BOD, total hardness, calcium, magnesium, sodium, potassium, iron, sulfate, phosphate, chlorides, nitrogen, solids, tanin and lignin, coliforms and total plate counts. Leachate analyses indicated an initial increase of pollutants which decreased after four weeks depending upon the depth of fill and extent of stabilization. The deeper fills took longer to become saturated so that leaching started later. Moreover, leachate liquors from the deeper fills were stronger although concentrations of pollutants per foot of fill decreased as the depth of fill increased.

Fungaroli and Steiner[18] have reported the results from examination of leachate from an insulated lysimeter. The leachate was generally acidic with the usual pH range between 5.0 and 6.5 except for some high and low peaks. Erratic fluctuations in pH occurred during low leachate production whereas relatively constant pH corresponded to periods of large production. This implied that the volumetric flow rate of leachate through the refuse was a moderating factor for pH. In addition, during low flow periods when the pH was greater than 5.5, the iron concentration in the leachate was low, about 100 mg/l. Conversely, when leachate production was high and the pH less than 5.5, the iron concentration was high. The maximum concentration for both ferric and ferrous iron exceeded 1600 mg/l. The quantity of leachate produced also influenced the total solids concentration. The total solids increased with increasing leachate volume and decreased with decreasing volume. This indicated the "washing-action" as the leachate moved through the refuse. Similarly, after the initially high concentration of 50,000 mg/l COD, the COD remained between 20,000 to 22,000 mg/l during the duration of the two-year study. The leachate was also analyzed for chlorides, copper, zinc, nitrogen, phosphorous, sodium, sulfate, and hardness; no trends or interrelationships between various ions were apparent.

Merz[19] reported results from examination of leachate from two "percolation bins" containing 10 feet of compacted domestic refuse. The concentrations of the organic and inorganic components was high in the first samples of leachate and increased for five weeks. The initial BOD was 33,100 mg/l and remained high for eight months. An 80 percent decrease in BOD occurred after eight months; after 13 months the BOD had been reduced to 375 mg/l. The maximum ion concentration in the leachate was 10 to 20 times the concentration found in the water applied to the refuse. The ammonia, organic nitrogen and phosphate concentrations of the leachate were as much as 10,000 times the concentration found in natural waters. It was concluded that continuous leaching of an acre-foot of fill would result in minimum extraction of about 1.5 tons of sodium and potassium, 1.0 ton of calcium and magnesium, 0.91 ton of chlorides, 0.23 ton of sulfates, and 3.9 tons of bicarbonate. Removals of these quantities would take place in less than one year after which removals would continue slowly with some ions always remaining.

Table 1 contains the results of several leachate studies. These results are influenced by differences in characteristics of the refuse and percolating water and by limitations in sampling and analytical techniques.

PARAMETRIC CONSIDERATIONS IN LANDFILL STABILIZATION

Moisture Content

One of the parameters of importance to the stabilization processes occurring in a landfill is the moisture content of the refuse material as placed. Refuse usually contains a large amount of paper which more than counteracts any moisture from the garbage fraction and other moist materials. However, moisture content increases with age and depth mainly because of infiltration

Table 1. VARIATIONS IN LEACHATE COMPOSITION

Analysis	1	2	3	4	5	6	7	8	9		10	11	12	13	14		15	16	17
pH	5.6	5.9	8.3	-	-	-	-	-	7.63	5.60	7.4	6.4	4.9	5.6	8.4	5.7	6.3	6.48	5.88
Total hardness, mg/l as $CaCO_3$	8,120	3,260	537	-	8,700	500	900	290	8,120	650	-	-	2,500	30	-	-	7,600	13,100	10,950
Total alkalinity, mg/l as $CaCO_3$	8,100	1,710	1,290	-	-	-	-	-	9,520	730	-	-	-	-	9,450	100	10,630	16,200	20,850
Total iron, mg/l	305	336	219	1,000	-	-	40	2	305	6	-	206	152	28	-	-	175	546	860
Sodium, mg/l	1,805	350	600	-	-	-	-	-	1,805	85	-	1,200	1,100	300	-	-	584	1,428	1,439
Potassium	1,860	655	-	-	-	-	-	-	1,860	28	-	-	920	110	-	-	1,050	2,535	3,770
Sulfate	630	1,220	99	-	940	24	225	100	730	248	248	940	970	65	-	-	615	1,002	768
Chloride	2,240	-	300	2,000	1,000	220	-	-	2,350	90	1,845	1,100	1,600	485	12,300	280	951	2,000	2,310
Nitrate, mg/l N	-	5	18	-	-	-	-	-	-	-	-	-	196	10	-	-	-	-	-
Ammonia, mg/l N	845	141	-	-	-	-	160	100	845	0.2	668	-	-	-	-	-	473	756	1,106
Total organic nitrogen, mg/l N	550	152	-	-	-	-	-	-	550	2	101	-	-	-	-	-	288	664	1,416
COD, mg/l	-	7,130	-	750,000	-	-	3,850	246	-	-	-	35,700	21,120	282	-	-	-	-	-
BOD_5, mg/l	32,400	7,050	-	720,000	-	-	1,800	18	33,100	81	5,491	-	-	-	7,330	5.9	14,760	26,940	33,360
Total dissolved solids, mg/l	-	9,190	2,000	-	11,254	2,075	-	-	-	-	-	11,254	15,830	1,740	-	-	-	-	-
Specific conductance, μmhos/cm	-	-	-	-	-	-	3,000	2,500	-	-	-	-	-	-	-	-	-	-	-

Sample Identification:

1., 2., 3. From Ref. 19; no age of fill specified.
4. From Ref. 44; Initial leachate.
5. From Ref. 44; 3-year old fill.
6. From Ref. 44; 15-year old fill.
7. From Ref. 33; new fill.
8. From Ref. 33; old fill.
9. From Ref. 45; maximum and minimum.
10. From Ref. 46
11. From Ref. 7
12. From Ref. 1; Site 4.
13. From Ref. 1; Site B
14. From Ref. 11; maximum and minimum.
15. From Ref. 16; Cylinder A, maximum.
16. From Ref. 16; Cylinder B, maximum.
17. From Ref. 16; Cylinder C, maximum.

and percolation of rainfall and surface water with time. In landfill studies by Eliassen[20], the moisture content ranged from 18.9 to 34.3 percent. Merz[19] found a moisture retention of 39.5 gallons per cubic yard of refuse from which cans and bottles had been removed. However, in California, rainfall did not penetrate a fill 7.5 feet thick.

The decomposition and stabilization in a landfill is dependent upon many factors including the moisture content. In general, the rate of chemical and biological reactions in a landfill increases with increasing moisture content. In California, where a large amount of water was applied to the fill, the settlement was about four times greater than a similar fill without water addition[19]. Other studies have also indicated that moderate amount of moisture in the landfill hastened decomposition[20]. Eliassen[20] carried out studies to determine the optimum moisture content for decomposition of landfill material. The procedure involved adding given amounts of moisture to 5-gram, dried samples of refuse. The results indicated that for fresh landfill material, the optimum moisture content for biological decomposition ranged between 50 and 70 percent and for older fills between 30 and 80 percent.

Temperature

Another parameter of considerable significance is temperature. Although a fill may be placed during cold weather, the material is insulated so that heat is not readily transmitted to the atmosphere. In the study by Eliassen[20], the reactions in the fills were considered thermogenic initially and the temperatures at the depths of 3 and 7 feet were between 50-70°C; at a depth of 11 feet, the temperature ranged between 25-40°C even though the air temperature was between 10-20°C. These temperatures were in the range betwen the optimum temperatures for mesophilic (20-40°C) and thermophilic (50-70°C) organisms and both types of organisms may be presumed to assist in the decomposition of fill material.

Temperature has been monitored in several simulated landfill studies. Fungaroli[18] reported a peak temperature of 68°C within the first week of testing an insulated lysimeter, followed by a slow decline to 60°C and a subsequent rapid decrease to a constant 30°C during the remainder of the study. Sixteen days after placement, Carpenter and Setter[11] reported a temperature of 48°C at three feet and 55°C at seven feet; the air temperature was about 24°C. Temperatures recorded after 10 months indicated that the temperature of the fill had become stabilized at or near air temperature.

Merz and Stone[14] reported the maximum temperatures of two simulated fills to be 49°C and 42°C and that during the final two years of the study, the temperature ranged from 16°C in the winter to 32°C in the summer in one fill and from 12°C in the winter to 31°C in the summer in the other.

pH

The chemical and biological reactions occurring in a landfill are a function of pH. Since these reactions occur primarily within an anaerobic environment, the pH established during a particular stage of stabilization is dependent upon the relationship between the volatile acids and alkalinity in the leachate and carbon dioxide content in the gas evolved from the process.

Therefore, landfill stabilization is much analogous to anaerobic digestion[22,23].

The optimum pH for the anaerobic stabilization process with methane production as determined by studies on wastewater sludge has been reported in the range of 6.8 to 7.2 with the limits of operation without significant inhibition being 6.6 to 7.4[24-28]. Dague[23] reported that lime, sodium bicarbonate, sodium hydroxide, potassium hydroxide, and ammonia may be used to control pH during digestion with the quantity necessary for neutralization usually below toxic limits.

Published results concerning the toxicity of light metal cations on the anaerobic digestion process by McCarty[29] and Kugelman and Chin[30] indicated that alkali and alkaline-earth cations can be moderately inhibitory at certain ranges of concentration. As indicated in Table 2, a concentration defined as moderately inhibitory was one which normally could be tolerated, but required some acclimation by the microorganisms. When introduced suddenly, the concentrations could be expected to retard the process significantly for periods ranging from a few days to over a week. Table 2 also includes ranges where the cations were considered stimulatory and strongly inhibitory. Similarly, Kugelman and Chin[30] found that the toxic upper limit for cation concentrations was 6900 mg/l for sodium, 5100 mg/l for potassium, 6000 mg/l for calcium, and 1580 mg/l for magnesium.

Table 2. STIMULATING AND INHIBITORY CONCENTRATIONS OF ALKALI AND ALKALINE-EARTH CATIONS TO THE DIGESTION OF SEWAGE SLUDGE
(mg/l)

Cation	Stimulatory	Moderately Inhibitory	Strongly Inhibitory
Sodium	100-200	3500-5500	8000
Potassium	200-400	2500-4500	12,000
Calcium	100-200	2500-4500	8000
Magnesium	75-150	1000-1500	3000

Dague[23] emphasized that the addition of chemicals in order to raise the pH during digestion may be only a temporary, holding action, and that such measures will not correct the basic cause of poor methane formation. However, since the methane formers grow less rapidly than the organisms responsible for the production of volatile acids, pH control could allow for their development before they had been adversely influenced by low pH conditions. As early as 1954, Sawyer, *et al.*[31] concluded that, "since it is known that raw sludge is deficient in buffering capacity, that highly buffered materials are most resistant to changes in pH, and that natural buffers in digesting sewage sludge consist of calcium, magnesium and ammonium bicarbonate, it seems reasonable to conclude that the judicious addition of lime to neutralize organic acids in order to maintain favorable pH values, will result in a desirable climate for methane formers, thereby allowing normal digestion to progress and at the same time adding to the total buffering capacity of the system." A similar effect could be anticipated for possible control of pH during landfill stabilization in order to accelerate anaerobic biological decomposition processes and maximize the rate of methane production.

LANDFILL DESIGN AND OPERATIONAL CRITERIA

Some attempts have been made to include information on leachate characteristics and behavior in design considerations for sanitary landfills. Hughes[6] suggested several criteria including a thorough knowledge of the ground water flow system and soil characteristics at the proposed site. The hydrological and geological suitability of the site could then be ascertained with respect to retardation of ground water pollution. To preclude percolation and leaching, impermeable liners or covers were recommended together with the possible collection and disposal of leachate by an underdrain system. Culham and McHugh[32] have recommended the collection and treatment of leachate from landfills including consideration of filtration, flocculation, and the addition of lime for pH control. The diversion of water from landfill areas was emphasized as an important method for alleviating leachate problems which should be included in design and operational procedures. The pollutional characteristics of leachate can be attenuated or renovated as it moves through the underlying earth material before being discharged to the surface or into the ground water. Emrich[33] recommended one foot of suitable earth material for every foot of refuse. Anderson and Dornbush[3] reported that a pond and a trench located in the downstream direction from the slope of the water table improved the quality of water emanating from a refuse disposal area.

Site selection proposed by Cartwright and Sherman[34] included location of landfills in areas where soils of low permeability exist between the bottom of the fill and the highest estimated water table. An interim report[35] from the County of Los Angeles on the development of construction and use criteria for sanitary landfills recommended a geohydrological classification of landfill sites in addition to reduction of leachate problems by diversion of surface runoff in lined channels or storm drains, proper grading and use of relatively impervious surface materials, and construction of suitable barriers to restrict the infiltration of ground water into the landfill. Hughes[36] discussed the importance of considering the stabilization time in selecting sites, particularly if treatment facilities are planned or if future use of the site is contemplated. Decrease in stabilization time was considered advantageous when leaching is rapid. Permeable cover material and rapid drainage will accelerate leaching and also increase the amount of leachate moving from the fill. The advantage of reducing infiltration into a landfill would be the reduction of quantity and rate of leachate produced. However, reduction of infiltration would extend the "polluting life" of the landfill and if the cover material used had a low permeability, it would tend to force the gases produced during decomposition laterally rather than upward through the surface and thereby cause problems due to the escape of gases at unsuspected locations.

SECTION IV

MATERIALS AND METHODS

SIMULATED LANDFILL CONSTRUCTION

Since the purpose of the research was to develop and study the feasibility of a leachate recycle system to provide leachate treatment and pollution control as well as accelerated rates of biological stabilization within sanitary landfills, four simulated landfills were constructed on the campus of the Georgia Institute of Technology in Atlanta, Georgia. The construction was accomplished in two phases. The two fills of Phase I were completed in the spring of 1971; the two fills of Phase II were completed in the spring of 1972. As indicated in Figure 1, all four simulated landfills were basically similar except for a few modifications instigated during Phase II.

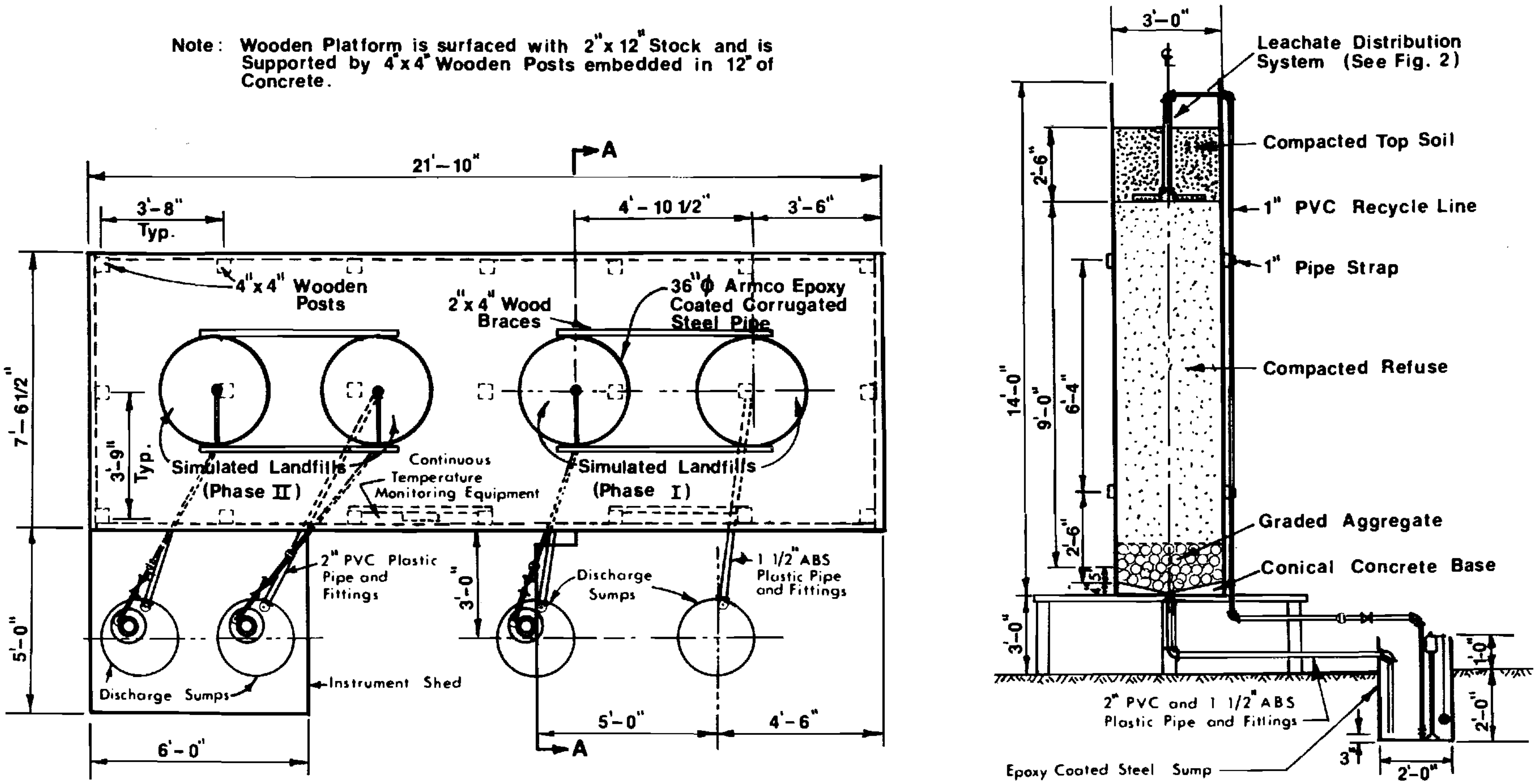
Phase I

The purpose of the initial phase of the study was to demonstrate the advantages of leachate recycle in accelerating the stabilization processes within sanitary landfills and in removing readily degradable pollutants from the leachate. To accomplish this purpose, two simulated landfill columns were constructed; one with leachate recycle capabilities and the other to be used as a control without recycle.

The units were constructed 14 feet high by joining sections of 36-inch diameter ARMCO corrugated steel pipe. The pipes were lined with two coats of epoxy paint, placed on a wooden platform, and secured with steel angles bolted around the base of each column. A conical concrete bottom with a 1.5-inch drain was formed in each simulated fill to seal the bottom of the pipe section and facilitate the drainage and collection of leachate. Nine inches of coarse gravel (3/4 to 2-inch) were placed in the bottom of each column to prevent clogging by the compacted refuse. The two columns were connected by cross ties and guyed in two directions for stability.

After the units had been erected, all joints and connections were caulked with a sealing compound to prevent air from entering the fill by any means other than from diffusion through the soil cover. Leachate from the simulated landfills was collected in epoxy-lined, 55-gallon drums. A 1.5-inch ABS plastic pipe provided for drainage of the leachate from the conical base of the simulated fills into the collection sumps. The drums were covered to exclude rainfall and other external contaminants.

Initially it was proposed to have a proportional sampling device to automatically sample leachate from the sump of the control (non-recycling fill). However, due to the small volume and the intermittent nature of the leachate from this fill, the use of the device was not feasible. Instead, leachate from the control, Fill 1, was collected in a sealed drain line which was unplugged only to manually collect a leachate sample.



Note: Wooden Platform is surfaced with 2"x 12" Stock and is Supported by 4"x 4" Wooden Posts embedded in 12" of Concrete.

PLAN OF SIMULATED SANITARY LANDFILLS
(NO SCALE)

SECTION A-A: RECIRCULATING SIMULATED LANDFILL
(NO SCALE)

FIGURE 1 SIMULATED SANITARY LANDFILLS

The leachate collected from the fill with leachate recycle, Fill 2, was removed from the sump and pumped back through a distributor buried between the top of the compacted refuse and the soil cover and allowed to percolate through the refuse (See Figure 1 and Figure 2). An upright float-operated sump pump (Sears) was used to recycle the leachate to the distribution arm. The drain pipe in the sump was completely submerged in the leachate at all times by adjusting the float control to cut-off and maintain the lowest leachate level about 6 inches above the drain discharge.

Three ports were installed in each fill; two for sampling, the third (center) port contained a temperature probe. The ports were constructed of 0.5-inch GVS pipe lengths inserted through the sides of the fill. The lengths were secured on both sides of the columns by nuts and rubber washers and the connections were covered with sealing compound.

Ten feet of compacted simulated refuse were placed in each of the landfill columns. The composition indicated in Table 3 was chosen to reflect that of a typical residential refuse. A total of 2,800 pounds of refuse was coarsely ground with a brush chipper and the dry refuse was mixed in 200-pound batches. The ground refuse was then hauled manually to the top of the simulated fills and dumped into the columns. The refuse was manually compacted to a dry density of about 535 lb/cu.yd.

Table 3. COMPOSITION OF SIMULATED REFUSE

Constituent	Dry Weight, %
Paper	50.0
Plastic	3.0
Glass	7.0
Garbage	25.0
Rags	5.0
Stone & Sand	5.0
Metal	4.0
Wood	1.0
Total	100.0

A 2-week period was allowed to elapse before the placement of the soil cover, during which time the two fills, which were capped to exclude rainfall, settled approximately 6 inches. Due to this settlement, 30 inches of sandy clay top soil were manually placed and compacted over the refuse to bring the total height of each fill to 12 feet.

To expedite the production of leachate by the fills, 250 gallons of tap water were added after the placement of the compacted soil cover. Based on the moisture holding capacity of simulated refuse reported in other studies, the addition of 250 gallons of water was considered sufficient to bring the fills to field capacity. However, since this quantity was applied in a 12-hour period, some initial short-circuiting resulted. The addition of the water and

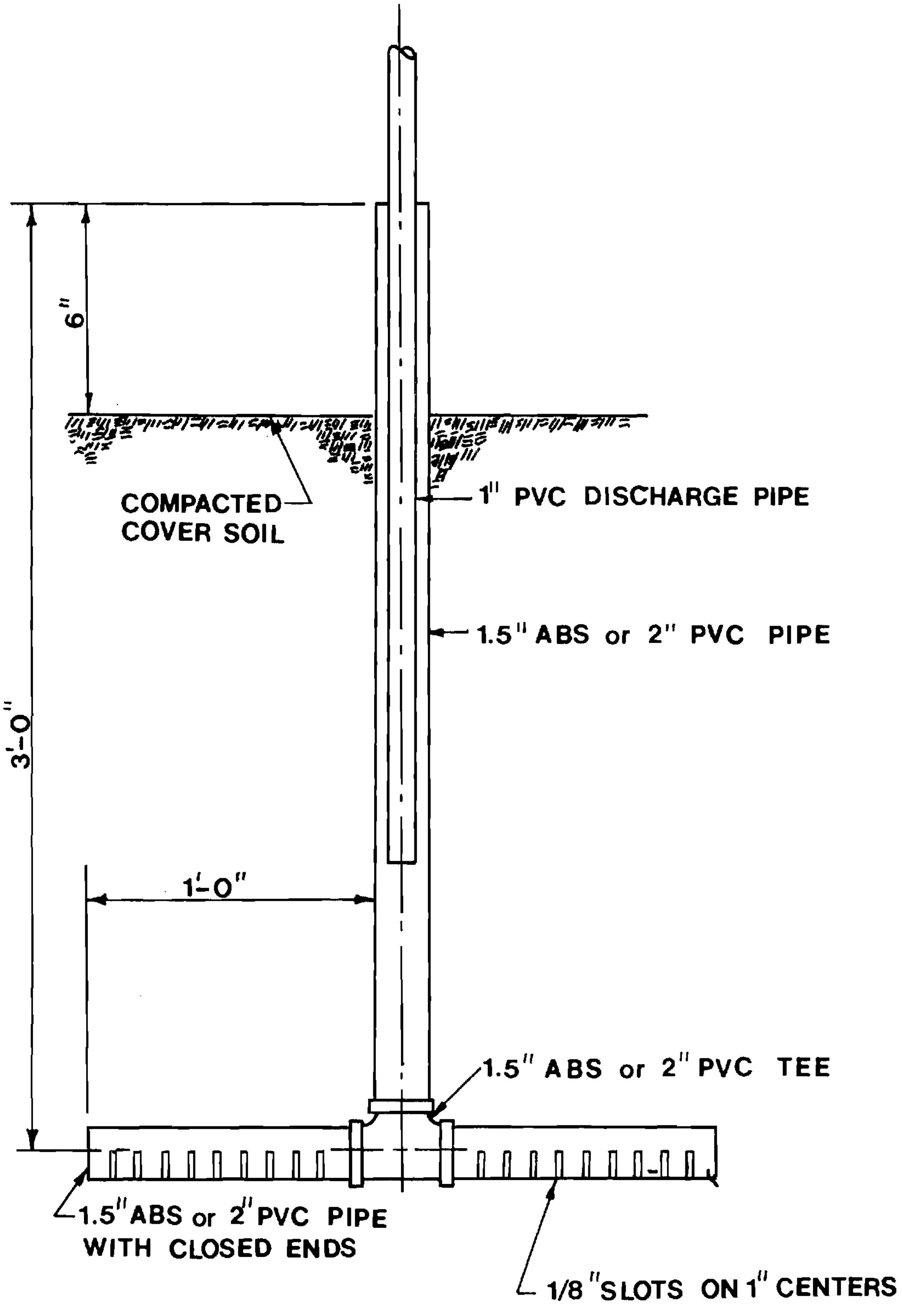


FIGURE 2 LEACHATE DISTRIBUTION SYSTEM

the added weight of the cover soil resulted in an initial settlement of 8.5 and 16.5 inches, respectively, in the control and leachate recycle fills.

The production of 30 gallons of leachate by both fills after the initial addition of water indicated that short-circuiting was occurring. To minimize short-circuiting by rainfall, a blanket of sod was placed over the soil cover to provide better distribution of rainfall across the fill surface and prevent water from flowing down the sides of the fills. Short-circuiting of recycled leachate was minimized by using a gravity flow distributor and capping the ends of the distributor pipe to direct the flow through the center of the fill.

Phase II

The purpose of the second phase of the study was to illustrate the effects of leachate recycle plus nutrient addition and pH control on the stabilization of sanitary landfills. Therefore, two additional simulated landfills were constructed with leachate recycle capabilities. Because these units were completed approximately one year after construction of the initial two fills, it was possible to initiate some minor improvements.

The basic columns in Phase II were identical to those in Phase I (Figure 1). However, the leachate drains in the conical concrete bases were changed from 1.5-inch ABS to 2.0-inch PVC pipe. The drains from each column discharged into 55-gallon drums which were equipped with polypropylene liners to provide a more corrosion resistant container. The sumps for both fills were housed in a metal building (5' X 6') which provided cover and also served as an instrument shed.

Leachate recycle was provided as for Phase I except that the distribution pipe (Figure 2) was increased in diameter from 1.5 to 2.0 inches. This provided more volume in the pipe and thus reduced the chance of leachate overflowing the distributor system.

The refuse used in the Phase II units had the same composition (by weight) as that used in Phase I (Table 3). The refuse was coarsely chopped manually and placed in the columns. The refuse was manually compacted to a dry density of about 535 lb/cu.yd. In one fill, Fill 4, 30 gallons of primary sewage sludge was added in three 10-gallon increments while the refuse was being compacted. To avoid discrepancies, similiarity in volume of liquid added, an equal volume of tap water was added to the other column, Fill 3.

To prevent clogging, the distributor was separated from the top of the refuse by a 3-inch layer of coarse gravel (1 to 3-inch). Two feet of soil cover was added immediately to each unit and rainfall was not excluded. In order to bring the fills up to field capacity, 220 gallons (30 gallons previously added by sludge and water) of tap water were added to each fill. In an attempt to minimize short-circuiting, the water was added over a 72-hour period. Finally, sod was placed on top of the soil cover as in Phase I.

To facilitate the collection of representative refuse samples at periodic intervals, two sampling ports were installed on each of the new columns. The ports were constructed by placing a section of 3-inch ABS plastic pipe through the sides of the columns. The pipes were equipped with threaded plugs and all joints and connections were caulked with sealing compound.

In each new fill, a 0.75-inch PVC pipe was placed to a depth of five feet below the sod layer along the side of the corrugated metal pipe. To this pipe was connected a rubber hose which was directed into a large beaker of water. The purpose of this pipe-hose-beaker apparatus was to detect and collect gas for analysis. The sod used for cover in Phase II was identical to that used in Phase I and was obtained from the same location on the Georgia Tech campus.

SAMPLING PROCEDURES

Phase I

Samples were obtained from the control fill whenever a sufficient quantity of leachate was produced from rainfall to yield a sample of one to three liters. When a sufficient volume of leachate had collected in the base of the control fill, the drain line was opened and the leachate was allowed to flow into a sampling container. The line was then again closed after all the leachate had been collected for testing.

A 24-hour composite sample was taken from the sump of simulated landfill with leachate recycle at one to 3-week intervals. An Instrument Specialties Company Model 780 Automatic Sample Collector was used to obtain 24, 500-ml samples which were composited at the end of the sample period (a day). A 1.0-liter aliquot was taken from the composite for analysis. The remainder of the composite was initially discarded due to the large quantities of leachate collected from the leachate recycling fill, however, after 30 days of sampling, residual samples were returned to the collection sump.

Phase II

Samples collected during Phase II of the study were obtained by two different methods. The first method was used for the initial two weeks of the study and consisted of a grab sample from each of the two sumps; one with the leachate recycle and pH adjustment (Fill 3) and the other with the leachate recycle, pH adjustment and initial sludge addition (Fill 4). The second sampling method employed during the remainder of Phase II consisted of obtaining a 24-hour composite sample using an Instrumentation Specialties Company Model 780 Automatic Sample Collector to remove 500-ml samples from the appropriate sump every hour. A 1.0-liter aliquot was taken from the 24-hour composite for analysis and the remaining leachate was returned to its appropriate sump with none being discarded.

In order to manually control the pH of both fills near neutral, sodium hydroxide was added to each collection sump at various intervals during the day. The sodium hydroxide was added by two different methods. During the first nine weeks of the study, a predetermined amount of sodium hydroxide solution (approximately 150-200 ml) was added to the sumps, mixed, a 100-ml sample removed, the pH of the sample recorded, and the sample titrated with 0.1N NaOH (sodium hydroxide) to a pH of 7.0. Following the titration, the quantity in grams of sodium hydroxide required to bring the sump volume (17 gallons) to neutral was calculated. This quantity was weighed, diluted to 150-200 ml with distilled water, and set aside to cool. Six to 24 hours later, the process was again repeated with the addition of the prepared sodium hydroxide solution.

After the ninth week, the preceding procedure was changed and instead of placing the caustic solution in the sump prior to removing a sample for a pH reading and titration, a 100-ml sample was first removed, the pH recorded, and the sample was titrated with 0.1 N or 0.5 N NaOH solution. Following the titration, the number of grams of sodium hydroxide required to raise the sump volume to neutral was calculated, weighed and placed in a flask of 150-200 ml of distilled water to cool. The solution in the flask was then added to the sump within a period of less than 2 hours. This change in technique was instigated as a result of less need for semi-daily neutralization additions after the ninth week of the study since the pH drop became less drastic with time and there was the desire to know exactly how the pH had changed each day after nine weeks of neutralization. After the twelfth week, a Beckman Model 940 Automatic pH Control provided immediate pH control whenever the pH was not within the optimum range (pH 6.8 to 7.4).

The apparatus for collecting gas was also used during Phase II of the study. In order to collect a sample of gas, a clean, two-stopcock Orion gas sampler was attached to the sampling hose. Both stopcocks were opened for a period of approximately two minutes, then the one not attached to the hose was closed. This initial closure was followed by the closure of the stopcock attached to the sampling hose, thus sealing a sample of gas inside the sampler. Samples of gas were taken periodically and after the 7th, 12th, 32nd, 44th, 67th, 76th, 84th, 99th and 108th weeks of the study. The gas sampler employed featured an opening covered with a rubber septum which allowed the removal of a gas aliquot with a syringe when composition was desired.

Refuse samples of both Fills 3 and 4 were taken at the end of Phase II. Sampling consisted of removing approximately 700 grams of sample through the 3-inch ports constructed in the side of the two fills.

ANALYTICAL METHODS

Analysis of Simulated Refuse

At the beginning of both Phase I and Phase II, a 2-pound sample of the simulated refuse was collected and the organic fraction, consisting of paper, plastics, vegetable matter, meat, rags, and wood, was finely ground in a micromill and analyzed for carbon, hydrogen and nitrogen with a F and **M** Model 185 CHN Analyzer. Another portion of the finely ground sample was digested in concentrated sulfuric acid, neutralized, diluted with distilled water and analyzed for Kjeldahl nitrogen with a Technicon Auto-Analyzer; for potassium, sodium, calcium and magnesium with a Perkin-Elmer Atomic Absorption Spectrophotometer; and for phosphate using the procedures outlined in Standard Methods[37].

However, phosphate analysis in Phase II was performed using the Technicon Auto-Analyzer. In addition, the refuse removed from the simulated landfills during both the Phase I and Phase II studies was analyzed for carbon, hydrogen, and nitrogen using the CHN analyzer, and moisture content and volatile solids analyses were performed in accordance with Standard Methods[37].

Analysis of Soil Characteristics

The characteristics of the cover soil used in the Phase I study were determined. The same type and quantity of soil was used in Phase II and additional soil analyses were therefore not considered necessary.

Two plexiglass columns were each filled with 2000 grams of soil similar to that used as cover for the simulated landfills. The soil was leached with demineralized water to determine the potential contribution of substances in the cover soil to fill leachate. The leachate from one soil column was recycled back through the column and the leachate from the second column was discharged to waste. This allowed for the determination of the total quantities of iron, calcium, magnesium, manganese, sodium, ammonia nitrogen, total nitrogen, and total organic carbon leached from the soil and also indicated to some extent the ion exchange capacity of the soil. The soil leachate was analyzed for sodium, calcium, magnesium, manganese, and iron with a Perkin-Elmer Atomic Absorption Spectrophotometer ; total organic carbon with a Beckman Total Carbon Analyzer; and nitrogen with a Technicon Auto-Analyzer.

Analysis of Leachate, Sludge and Gas Samples

The simulated landfill leachate samples (Phase I and Phase II) were analyzed for 5-day biochemical oxygen demand (BOD_5), total organic carbon (TOC), chemical oxygen demand (COD), total suspended solids (TSS), volatile suspended solids (VSS), total solids (TS), alkalinity, acidity, total hardness, total and ammonia nitrogen, phosphate, calcium, magnesium, manganese, sodium, iron, chloride, pH and volatile acids. Similar but fewer tests were initially conducted on the primary sludge added to Fill 4. In addition, samples from the Phase II study were obtained to determine concentrations of chromium, copper, zinc, lead, potassium and nickel. During the first 125 days of leachate production in the Phase I study, nitrate determinations were also made using both specific ion electrodes and colorimetric methods. However, due to matrix interference difficulties with high concentrations of iron and chlorides, the results were considered questionable. Therefore, in order to avoid the problem experienced in Phase I, the Technicon Auto-Analyzer was used during Phase II to determine nitrate concentration. Sulfates were also determined during the first 125-day period of Phase I, but since the concentrations were very low, this analysis was subsequently deleted. Nitrate and sulfate concentrations were converted to their corresponding reduced states as anaerobic conditions were established. In addition, sulfate analysis was deleted completely from the Phase II study due to the interference of phosphate on the specific-ion electrode method used. Moreover, since it was the purpose of this research to determine the effect of leachate recycle, pH adjustment and initial sludge addition on landfill stabilization, these analyses were considered of lesser significance as compared to the other analytical parameters.

Calcium, magnesium, manganese, sodium, iron, zinc, potassium,chromium, copper, lead, and nickel were measured with a Perkin-Elmer Atomic Absorption Spectrophotometer. Phosphates were determined by Hach Kit methods for both Phase I and II, while the Auto-Analyzer was used to obtain total and ammonia nitrogen during both test phases. Phosphates were also determined in Phase II by using the Auto-Analyzer as a comparison to the Hach Kit procedure. Chlorides were measured with an Orion Specific Ion Electrode using the known increment method. Because the concentrations of the hardness producing cations were determined, total hardness was calculated in accordance with the method suggested in Standard Methods[37]. Volatile acids were measured with the F and M Scientific 700 Chromatograph; pH was determined with a Leeds and Northrup pH meter; total organic carbon was measured with a Beckman Model 915 Total Organic Carbon Analyzer; and the remaining analyses were performed according to Standard Methods[37]. Gas samples were analyzed for methane and carbon dioxide content using a Fisher Gas Partitioner.

SECTION V

PRESENTATION OF THE DATA

Results of the analyses performed on the simulated refuse and the leachate samples of Phase I and Phase II are presented in this section. The time scales used in this presentation (time since placement of refuse and time leachate production began) are related in that leachate production began 33 days after refuse placement in Phase I and seven days after refuse placement in Phase II.

REFUSE COMPOSITION

Analysis of the organic portion (paper, plastic, vegetable matter, meat, rags and wood) of the refuse used to fill the simulated landfill columns indicated an initial composition of major constituents as shown in Table 4. The comparisons of the initial composition of the organic fraction of the refuse with the composition of samples taken from the four simulated landfills at the end of each study period are presented in Table 5.

Table 4. INITIAL COMPOSITION OF THE ORGANIC FRACTION[a] OF THE SIMULATED REFUSE USED DURING PHASE I AND PHASE II

Refuse constituent	Composition, percent by weight Phase I	 Phase II
Carbon	47.20	49.50
Hydrogen	5.15	5.86
Oxygen	46.73	43.68
Nitrogen	0.65	0.25
Potassium	0.12	0.10
Sodium	0.12	0.59
Phosphorous	0.03	0.02
Calcium	trace	trace
Magnesium	trace	trace
	100.00	100.00
Volatile Solids	98.62	98.32

[a] Organic fraction included paper, plastic, vegetable matter, meat, rags and wood.

Table 5. CHANGES IN COMPOSITION OF THE ORGANIC FRACTION OF THE SIMULATED REFUSE FOR EACH TEST UNIT DURING PHASE I AND PHASE II

	Refuse Composition, percent by weight									
	Phase I					Phase II				
Refuse constituent	Initial	320 days[a]		1063 days[a]		Initial	90 days[b]		747 days[b]	
		Fill 1	Fill 2	Fill 1	Fill 2		Fill 3	Fill 4	Fill 3	Fill 4
Carbon	47.20	46.00	37.00	89.8	68.2	49.50	43.20	42.90	80.4	80.3
Hydrogen	5.15	5.97	4.68	6.5	6.0	5.86	5.18	5.20	6.2	6.3
Oxygen	46.73	47.80	57.98	---	---	43.68	50.10	49.57	---	---
Nitrogen	0.65	----	----	0.0	1.2	0.25	1.52	2.33	0.5	1.2
Volatile solids	98.62	90.80	73.00	88.1	65.2	98.32	84.00	97.91	80.3	84.1

[a] Refuse sample obtained near surface of columns.
[b] Refuse sample obtained at sampling ports at mid-depth of columns.

COVER SOIL CHARACTERISTICS

Figure 3 and Table 6 indicate the results of the leaching column tests on the cover soil used for each landfill column. Calcium, magnesium, and sodium were the only cations leached from the cover soil in measurable quantities with total quantities of 0.049, 0.005 and 0.001 mg per gram of soil respectively for the single pass tests. During recirculation, indicated equilibrium concentrations of 3.4, 0.5 and 1.0 mg/l respectively for these cations were obtained. The concentrations of calcium, magnesium and sodium were initially high but dropped sharply during the first 30 hours of leaching. As was expected, the concentrations of iron in the leachate was very low.

Graphical integration of the mass flow curves of each element indicated that the quantity of cover soil on each fill would produce a negligible amount of each of these elements. Accordingly, the 2.5 feet of cover soil placed on the top of each fill should leach 58.9 grams of calcium, 11.9 grams of magnesium, and 1.27 grams of sodium with continuous leaching.

The equilibrium concentrations reached during the leachate recirculation indicated that the cover soil was a rather poor ion exchange medium for the indicated constituents. The highest affinity demonstrated by the soil was for calcium with sodium being held less than calcium but more than magnesium.

LANDFILL TEMPERATURE

Temperature in the Phase I simualted landfills varied with daily ambient temperature fluctuations. The maximum (July) temperatures reached were 32°C in the control fill and 31°C in the fill with leachate recycle; the minimum (December) temperatures were 5°C and 4°C, respectively. The temperature variations in the control fill were slightly more dramatic than in Fill 2 where temperature was also moderated by the recycled leachate.

To determine whether insulation would provide control of large temperature fluctuation during extreme temperature periods, the columns were wrapped with 3-inch fiberglass insulation and covered with 4-mil polyethylene plastic to exclude moisture. After the insulation was placed around the columns, temperature fluctuations were greatly reduced but continued to correspond to seasonal changes as indicated in Figure 4.

Because insulation of the columns was considered beneficial, the simulated landfills of Phase II were also insulated; after ten weeks of operation for Fill 3 and after seven weeks for Fill 4. The time of exposure of the fills without insulation was similar as for Phase I and the moderation of temperature fluctuations was determined also to be similar. Moreover, the temperature attained in the fills during the months of May, June, and July when insulation was not provided during Phase II was considered to be beneficial to the anaerobic stabilization process.

LANDFILL SETTLEMENT

The cumulative surface settlement of both Phase I and Phase II fills is

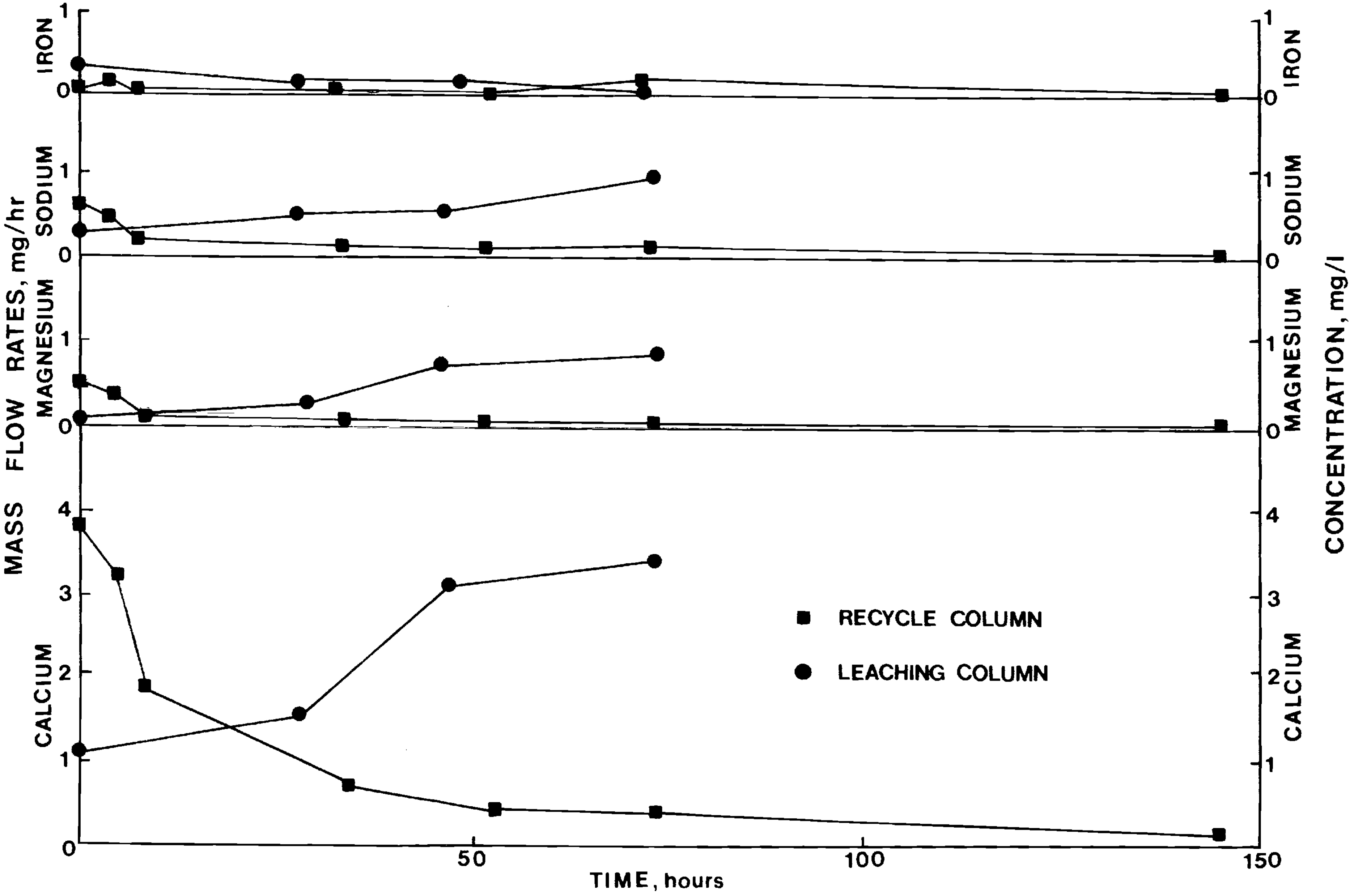
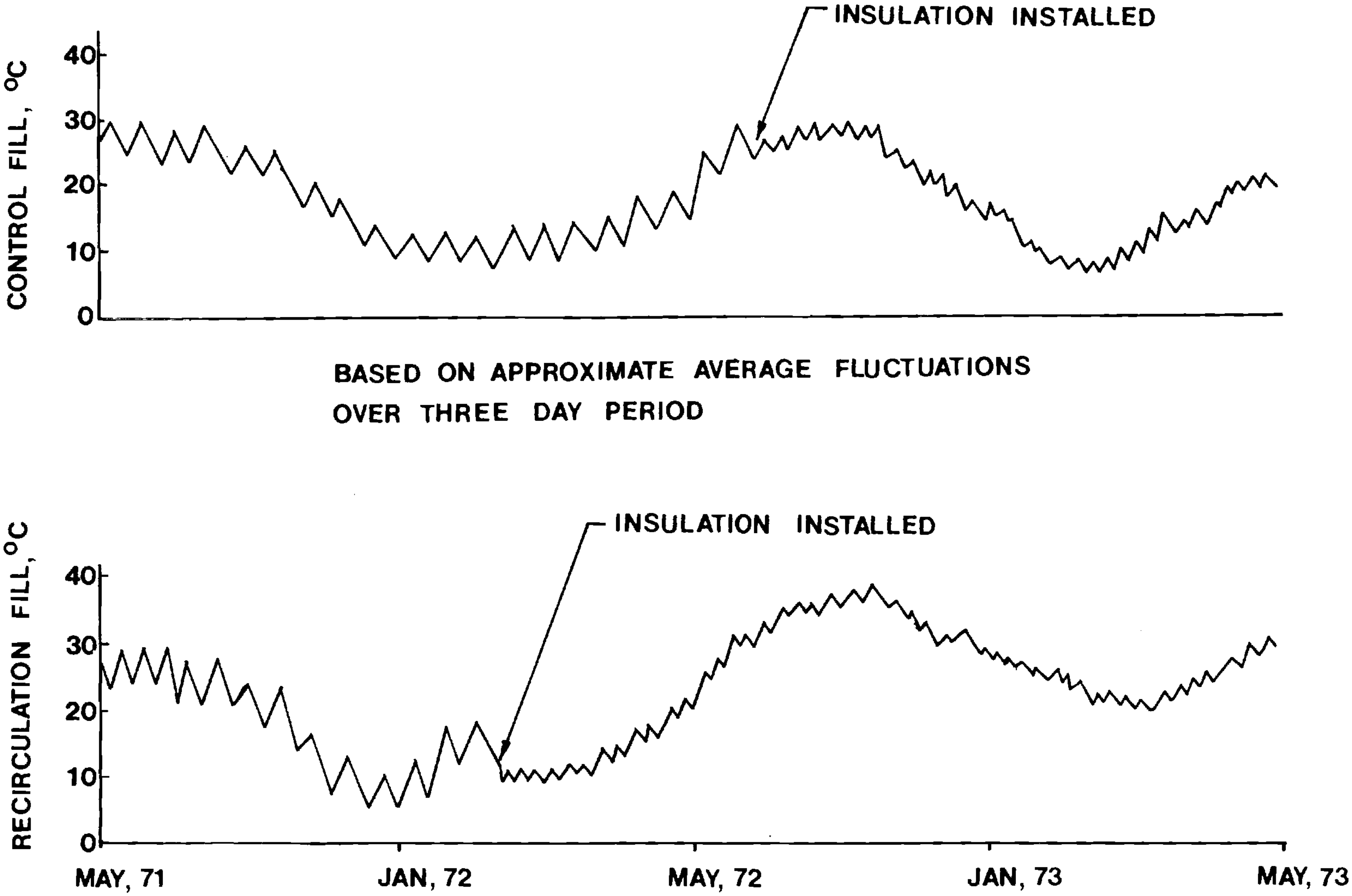


FIGURE 3 RESULTS OF COVER SOIL LEACHING STUDY

Table 6. RESULTS OF COVER SOIL LEACHING EXPERIMENTS

Single Pass Tests					Recirculation Tests				
Time, hours	Mass flow rate, mg/l				Time, hours	Concentration, mg/l			
	Ca	Mg	Na	Fe		Ca	Mg	Na	Fe
0	3.86	0.59	0.80	0	0	1.1	0.1	0.5	0.2
4	3.19	0.50	0.76	0.04	24	1.6	0.2	0.5	0.3
7.5	1.68	0.21	0.29	0.04	48	3.3	0.5	0.6	0.2
32.5	0.63	0.04	0.17	0	72	3.4	0.5	1.0	---
52.5	0.50	0.40	0.08	0	144	3.4	0.5	1.0	---
72	0.50	0.04	0.17	0.04					
144	0.25	0.04	0.04	---					



BASED ON APPROXIMATE AVERAGE FLUCTUATIONS OVER THREE DAY PERIOD

FIGURE 4 INTERNAL TEMPERATURE FLUCTUATIONS OF THE SIMULATED LANDFILLS shown in Table 7. As previously mentioned, the fills experienced settlement due to the placement of cover soil and the initial addition of moisture. For comparison, this initial settlement was not included in the settlement data of Phase I but was included in the settlement data of Phase II.

LEACHATE ANALYSIS

Cumulative moisture and precipitation intercepted by the two Phase I fills is shown in Table 8 and in Table 9 for the two Phase II fills. The total precipitation intercepted by each fill during Phase I was 235.43 inches including the water equivalent of 56.6 inches initially added to saturate the fills. During Phase II, the total precipitation was 165.90 inches including 56.6 inches of water and/or sludge equivalent added initially to saturate the fills. No attempt was made to determine total leachate production which resulted from the accumulated moisture and precipitation since such an analysis would be influenced by extent of evaporation, quantities of leachate used during sampling and, for Fills 3 and 4, the liquid additions during neutralization and pH adjustment.

The concentrations of extracted materials in the leachates obtained from the simulated landfills of Phase I are tabulated in Tables 10 and 11, while those materials extracted from the simulated landfills during Phase II are tabulated in Tables 12 and 13. Changes in concentration are displayed graphically for all four fills in Figures 5 through 20. The concentrations indicated on the figures have been plotted at 30 to 60-day intervals to provide sufficient data to establish trends and yet avoid excessive clustering of data points.

Screening analyses for metals including chromium, copper, lead and nickel were also performed during Phase II but none were found to exist in measurable quantities in the leachate. These analyses were performed for approximately the first five weeks of Phase II.

The initial leachate samples taken from the four fills were dark green in color and had the odor of decaying garbage. The samples from the fills with leachate recirculation later lost this characteristic color and acquired a putrid odor characteristic of the short-chained organic acids until the acids were biologically utilized. Upon exposure to air, the color of the control samples rapidly changed from green to dark brown as the ferrous iron was oxidized.

Leachate Neutralization during Phase II

Daily and cumulative quantities of sodium hydroxide used for temporary neutralization during Phase II are graphically represented in Figure 21 together with the corresponding daily pH readings. At the end of 95 days, the sodium hydroxide added to the leachate from Fill 3 began to level off as the demand diminished and until a value of 1020 grams of sodium hydroxide had been added to maintain a pH of 6.9. On the other hand, the leachate from Fill 4 continued to require more neutralization until 2080 grams of sodium hydroxide had been added after 120 days of leachate production and an adjusted pH of 6.5.

Table 7. CUMULATIVE SURFACE SETTLEMENT OF THE SIMULATED LANDFILLS

Time since leachate production, days	Cumulative Surface Settlement, feet			
	Phase I[a]		Phase II[b]	
	Fill 1	Fill 2	Fill 3	Fill 4
0	0	0	0	0
1	----	----	2.17	2.67
2	1.00	0.50	----	----
3	----	----	2.17	2.96
6	1.21	0.79	----	----
8	----	----	2.62	3.17
10	1.21	0.79	----	----
11	----	----	2.83	3.33
13	1.21	0.79	----	----
14	----	----	3.04	3.62
17	1.22	0.78	----	----
20	1.28	0.78	----	----
22	----	----	3.13	3.75
24	----	0.88	----	----
27	1.44	0.88	----	----
31	1.48	0.95	----	----
38	1.48	0.95	----	----
50	1.48	0.98	----	----
52	----	----	3.42	3.92
65	----	----	3.50	4.00
72	----	----	3.50	4.00
81	1.50	0.99	3.63	4.25
94	1.50	1.01	3.68	----
117	1.50	1.02	----	----
140	1.50	1.03	3.74	----
160	1.50	1.03	3.81	----
180	1.51	1.04	3.88	4.31
210	1.51	1.05	3.88	----
260	1.51	1.06	----	----
280	1.51	1.07	----	----
310	1.51	1.07	3.88	4.31
340	----	----	3.91	4.31
400	----	----	3.94	4.31
490	1.61	1.18	----	----
580	1.77	1.31	----	----
640	1.91	1.41	----	----

[a] Initial settlement due to addition of cover soil and initial moisture not included.

[b] Initial settlement due to addition of cover soil and initial moisture included.

Table 7. (Continued) CUMULATIVE SURFACE SETTLEMENT OF THE SIMULATED LANDFILLS

Time since leachate production, days	Cumulative Surface Settlement, feet			
	Phase I[a]		Phase II[b]	
	Fill 1	Fill 2	Fill 3	Fill 4
649	----	----	3.95	4.31
690	1.92	1.43	----	----
720	1.94	1.47	----	----
745	----	----	3.95	4.31
969	1.95	1.47	----	----
1065	1.96	1.48	----	----

[a] Initial settlement due to addition of cover soil and initial moisture not included.

[b] Initial settlement due to addition of cover soil and initial moisture included.

Table 8. MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE I

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
0	0	0
5[a]	0.37	0.37
21	0.68	1.05
27	0.23	1.28
29	1.22	2.50
32	0.37	2.87
33[b]	56.60	59.47
36	0.98	60.45
38	0.18	60.64
40	3.07	63.71
45	1.11	64.82
46	0.98	65.80
47	1.72	67.52
61	1.02	74.54
66	3.70	78.24
70	1.23	79.47
77	1.90	81.37
90	3.50	84.87
124	0.74	85.61
134	0.86	86.47
136	1.84	88.31
165	1.85	90.16
169	4.06	94.22
180	1.23	95.45
194	1.84	97.29
197	3.69	101.98
204	6.15	108.13
205	3.69	111.82
207	2.09	113.91
224	3.12	117.03
227	1.61	118.64
231	1.24	119.88
237	1.12	121.00
241	0.36	121.36
255	0.72	122.08
267	2.81	124.89
270	1.12	126.01
288	1.82	127.83
307	2.54	130.37
317	0.74	131.11

Table 8 (continued). MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE I

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
320	0.99	132.10
328	3.92	136.02
335	0.19	136.21
337	0.12	136.33
338	0.37	136.70
351	0.12	136.82
354	0.62	137.44
365	4.80	142.24
366	0.12	142.36
373	0.62	142.98
378	0.23	143.21
381	0.38	143.59
394	0.84	144.43
400	0.71	145.15
404	1.13	146.27
406	0.24	146.51
433	0.24	146.75
444	0.40	147.15
459	1.33	148.48
468	1.00	149.48
482	0.34	149.92
493	0.54	150.36
498	2.20	152.56
508	1.20	153.76
514	0.93	154.69
520	0.54	155.23
526	1.36	156.59
531	0.25	156.84
536	0.36	157.20
539	0.14	157.34
542	0.21	157.55
543	0.20	157.75
546	0.68	158.43
553	2.84	161.27
561	1.31	162.58
565	0.24	162.82
570	2.20	164.82
583	2.10	166.92
589	0.78	167.70
601	0.24	167.94

Table 8. (Continued) MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE I

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
606	0.35	168.29
623	1.85	170.14
627	0.04	170.18
631	0.44	170.72
633	1.12	171.74
639	2.14	173.88
649	4.16	178.04
655	0.10	178.14
659	2.60	180.74
673	1.60	182.30
683	0.77	183.98
697	2.29	186.27
707	2.95	189.22
715	0.24	189.46
724	0.89	190.35
745	1.65	192.00
749	0.72	192.72
751	0.53	193.25
756	0.19	193.44
759	0.54	193.98
764	0.06	194.04
769	1.65	195.69
774	0.47	196.16
779	1.07	197.23
786	0.38	197.61
787	0.06	197.67
816	0.90	198.57
819	2.35	200.92
823	0.82	201.74
834	1.13	202.87
837	2.03	204.90
838	0.12	205.02
864	0.27	205.29
868	0.14	205.43
876	0.19	205.62
888	1.64	207.26
892	0.09	207.35
895	0.35	207.70
898	1.65	209.35
909	0.88	210.23
914	0.69	210.92

Table 8. (Continued) MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE I

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
919	0.03	210.95
920	1.35	212.30
923	0.87	213.17
924	0.09	213.26
925	2.42	215.68
926	0.06	215.74
927	0.36	216.10
928	0.51	216.61
929	0.17	216.78
932	0.18	216.96
933	0.14	217.10
934	0.22	217.32
936	0.22	217.54
939	0.26	217.80
944	0.91	218.71
948	0.38	219.09
949	0.04	219.13
950	0.35	219.48
951	0.33	219.81
952	0.25	220.06
953	0.23	220.29
954	0.04	220.33
958	0.21	220.54
964	2.05	222.59
965	0.59	223.18
970	1.38	224.56
971	1.26	225.82
972	0.05	225.87
975	0.34	226.21
978	0.67	226.88
1003	0.55	227.43
1005	0.39	227.82
1011	0.20	228.08
1013	0.82	228.84
1014	0.33	229.17
1017	0.67	229.84
1019	1.53	231.37
1023	0.59	231.96
1028	0.40	232.36
1029	0.12	232.48
1037	0.63	233.11

Table 8. (Continued) MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE I

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
1047	0.07	233.18
1053	0.30	233.48
1054	0.02	233.50
1055	0.38	233.88
1056	0.55	234.43
1057	0.57	235.00
1060	0.43	235.43

[a] Fills were capped until 5 days after refuse was placed.

[b] 250 gal. of tap water initially added to each fill.

Table 9. MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE II

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
0	0	0
1	2.26	2.26
5	23.75[a]	26.01
6	15.83[b]	41.84
7	8.66[c]	50.50
10	0.98	51.48
12	8.66[c]	60.14
18	3.92	64.06
25	0.19	64.25
27	0.12	64.37
28	0.37	64.74
41	0.12	64.86
43	0.62	65.48
54	4.80	70.28
55	0.12	70.40
62	0.62	71.02
67	0.23	71.25
70	0.38	71.63
83	0.84	72.47
89	0.71	73.18
93	2.32[d]	75.50
95	0.24	75.74
122	0.24	75.98
133	0.40	76.38
148	1.33	77.71
157	1.00	78.71
171	0.34	79.05
182	0.54	79.59
189	2.20	81.79
197	1.20	82.99
203	0.93	83.92
209	0.54	84.46
214	1.36	85.82
220	0.25	86.07
225	0.36	86.43

---

[a] 105 gallons of tap water added to each fill; includes 30 gallons of sludge equivalent initially added to Fill 4.

[b] 70 gallons of tap water added to each fill.

[c] 35 gallons of tap water added to each fill; includes natural rainfall.

[d] 5 gallons of tap water added to each fill; includes natural rainfall.

Table 9. (Continued) MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE II

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
228	0.14	86.57
231	0.21	86.78
232	0.20	86.98
235	0.68	87.66
242	2.84	90.50
250	1.31	91.81
254	0.24	92.05
259	2.20	94.25
272	2.10	96.35
278	0.78	97.13
290	0.24	97.37
295	0.35	97.72
312	1.85	99.57
316	0.04	99.61
321	0.44	100.05
322	1.12	101.17
328	2.14	103.31
338	4.16	107.47
344	0.10	107.57
348	2.60	110.17
362	1.60	111.77
372	0.91	112.68
377	0.77	113.45
386	2.29	116.74
396	2.95	119.69
404	0.24	119.93
413	0.89	120.82
434	1.65	122.47
438	0.72	123.19
440	0.53	123.72
444	0.19	123.91
447	0.54	124.45
452	0.06	124.51
457	1.65	126.16
461	0.47	126.63
466	1.07	127.70
473	0.38	128.08
474	0.06	128.14
501	0.90	129.04
504	2.35	131.39
508	0.82	132.21

Table 9. (Continued) MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE II

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
522	1.13	133.34
525	2.03	135.37
526	0.12	135.49
552	0.27	135.76
556	0.14	135.90
564	0.19	136.09
576	1.64	137.73
580	0.09	137.82
583	0.35	138.17
587	1.65	139.82
598	0.88	140.7
603	0.69	141.39
608	0.03	141.42
609	1.35	142.77
612	0.87	143.64
613	0.09	143.73
614	2.42	146.15
615	0.06	146.21
616	0.36	146.57
617	0.51	147.08
618	0.17	147.25
621	0.18	147.43
622	0.14	147.57
623	0.22	147.79
625	0.22	148.01
628	0.26	148.27
633	0.91	149.18
637	0.38	149.56
638	0.04	149.60
639	0.35	149.95
640	0.33	150.28
641	0.25	150.53
642	0.23	150.76
643	0.04	150.80
647	0.21	151.01
653	2.05	153.06
654	0.59	153.65
659	1.38	155.03
660	1.26	156.29
661	0.05	156.34
664	0.34	156.68
667	0.67	157.35

Table 9. (Continued) MOISTURE AND PRECIPITATION INTERCEPTED BY SIMULATED LANDFILLS DURING PHASE II

Time since placement of refuse, days	Moisture or precipitation, inches	Cumulative moisture and precipitation, inches
692	0.55	157.90
694	0.39	158.29
700	0.20	158.49
702	0.82	159.31
703	0.33	159.64
706	0.67	160.31
708	1.53	161.84
712	0.59	162.43
717	0.40	162.83
718	0.12	162.95
726	0.63	163.58
736	0.07	163.65
742	0.30	163.95
743	0.02	163.97
744	0.38	164.35
745	0.55	164.90
746	0.57	165.47
749	0.43	165.90

Table 10. CONCENTRATIONS OF EXTRACTED MATERIALS IN LEACHATE OBTAINED FROM CONTROL LANDFILL (FILL 1)

Time Since Leachate Production Began, days	0	14	24	32	39	48	81	116	125	153	173	189	197	228	249	284	312	332	347	398	428	473	506
COD, mg/l	4,320	9,150	10,380	10,260	12,000	11,700	9,200	10,100	11,700	12,200	12,300	14,400	15,600	18,100	15,600	13,300	13,800	---	11,100	9,000	9,500	8,950	8,050
BOD_5, mg/l	2,500	5,000	9,200	6,330	11,000	8,200	8,800	9,600	8,700	11,100	9,200	12,000	9,300	13,400	12,600	9,560	8,800	---	7,750	5,300	6,500	6,050	6,600
TOC, mg/l	1,230	1,910	2,622	2,622	2,802	2,835	2,864	2,259	2,418	2,680	2,696	3,049	3,409	5,000	3,590	3,000	2,930	3,180	3,005	2,430	2,910	2,910	2,665
TSS, mg/l	125	34	59	61	47	213	270	640	550	292	470	360	175	85	175	605	610	308	880	1,243	800	680	800
VSS, mg/l	45	20	47	52	37.6	93	160	332	314	182	268	210	104	76	141	283	286	146	432	602	400	470	310
TS, mg/l	2,442	5,819	6,323	8,300	8,736	6,789	5,530	7,250	7,358	7,620	7,875	8,320	8,130	12,500	8,780	7,716	7,167	6,965	6,260	5,602	5,800	3,750	3,650
Total Alkalinity, mg/l as $CaCO_3$	558	1,610	1,640	1,920	2,280	2,110	2,420	2,650	2,120	2,350	2,100	2,482	1,760	2,480	1,580	2,430	1,930	1,960	1,725	1,500	1,750	2,040	2,040
Total Acidity, mg/l as $CaCO_3$	690	1,100	1,350	1,400	1,780	2,170	1,836	1,390	2,090	2,230	2,780	2,865	3,260	3,460	2,610	2,000	2,400	3,360	3,460	1,950	2,100	1,710	1,440
pH	5.2	5.6	5.3	5.3	5.3	5.3	5.7	5.3	5.2	5.3	5.1	5.2	5.1	5.1	5.2	5.2	5.3	5.3	5.25	5.33	5.60	5.68	5.90
Total Hardness, mg/l as $CaCO_3$	450	1,400	1,850	1,810	1,940	1,754	1,410	1,429	1,694	2,232	2,354	2,306	2,449	5,555	3,463	2,424	2,299	1,622	1,326	1,576	1,840	1,580	1,310
Acetic Acid, mg/l	500	2,111	2,360	2,664	3,666	3,268	2,789	3,285	2,590	3,280	3,440	3,393	3,550	5,160	3,754	3,460	2,830	2,275	2,210	1,000	2,410	2,520	2,220
Propionic Acid, mg/l	369	1,595	1,834	2,038	2,313	2,108	1,875	2,625	2,110	2,290	2,190	2,400	2,214	2,840	1,742	1,640	1,580	1,380	1,330	720	1,100	1,520	1,260
Butyric Acid, mg/l	110	965	1,075	1,050	1,280	1,164	1,000	1,203	1,424	1,195	1,215	1,350	1,750	1,830	1,770	1,800	1,740	1,540	1,460	970	940	500	704
Valeric Acid, mg/l	Nil	425	575	625	535	612	643	893	656	708	652	730	801	1,000	705	750	768	590	560	855	710	395	428
Phosphate, mg/l $PO_4^{\equiv}$	26	3.0	5.0	7.8	2.8	2.9	3.3	4.2	3.4	2.8	1.7	1.6	1.5	1.3	1.5	0.9	1.1	.6	.40	.5	0.51	0.51	0.27
Organic Nitrogen, mg/l as N	56	47	61.4	62	75	48	40	177	64	6	20	12	43	107	116	76	63	28	40	124	48	46	42
Ammonia Nitrogen, mg/l as N	56	150	167.6	187	185	192	148	103	130	260	214	218	264	117	52	110	103	152	132	88	88	86	80
Nitrate Nitrogen, mg/l NO_3^-	13.3	32	89	84	115	15.0	---	9.5	12	---	---	---	---	---	---	---	---	---	---	6.4	.09	.07	.07
Chloride, mg/l	322	385	109.8	105.1	97.9	340	---	170	240	210	208	312	308	180	300	280	295	124	137	143	150	130	164
Sulfate, mg/l $SO_4^{=}$	84	126	108	81	156	17	2	7	1	16	---	---	---	---	---	---	---	---	---	---	---	---	---
Calcium, mg/l	125	430	470	590	750	545	430	375	420	600	578	565	545	1,250	850	550	490	433	385	350	400	350	230
Magnesium, mg/l	26	71.8	67	75	68	64	52	49	53	80	85	85	75	260	210	90	65	40	53	39	45	45	12
Manganese, mg/l	3	10	5	6.2	8.8	8.5	10	7.5	10	16	14	15	16	18	19	12	12	19	11	10	15	6.5	7.5
Sodium, mg/l	63.8	125	132	132	143	150	180	118	135	155	154	155	148	160	140	85	140	103	110	130	130	145	130
Iron, mg/l	9	21	70	30	95	65	60	155	230	200	300	290	420	185	250	370	440	190	70	292	240	280	295
Total Volatile Acids, mg/l as Acetic Acid	874	4,310	4,925	5,399	6,721	6,133	5,370	6,750	5,655	6,370	6,420	6,693	7,000	9,300	6,785	6,460	5,745	4,795	4,615	2,745	4,361	4,325	3,974

Table 10 (continued). CONCENTRATIONS OF EXTRACTED MATERIALS IN LEACHATES OBTAINED FROM CONTROL LANDFILL (FILL 1)

Time Since Leachate Production Began, days	530	556	606	636	672	704	758	785	820	858	874	895	899	928	949	964	972	979	993	1007	1028	1042	1063
COD, mg/l	7,845	6,210	6,120	6,140	5,750	4,990	3,490	3,560	3,788	2,210	2,560	2,250	3,725	3,890	4,530	5,125	3,680	3,480	3,653	3,180	3,580	3,400	4,175
BOD$_5$, mg/l	4,800	3,835	4,300	4,200	4,300	3,350	2,090	2,250	1,854	1,450	1,140	1,100	2,015	2,915	2,590	2,915	2,305	1,940	2,170	2,020	2,280	2,550	1,937
TOC, mg/l	2,127	2,410	1,400	2,090	2,190	1,990	1,098	1,158	1,018	1,100	1,050	1,040	1,160	1,600	1,960	2,080	2,000	1,600	1,760	1,550	1,838	1,813	1,920
TSS, mg/l	540	1,170	1,010	510	750	750	340	300	152	200	134	---	192	57	41	151	16	18	39	41	48	50	36
VSS, mg/l	340	380	300	210	305	310	200	190	106	68	65	---	100	47	27	82	16	18	39	36	41	40	25
TS, mg/l	2,425	2,400	2,100	2,050	2,100	2,100	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Total Alkalinity, mg/l as CaCO$_3$	1,970	2,040	2,040	1,800	2,040	2,240	1,360	1,012	840	1,014	887	1,285	995	1,030	1,140	1,085	960	995	850	815	870	670	760
Total Acidity, mg/l as CaCO$_3$	1,840	1,670	1,670	2,350	1 740	1,640	860	1,226	1,059	908	1,000	887	832	1,040	1,273	1,300	1,300	1,300	1,080	1,090	1,080	1,240	1,290
pH	5.95	6.10	6.00	6.10	6.20	6.30	5.8	6.05	6.10	6.35	6.4	6.45	6.12	5.80	5.60	5.30	5.25	5.40	5.60	5.80	5.90	5.70	5.80
Total Hardness, mg/l as CaCO$_3$	1,190	1,170	1,160	1,840	790	750	1,192	1,396	1,538	1,348	1,348	1,305	1,401	1,450	1,807	1,797	1,966	1,501	1,602	1,567	1,850	1,744	1,542
Acetid Acid, mg/l	2,750	2,920	2,910	1,750	1,750	1,550	1,000	1,100	1,000	1,250	750	---	930	2,420	1,955	2,160	1,822	1,338	1,352	1,035	835	970	1,330
Propionic Acid, mg/l	720	400	410	1,200	1,100	1,150	300	320	350	300	250	---	384	450	494	442	423	308	321	415	368	440	476
Butyric Acid, mg/l	714	90	40	410	400	400	250	270	125	100	50	---	250	386	428	436	423	314	302	303	244	275	496
Valeric Acid, mg/l	420	70	30	395	395	200	30	30	20	10	5	---	262	119	179	132	123	95	95	140	74	123	138
Phosphate, mg/l PO$_4^{\equiv}$	0.29	0.23	0.32	0.28	0.27	0.26	1.2	0.9	0.7	1.0	1.1	0.8	0.5	1.2	1.1	1.0	0.9	1.3	1.0	0.45	3.2	1.9	2.0
Organic Nitrogen, mg/l as N	85	87	85	59	16	26	25	26	27	27	22	23	15.0	13.5	15.5	15.0	13.5	14.0	12.5	8.9	9.5	9.9	14.0
Ammonia Nitrogen, mg/l as N	35	28	19	8	8	12	13	10	14	11	9	7	9.0	7.5	4.5	6.0	4.5	2.0	3.5	1.1	1.5	1.1	2.0
Nitrate Nitrogen, mg/l NO$_3^-$	.07	.06	.17	.04	.04	.15	.04	.05	.03	.08	.04	.04	0.08	0.21	0.02	0.24	0.12	0.10	0.12	0.18	0.09	0.10	0.16
Chloride, mg/l	164	200	134	134	85	110	200	115	105	86	86	88	27	29	42	28	28	29	30	22	26	22	30
Sulfate, mg/l SO$_4^{=}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Calcium, mg/l	200	175	155	140	110	142	150	160	215	175	175	175	175.0	187.5	192.5	145.0	111.0	90.0	100.0	90.0	65.0	65.0	112.0
Magnesium, mg/l	22	22	20	20	11	12	22	22	24	24	24	24	21. 7	26.2	19.5	21.7	18.5	16.2	17.5	15.0	17.5	15.5	20.0
Manganese, mg/l	3.5	4.5	4.5	3.5	4.5	2.5	4.5	4.6	3.5	3.5	3.2	4.0	7.5	17.5	13.75	13.00	11.70	15.00	11.20	8.75	3.80	5.90	5.40
Sodium, mg/l	140	170	275	235	235	210	50	44	50	45	43	45	40.0	37.5	32.5	25.0	22.5	17.5	22.5	21.2	18.8	18.8	15.0
Iron, mg/l	280	270	270	250	245	240	400	500	500	450	450	425	325	325	463	500	600	450	475	475	600	564	438
Zinc, mg/l	---	42.5	41	10	12	9	13	15	10	9	12	10	10.0	30.0	33.8	31.3	21.2	13.8	17.0	12.5	10.0	13.8	18.7
Total Volatile Acids, mg/l as Acetic Acid	4,068	3,300	3,287	3,235	3,147	2,873	1,431	1,561	1,381	1,567	990	---	1,565	3,117	2,752	2,893	2,525	1,857	1,874	1,659	1,353	1,585	2,135

Table 11. CONCENTRATIONS OF EXTRACTED MATERIALS IN LEACHATE OBTAINED FROM RECIRCULATING LANDFILL (FILL 2)

Time Since Leachate Production Began, days	0	10	18	24	31	39	48	58	67	96	111	126	140	161	189	197	219	228	249	264	284	312	332
COD, mg/l	4,280	9,288	8,870	9,080	8,111	7,700	8,140	9,580	10,400	10,025	10,500	10,500	10,350	8,890	5,810	4,270	3,550	2,970	2,840	2,580	1,950	1,280	1,050
BOD$_5$, mg/l	2,750	5,200	6,900	6,800	4,300	5,400	6,202	6,400	6,380	7,200	8,700	8,500	10,100	9,405	6,650	3,500	2,860	1,400	2,500	2,420	760	760	540
TOC, mg/l	2,130	1,120	2,260	2,040	2,394	1,818	2,665	2,000	2,675	2,796	1,990	1,979	1,952	1,542	1,280	1,067	914	710	565	500	308	256	480
TSS, mg/l	93	13.6	12	36.5	70.5	25	37.0	120	301	143	222	258	385	187	232	220	131	122	145	124	67	305	538
VSS, mg/l	22,5	---	9	27.5	45	18.8	16.9	70	161	78	158	142	188	113	156	116	76	74	87	56	37	18	41
TS, mg/l	2,349	4,329	4,552	5,023	5,400	4,728	4,941	5,250	5,440	5,980	5,830	6,918	5,106	5,336	4,090	3,987	3,240	2,792	2,370	2,510	1,848	1,627	1,784
Total Alkalinity, mg/l as CaCO$_3$	302	700	865	1,080	1,200	1,370	1,525	1,438	1,035	1,900	2,350	1,640	1,670	1,640	1,550	1,342	1,115	952	980	925	738	692	800
Total Acidity, mg/l as CaCO$_3$	554	1,900	1,540	1,350	1,000	1,390	1,265	1,530	1,765	1,798	1,730	1,830	1,700	1,630	500	333	240	180	166	133	84	80	152
pH	5.05	4.8	5.0	5.1	5.3	5.4	5.3	5.3	5.1	5.4	5.5	5.3	5.3	5.2	6.3	6.6	6.8	6.9	7.0	7.1	7.4	7.3	.7.1
Total Hardness, mg/l as CaCO$_3$	370	895	880	1,010	890	1,040	1,222	1,483	1,532	1,701	1,987	1,495	2,296	1,948	1,469	1,146	978	677	539	661	513	377	146
Acetic Acid, mg/l	1,638	556	2,000	1,843	1,475	1,583	1,795	2,146	2,438	2,742	2,438	2,470	2,380	1,877	2,925	608	734	770	670	111	234	365	400
Propionic Acid, mg/l	960	394	1,242	1,467	1,554	1,594	1,580	1,752	1,953	2,203	1,953	1,865	2,020	1,472	1,995	714	195	111	104	57	223	110	160
Butyric Acid, mg/l	1,300	235	1,235	1,163	1,375	1,250	1,200	1,198	1,904	1,156	1,047	1,124	937	735	665	286	194	68	65	Nil	62	44	20
Valeric Acid, mg/l	500	735	50	833	688	670	714	800	858	857	786	842	625	556	585	276	87	65	50	Nil	35	Nil	13
Phosphate, mg/l $PO_4^{\equiv}$	22	1.5	2.1	0.65	0.81	0.67	0.82	0.85	0.98	0.65	0.38	0.50	0.39	0.82	0.47	0.26	0.24	0.07	0.08	0.09	0.12	0.09	.03
Organic Nitrogen, mg/l as N	20	30	30	405	37 5	39 5	41	30	39	62	92	228	7	3	4	Nil	Nil	1	3	2	1	7	Nil
Ammonia Nitrogen, mg/l as N	70	68	113,5	86.5	77.5	76.5	64	69	81	84	80	71	135	126	80	62	56	39	31	35	27	13	30
Nitrate Nitrogen, mg/l NO_3^-	6.2	71.4	56.6	76.6	48	49	11 0	11 5	12.0	16.0	21.0	14.0	---	---	---	---	---	---	---	---	---	---	---
Chloride, mg/l	210	210	248	94.5	91	115	220	164	176	140	188	170	210	236	300	270	260	248	224	220	218	202	119
Sulfate, mg/l $SO_4^{=}$	102	138	81	51	30	12	11	Nil	12	2	1	3	---	----	---	---	---	---	---	---	---	---	---
Calcium, mg/l	60	315	350	435	420	430	420	415	440	500	550	385	600	475	400	340	290	190	145	175	135	82	115
Magnesium, mg/l	16.5	59	53.5	62.5	56	56	50	50	53	55	62	44	70	60	50	45	40	40	38	40	35	38	32
Manganese, mg/l	4	30	50	65	62	62	75	75	80	80	85	60	93	80	59	50	44	19	10	19	14	8	3
Sodium, mg/l	61.5	109	81.4	91.4	85	84	95	85	88	90	98	70	84	75	61	59	50	60	55	60	55	75	53
Iron, mg/l	4.4	19.5	19	80	43	110	25	35	40	45	110	150	150	210	90	13	5	1.4	1.9	14	4	1.2	5
Total Volatile Acids, mg/l as as Acetic Acid	3,605	1,465	3,875	4,315	4,080	4,120	4,315	4,855	5,825	5,815	5,195	5,245	5,025	3,895	5,340	1,545	1,075	945	830	155	475	485	555

Table 11. (continued). CONCENTRATIONS OF MATERIALS IN LEACHATES OBTAINED FROM RECIRCULATION LANDFILL (FILL 2)

Time Since Leachate Production Began, days	366	398	428	473	506	530	556	606	636	672	704	758	785	820	843	894	882	899	928	964	993	1028	1063
COD, mg/l	1,110	800	870	490	225	258	192	113	56	84	70	113	99	---	33	43	45	102	78	61	80	67	79
BOD_5, mg/l	700	510	440	264	120	85	75	46	44	45	44	42	24	20	26	---	16	23	31	29	32	28	39
TOC, mg/l	475	545	510	515	375	325	310	325	520	345	250	46	40	32	---	30	25	70	30	50	100	212	420
TSS, mg/l	370	405	350	310	250	140	140	510	400	310	200	---	22	25	36	20	---	26	30	23	39	26	17
VSS, mg/l	69	72	50	100	90	110	80	280	250	110	70	---	6	5	6	4	---	25	29	23	28	26	16
TS, mg/l	2,038	---	2,100	2,800	2,000	820	720	950	900	850	700												
Total Alkalinity, mg/l as $CaCO_3$	780	800	800	840	840	780	760	620	840	880	840	1,120	401	497	434	380	362	417	398	416	398	416	417
Total Acidity, mg/l as $CaCO_3$	200	250	250	250	250	230	240	260	110	180	140	50	115	168	38	47	56	56	65	100	85	100	110
pH	6.91	6.90	6.90	6.82	7.10	6.95	7.05	6.45	7.0	7.10	7.0	7.1	6.8	6.5	7.2	7.05	7.15	6.78	6.60	6.50	7.00	6.80	6.80
Total Hardness, mg/l as $CaCO_3$	520	---	375	250	200	200	170	110	100	90	105							284	247	291	237	217	239
Acetic Acid, mg/l	525	1,050	1,110	1,000	875	940	865	740	410	140	75	60	---	---	50	---	60	595	208	167	125	300	314
Propionic Acid, mg/l	120	55	70	90	40	38	42	75	75	35	35	0	---	---	0	---	0	92	34	25	17	159	430
Butyric Acid, mg/l	26	95	110	120	20	40	40	75	120	30	0	0	---	---	0	---	0	47	12	12	6	24	104
Valeric Acid, mg/l	33	180	170	145	50	70	60	85	20	10	0	0	---	---	0	---	0	12	0	0	0	0	00
Phosphate, mg/l $PO_4^=$	.15	.09	.08	.08	.05	.06	.05	.06	.10	.05	.07	1.0	.4	.5	.4	.3	.5	0.7	0.4	0.5	0.5	0.4	0.4
Organic Nitrogen, mg/l as N	16	---	3	4	6.5	14	7	0	0	0	0	3	3	5	3	3	3	3.0	1.0	1.0	2.5	.15	1.5
Ammonia Nitrogen, mg/l as N	26	---	18	15	3.5	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.5	0.5	0.5
Nitrate Nitrogen, mg/l NO_3^-	---	---	.09	.04	.08	.06	.04	.05	.05	.05	.05	.1	.06	.24	.03	.03	.08	0.08	0.04	0.09	0.16	0.10	0.16
Choloride, mg/l	116	---	158	204	236	176	150	110	76	70	70	69	69	73	55	55	---	40	26	37	30	28	30
Sulfate, mg/l $SO_4^=$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Calcium, mg/l	136	---	40	25	27	27	11	11	9	9	9	125	162	125	100	---	100	85.0	77.5	90.0	70.0	65.0	70.0
Magnesium, mg/l	34	---	30	14	13	12	11	11	10	11	10	20	18	18	15	---	15	15.7	11.7	13.2	11.2	11.2	12.5
Manganese, mg/l	8	---	8	10	0	0	.4	.1	.2	0	0	---	2.5	1.0	2.8	.5	.6	1.3	1.0	0.95	0.95	0.40	0.50
Sodium, mg/l	63	---	60	70	40	60	100	120	120	120	120	48	42	52	30	43	43	27.5	22.5	28.8	22.5	20.2	16.2
Iron, mg/l	14	---	0	0	0	0	0	0	0	0	0	---	15	10	4	---	3	3.0	2.0	4.5	6.0	3.5	5.0
Total Volatile Acids, mg/l as Acetic Acid	660	1,265	1,342	1,240	955	1,039	961	902	564	194	103	60	---	---	50	---	60	709	244	195	143	445	733

Table 12. CONCENTRATION OF EXTRACTED MATERIALS IN LEACHATE OBTAINED FROM FILL 3

Time Since Leachate Production Began, days	2	8	17	24	31	38	45	52	58	68	73	80	87	114	134	156	169	183	206	221
COD, mg/l	5,850	6,900	7,600	9,050	9,200	9,700	9,400	8,700	7,200	7,950	8,200	7,875	7,075	1,860	950	850	840	745	560	560
BOD_5, mg/l	4,150	3,900	4,400	6,600	7,150	6,800	6,800	5,200	5,400	5,900	5,600	4,600	5,300	1,400	860	500	367	232	220	130
TOC, mg/l	1,975	2,360	2,340	2,610	2,375	2,660	2,485	2,310	2,370	2,400	2,060	2,055	1,900	1,650	815	745	660	610	540	610
TSS, mg/l	---	126	253	281	401	374	569	880	---	978	926	747	1,060	470	490	480	510	610	420	350
VSS, mg/l	---	78	144	142	171	161	250	140	---	226	244	175	251	140	140	130	120	130	160	110
TS, mg/l	---	3,896	4,745	5,206	6,219	6,811	7,756	5,678	6,012	6,135	6,534	6,912	6,387	5,400	3,800	4,200	3,400	3,000	2,560	2,480
Total Alkalinity, mg/l as $CaCO_3$	1,500	1,870	2,530	2,830	2,710	2,660	3,220	2,740	2,940	2,780	2,540	4,360	3,150	2,960	2,680	2,660	2,620	2,580	2,480	2,400
Total Acidity, mg/l as $CaCO_3$	325	485	830	860	930	630	835	550	640	500	560	550	400	410	400	400	360	310	300	230
pH	6.61	6.52	6.28	6.50	6.32	6.34	6.30	6.81	6.69	6.61	6.19	6.88	7.00	7.10	7.20	7.45	7.30	7.20	7.25	7.15
Total Hardness, mg/l as $CaCO_3$	---	537	790	863	997	1,043	1,405	1,055	642	847	898	1,057	492	240	210	205	180	180	170	160
Acetic Acid, mg/l	950	1,575	1,810	1,825	2,250	2,350	2,065	380	272	220	1,230	900	1,410	1,160	1,120	1,000	640	310	210	110
Propionic Acid, mg/l	440	1,140	1,460	1,235	1,275	1,360	2,600	2,260	2,620	3,580	2,970	2,430	2,650	2,000	350	250	42	15	15	25
Butyric Acid, mg/l	175	800	765	738	825	1,000	1,040	665	145	320	95	nil	50	50	50	40	25	12	0	0
Valeric Acid, mg/l	0	25	130	200	225	300	395	385	260	440	nil	100	100	120	90	75	50	10	10	0
Phosphate, mg/l as $PO_4^{\equiv}$	3.9	---	0.22	0.10	0.26	1.20	1.50	0.25	0.29	0.29	---	0.18	0.27	0.42	0.37	0.22	0.30	0.31	0.24	0.23
Organic Nitrogen, mg/l as N	---	92	45	4	30	26	92	67	114	67	55	50	46	54	43	25	58	30	132	105
Ammonia Nitrogen, mg/l as N	---	325	413	427	392	437	396	343	304	268	260	244	176	216	224	192	176	197	154	105
Nitrate Nitrogen, mg/l as NO_3^-	---	5.3	4.4	3.5	4.0	4.2	3.5	3.1	1.9	2.0	0.6	0.6	0.5	0.23	0.17	0.17	0.15	0.17	0.13	0.12
Chloride, mg/l	---	191	254	252	253	316	305	293	287	290	331	324	307	330	300	380	380	350	350	340
Calcium, mg/l	---	136	205	230	270	275	390	285	165	220	225	230	80	80	2.3	2.4	2.6	5.5	5.5	11
Magnesium, mg/l	---	31	38	40	44	46	55	50	53	63	67	67	36	45	40	25.5	16	22	9	15
Manganese, mg/l	---	10	19	19	19	19	15	19	6	8	14	14	23	17	21	25	6,5	6.8	7,5	7.5
Sodium, mg/l	---	182	248	336	630	600	750	613	625	1,050	800	825	400	560	520	500	490	470	470	480
Iron, mg/l	---	42	53	50	91	68	80	174	100	160	18	100	57	25	12	8	8	3	3	5
Potassium, mg/l	---	---	---	690	740	---	500	392	345	360	385	400	231	235	340	340	340	340	350	350
Zinc, mg/l	---	---	---	0.8	0.8	---	0.6	1.3	0.8	0.8	1.3	1.0	0.6	1.0	0	0.02	0	0	0	0
Total Volatile Acid, mg/l as Acetic Acid	1,425	3,060	3,587	3,450	3,975	4,305	5,105	2,890	2,645	3,600	3,695	2,930	3,652	2,885	1,495	1,274	720	336	222	130

Table 12 (continued). CONCENTRATION OF EXTRACTED MATERIALS IN LEACHATE OBTAINED FROM FILL 3

Time Since Leachate Production Began, days	234	255	282	325	350	365	394	423	453	477	506	536	575	613	649	677	712	747
COD, mg/1	490	403	376	350	340	290	270	750	345	345	418	340	321	265	237	214	208	251
BOD$_5$, mg/1	125	44	62	66	85	90	88	61	13	29	40	29	23	33	26	28	29	45
TOC, mg/1	570	275	250	347	325	450	470	400	200	200	238	220	260	180	160	200	338	760
TSS, mg/1	330	280	310	260	310	340	410	115	43	---	148	33	90	27	14	25	23	24
VSS, mg/1	90	120	140	150	120	120	120	55	41	---	39	10	---	27	14	25	23	20
TS, mg/1	2,140	1,460	1,170	1,200	1,100	1,150	1,150	---	---	---	---	---	---	---	---	---	---	---
Total Alkalinity, mg/1 as CaCO$_3$	2,510	2,560	2,510	3,740	2,920	2,760	2,840	2,400	2,060	1,070	941	1,086	1,068	779	905	868	905	905
Total Acidity, mg/1 as CaCO$_3$	210	205	160	140	160	150	170	90	240	168	188	131	56	28	50	40	80	60
pH	7.3	7.05	7.15	7.10	7.03	7.03	7.00	7.2	7.0	7.1	6.7	7.4	7.4	7.50	7.30	7.75	7.30	7.70
Total Hardness, mg/1 as CaCO$_3$	160	140	140	120	110	110	110	403	433	377	314	340	272	177	212	155	128	244
Acetic Acid, mg/1	120	100	85	80	78	100	75	---	40	---	30	---	20	111	84	84	198	258
Propionic Acd, mg/1	30	20	60	60	40	40	40	---	0	---	0	---	---	12	12	8	97	233
Butyric Acid, mg/1	5	20	0	10	0	2	0	---	0	---	0	---	---	4	4	4	4	49
Valeric Acid, mg/1	0	0	0	0	0	0	0	---	0	---	0	---	---	0	0	0	0	0
Phosphate, mg/1 as $PO_4^{\equiv}$	0.37	0.21	0.17	0.06	0.09	0.11	0.14	0.9	1.0	0.4	1.0	0.9	2.0	1.2	0.8	0.4	0.4	0.5
Organic Nitrogen, mg/1 as NO	91	5	5	7	15	15	35	14	13	15	17	13	13	8.0	8.0	7.0	7.3	6.5
Ammonia Nitrogen, mg/1 as N	56	49	3	1	25	40	65	13	13	3	3	5	4	2.0	0.0	1.0	0.7	1.5
Nitrate Nitrogen, mg/1 as NO_3^-	0.13	0.14	64	64	9.6	12	12	.14	.10	.12	.15	.10	.10	0,23	0.16	0.20	0.15	0.07
Chloride, mg/1	360	340	240	180	130	110	130	---	206	226	---	238	270	100	135	125	120	120
Calcium, mg/1	12	12	9	8	13	12	12	100	112	100	75	90	75	50.0	60.0	30.0	25.0	70.0
Magnesium, mg/1	14	15	14	14	15	12	12	28	26	24	24	22	20	12.0	14.2	17.5	15.0	13.7
Manganese, mg/1	3.5	3.5	4.5	4.5	4.0	2.5	2.5	---	0.8	0.6	0.5	0.5	0.2	0.25	0.30	0.35	0.60	0.40
Sodium, mg/1	490	500	470	490	500	290	290	190	370	450	410	420	250	266.0	266.0	297.0	234.0	156.0
Iron, mg/1	5	7	7	12	12	8	8	---	25	15	15	10	13	1.0	1.5	3.0	1.5	5.0
Potassium, mg/1	310	310	340	340	340	340	340	205	212	200	200	200	200	144.0	145.0	160.0	202.0	140.0
Zinc, mg/1	0	0	0	0	0	0	0	0.4	0.4	04	0.3	0.3	0.3	0.16	0.12	0.10	0.40	0.60
Total Volatile Acid, mg/1 as Acetic Acid	147	130	134	135	110	130	100	0	40	---	30	---	20	124	97	93	280	480

Table 13. CONCENTRATION OF EXTRACTED MATERIALS IN LEACHATE OBTAINED FROM FILL 4

Time Since Leachate Production Began, days	2	8	17	24	31	38	45	52	58	68	73	80	87	114	134	156	169	183	206	221
COD, mg/l	460	5,200	7,200	9,250	11,750	11,200	11,000	15,000	15,400	17,400	18,000	15,800	17,600	17,710	16,650	16,540	14,000	13,200	14,500	13,000
BOD_5, mg/l	195	3,350	5,600	7,900	9,200	8,500	8,000	7,600	10,300	12,100	11,200	12,300	14,650	14,500	14,000	13,000	12,300	11,500	12,300	12,500
TOC, mg/l	332	2,030	2,720	2,860	3,655	3,820	3,440	4,000	4,430	4,330	4,800	4,500	4,925	5,700	5,655	5,685	5,080	5,210	4,940	4,220
TSS, mg/l	---	146	210	355	441	558	364	814	768	1,225	1,101	690	463	750	780	750	820	840	1,180	720
VSS, mg/l	---	100	72	111	146	205	85	270	280	393	342	192	151	110	60	70	100	70	85	65
TS, mg/l	---	3,154	4,983	8,097	9,699	10,478	11,860	11,006	11,346	12,169	12,314	13,458	12,770	12,000	10,500	8,500	8,500	7,800	7,000	6,440
Total Alkalinity, mg/l as $CaCO_3$	93	964	1,735	3,240	3,290	3,565	3,765	3,400	4,320	4,560	4,700	4,540	4,900	4,450	4,400	4,560	4,280	4,840	4,870	4,880
Total Acidity, mg/l as $CaCO_3$	30	920	2,010	690	520	590	420	1,020	1,370	860	900	580	800	890	1,010	11,090	1,070	1,240	1,340	1,390
pH	6 78	5 45	5 35	6 58	6 58	6 05	6 10	5 89	5 88	6 24	6 19	6 59	6 32	6 45	6 60	6 70	6 65	6 65	6 75	7.40
Total Hardness, mg/l as $CaCO_3$	---	563	872	989	1,206	1,249	1,293	1,639	1,168	1,335	1,428	1,455	1,167	750	540	260	210	200	190	180
Acetic Acid, mg/l	44	1,000	1,875	2,150	2,300	2,910	2,950	3,140	3,950	4,000	2,400	2,530	2,200	2,260	2,310	2,420	2,100	2,200	2,140	1,700
Propionic Acid, mg/l	14	1,020	1,800	2,025	2,160	2,550	2,650	2,750	3,380	3,750	2,270	2,210	2,320	5,780	5,350	5,100	3,620	2,420	1,540	890
Butyric Acid, mg/l	13	350	800	850	1,075	1,275	1,425	1,500	1,770	2,000	1,495	1,475	1,350	1,000	720	600	510	370	310	215
Valeric Acid, mg/l	13	88	295	375	475	610	725	855	1,220	1,970	1,790	1,820	1,670	1,420	1,300	1,200	640	540	400	210
Phosphate, mg/l as $PO_4^{\equiv}$	0.27	---	1.47	0 27	0 50	0 45	0 25	0 34	0 31	0 22	---	0 20	0 28	0 17	0 30	0 21	0 23	0 17	0 12	0 12
Organic Nitrogen, mg/l as N	---	92	45	4	30	26	92	67	114	67	75	83	75	48	48	32	96	254	157	133
Ammonia Nitrogen, mg/l as N	---	172	270	318	320	324	335	339	376	400	400	400	400	448	408	376	360	210	98	67
Nitrate Nitrogen, mg/l as NO_3^-	---	---	3 1	2 7	4 0	3 3	2 2	3 1	3 3	2 7	3 1	0 4	0 6	0 20	0 18	0 15	0 24	0 25	0 20	0 19
Chloride, mg/l	---	---	186	243	257	---	286	250	238	272	276	286	268	280	250	310	320	290	300	310
Calcium, mg/l	---	153	246	290	335	366	382	440	305	325	340	365	300	310	350	280	155	125	70	20
Magnesium, mg/l	---	17	31	34	41	43	43	47	49	52	53	52	53	55	24	12	12	31	31	34
Manganese, mg/l	---	19	19	19	19	19	10	19	13	12	13	12	11	13	11	4 5	3 1	2 7	0 4	0
Sodium, mg/l	---	118	294	1,210	1,410	1,880	1,600	1,100	1,590	1,400	1,600	1,600	2,300	1,600	1,400	1,200	1,250	1,150	1,125	1,200
Iron, mg/l	---	42	53	50	91	68	80	174	100	160	188	115	100	110	120	150	110	75	75	40
Potassium, mg/l	---	---	---	535	595	710	550	530	570	600	590	605	563	550	550	510	515	500	495	480
Zinc, mg/l	---	---	---	1.3	1.0	1.3	5.0	4.3	7.5	20	22	12	17	17	15	10	0 .95	0 .05	0	0
Total Volatile Acid, mg/l as as Acetic Acid	72	2,120	4,055	4,593	5,060	6,200	6,490	6,880	8,620	9,560	6,310	6,390	5,980	8,480	7,920	7,686	5,760	4,740	3,835	2,690

Table 13 (continued). CONCENTRATION OF EXTRACTED MATERIALS IN LEACHATE OBTAINED FROM FILL 4

Time Since Leachate Production Began, days	234	255	282	325	350	365	394	423	453	470	506	547	575	584	621	656	691	726	747
COD, mg/l	11,800	7,100	5,500	2,480	1,450	950	780	1,000	400	330	420	300	280	347	198	48	175	196	210
BOD_5, mg/l	9,450	5,500	5,050	2,300	1,100	660	250	310	35	70	75	36	53	43	46	38	38	38	31
TOC, mg/l	3,660	3,300	2,600	1,140	930	980	980	390	199	179	179	140	115	160	105	90	250	355	1,000
TSS, mg/l	760	1,030	720	900	850	800	650	145	70	48	46	40	86	52	102	46	60	54	44
VSS, mg/l	70	450	60	250	250	170	140	70	34	12	26	9	38	50	42	25	39	39	24
TS, mg/l	5,610	4,380	3,440	2,435	2,710	2,210	1,460	---	---	---	---	---	---	---	---	---	---	---	---
Total Alkalinity, mg/l as $CaCO_3$	5,400	5,800	6,010	6,180	5,840	5,760	5,420	3,600	3,280	1,795	1,593	1,665	1,647	1,555	1,450	1,320	1,375	1,375	1,375
Total Acidity, mg/l as $CaCO_3$	1,310	800	810	310	260	240	240	---	250	168	228	94	131	140	65	80	150	150	180
pH	7.40	7.45	7.50	7.40	7.20	7.20	7.10	7.6	7.2	7.2	6.9	7.3	7.1	7.05	7.11	7.10	7.05	7.10	7.00
Total Hardness, mg/l as $CaCO_3$	180	160	160	140	140	140	140	---	---	---	---	---	---	112	130	142	153	172	122
Acetic Acid, mg/l	2,000	1,800	1,600	1,400	540	280	90	120	110	---	80	---	50	139	111	98	300	513	412
Propionic Acid, mg/l	680	540	540	640	110	75	40	25	15	---	5	---	1	16	16	8	146	204	271
Butyric Acid, mg/l	210	110	80	25	10	5	1	5	2	---	0	---	0	8	4	4	23	61	0
Valeric Acid, mg/l	200	80	0	5	0	0	0	0	0	---	0	---	0	0	0	0	0	0	0
Phosphate, mg/l as $PO_4^{\equiv}$	0.12	0.17	0.4	0.28	0.31	0.28	0.24	1.3	1.3	1.1	0.6	1.0	0.9	0.6	0.6	1.1	0.5	0.4	0.5
Organic Nitrogen, mg/l as N	131	70	30	26	16	50	44	10	8	11	8	6	9	13.0	10.5	5.5	10.2	10.9	12.5
Ammonia Nitrogen, mg/l as N	67	126	104	101	76	62	16	39	36	24	26	26	23	6.0	4.5	4.5	2.8	3.1	4.5
Nitrate Nitrogen, mg/l as NO_3^-	0.19	0.23	0.05	0.05	0.15	0.11	0.11	0.1	0.08	0.17	0.1	0.1	0.1	0.04	0.05	0.05	0.14	0.07	0.06
Chloride, mg/l	320	340	170	160	130	130	130	238	---	310	190	---	220	250	115	100	130	130	130
Calcium, mg/l	15	14	17	12	12	15	15	75	75	67	70	70	70	25.0	35.0	37.5	31.3	32.5	20.0
Magnesium, mg/l	34	36	36	20	18	15	15	26	24	22	18	18	16	8.2	7.0	6.8	10.0	13.7	10.0
Manganese, mg/l	0	0	0	0	0	0	0	---	0.7	0.7	0.7	0.7	0.7	0.75	1.45	1.50	0.80	1.40	0.70
Sodium, mg/l	1,200	1,250	1,350	1,000	890	840	840	800	850	800	750	830	750	625.0	47.0	828.0	437.0	562.0	422.0
Iron, mg/l	20	21	118	15	15	22	22	---	23	20	17	21	10	6.0	5.0	7.5	12.5	13.0	11.5
Potassium, mg/l	310	310	310	300	300	300	300	225	220	220	205	200	200	162.5	132.5	130.0	147.5	145.0	140.0
Zinc, mg/l	0	0	0	0	0	0	0	0.9	1.0	0.9	0.8	1.0	1.8	0.85	0.40	0.58	1.33	0.20	0.60
Total Volatile Acid, mg/l as Acetic Acid	2,812	2,360	2,093	1,940	640	350	125	144	126		84		51	157	127	107	433	720	631

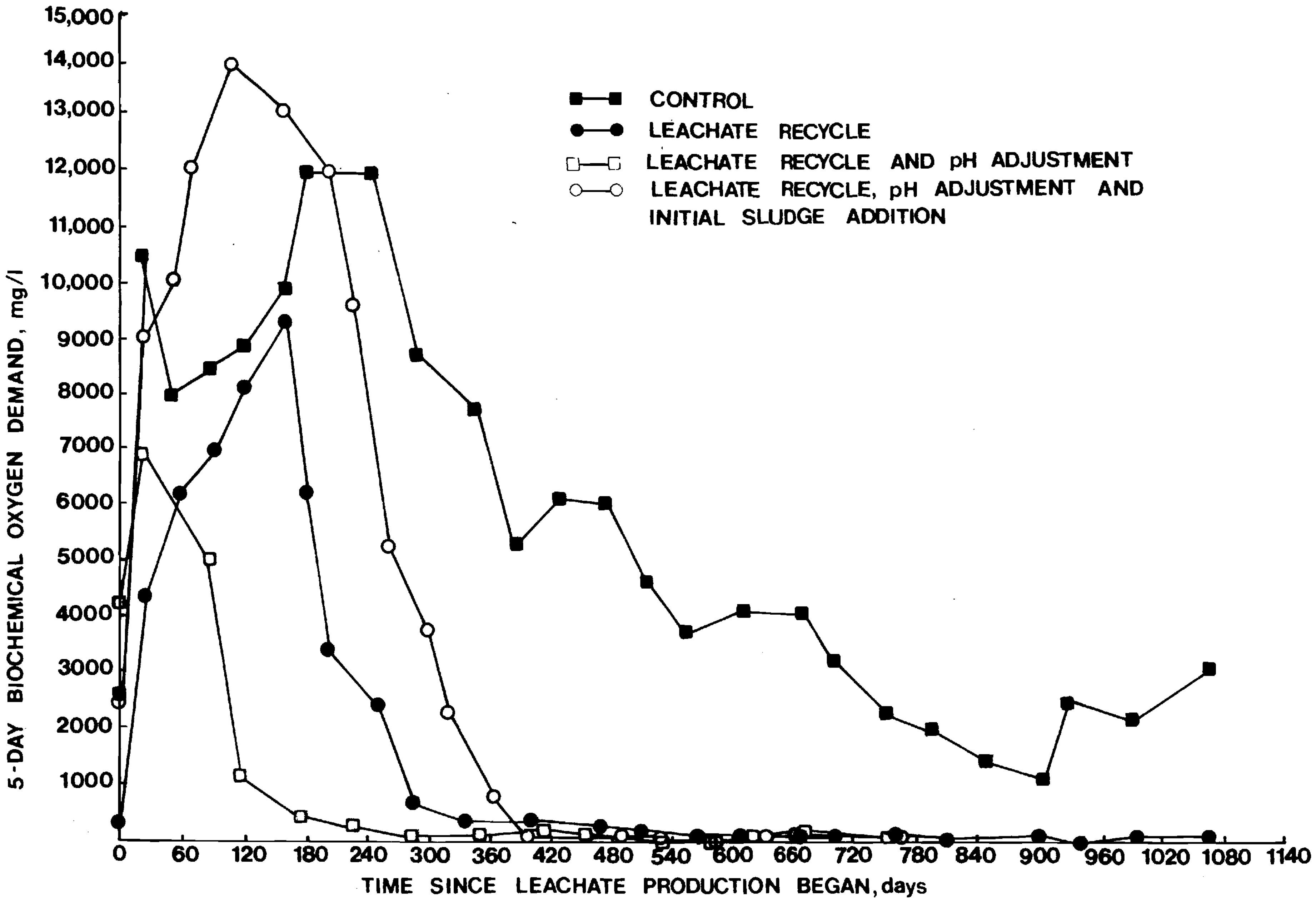


FIGURE 5 BIOCHEMICAL OXYGEN DEMAND OF LEACHATE

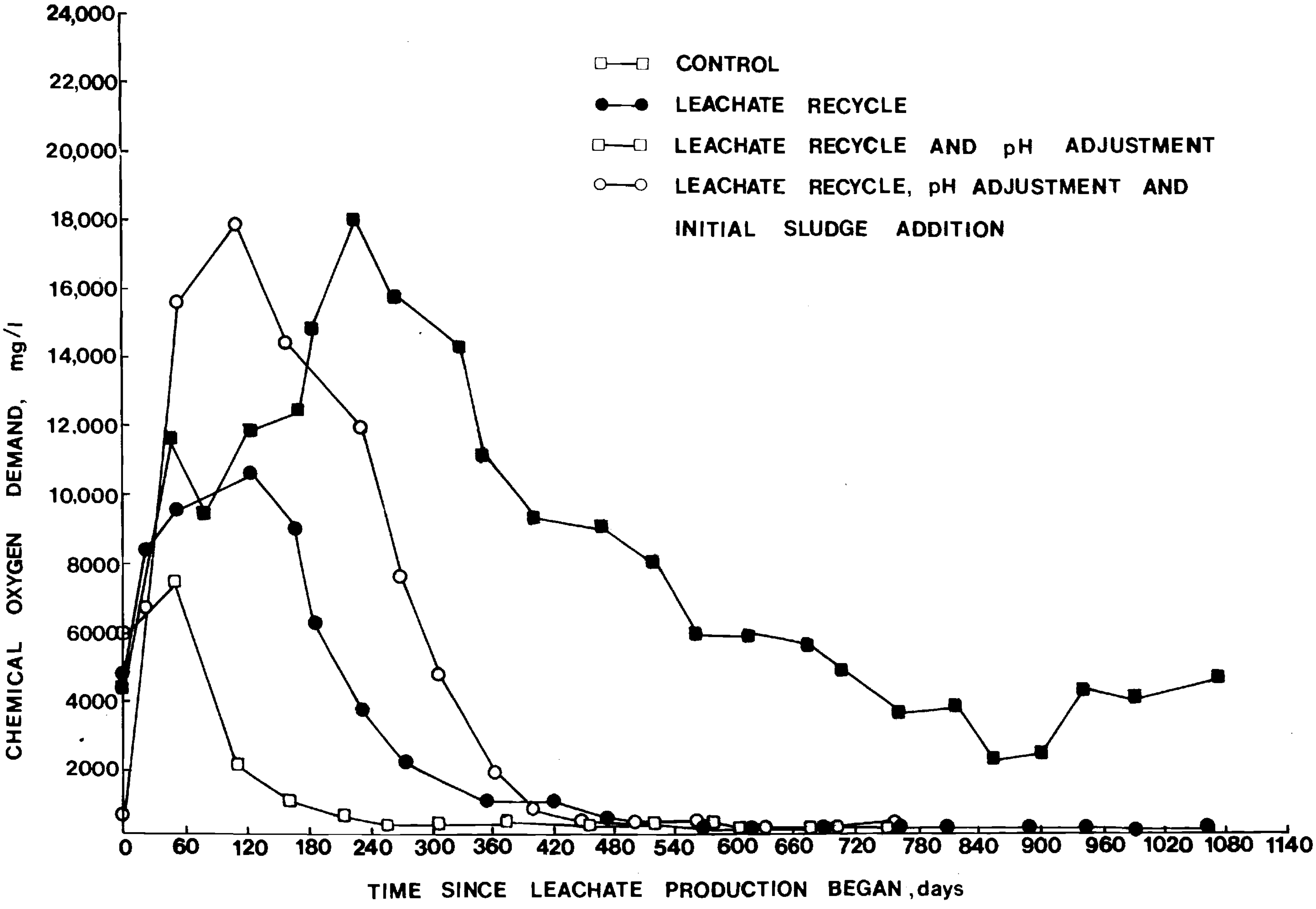


FIGURE 6 CHEMICAL OXYGEN DEMAND OF LEACHATE

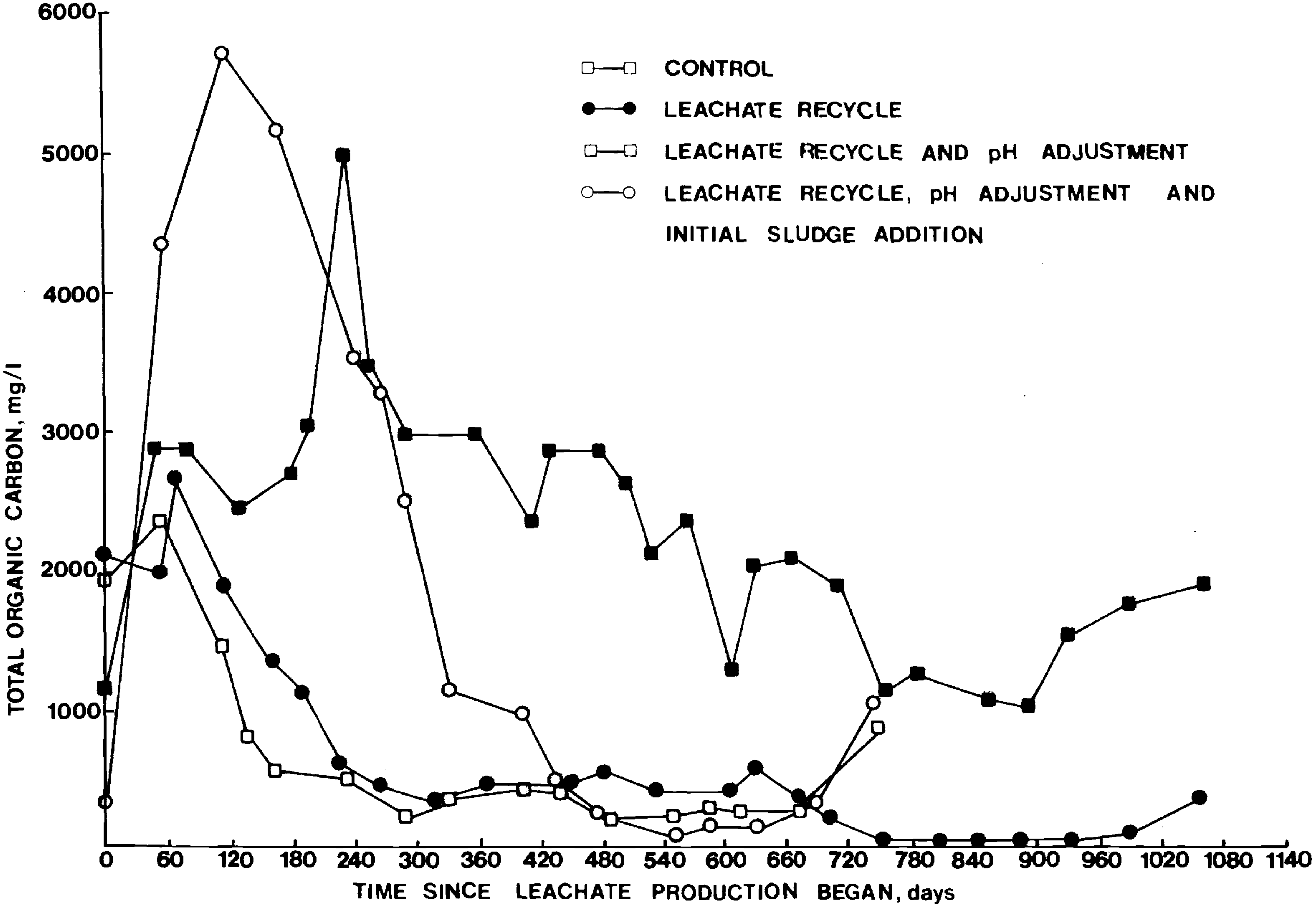


FIGURE 7 TOTAL ORGANIC CARBON CONCENTRATION OF LEACHATE

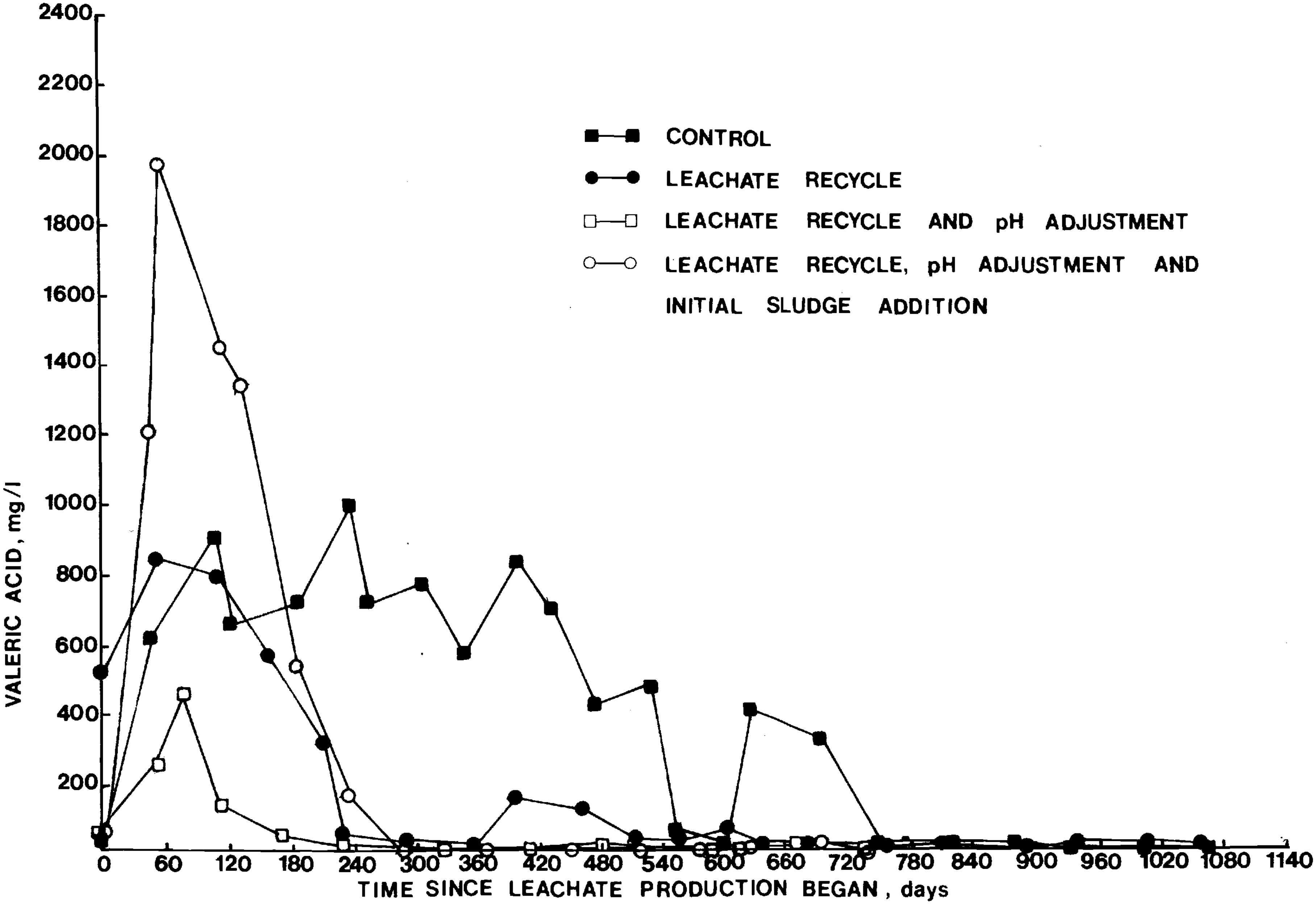


FIGURE 8 VALERIC ACID CONCENTRATION OF LEACHATE

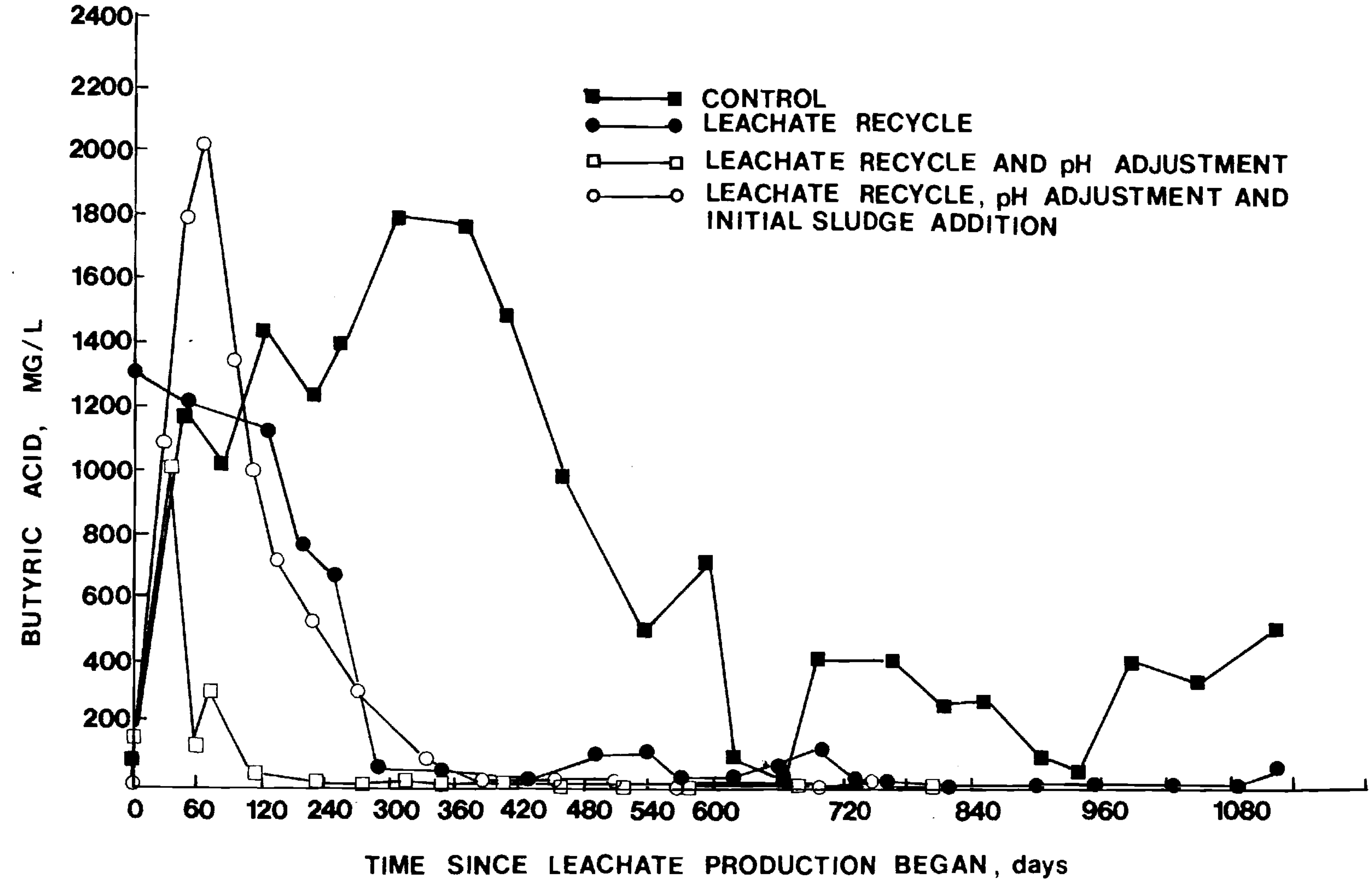


FIGURE 9 BUTYRIC ACID CONCENTRATION OF LEACHATE

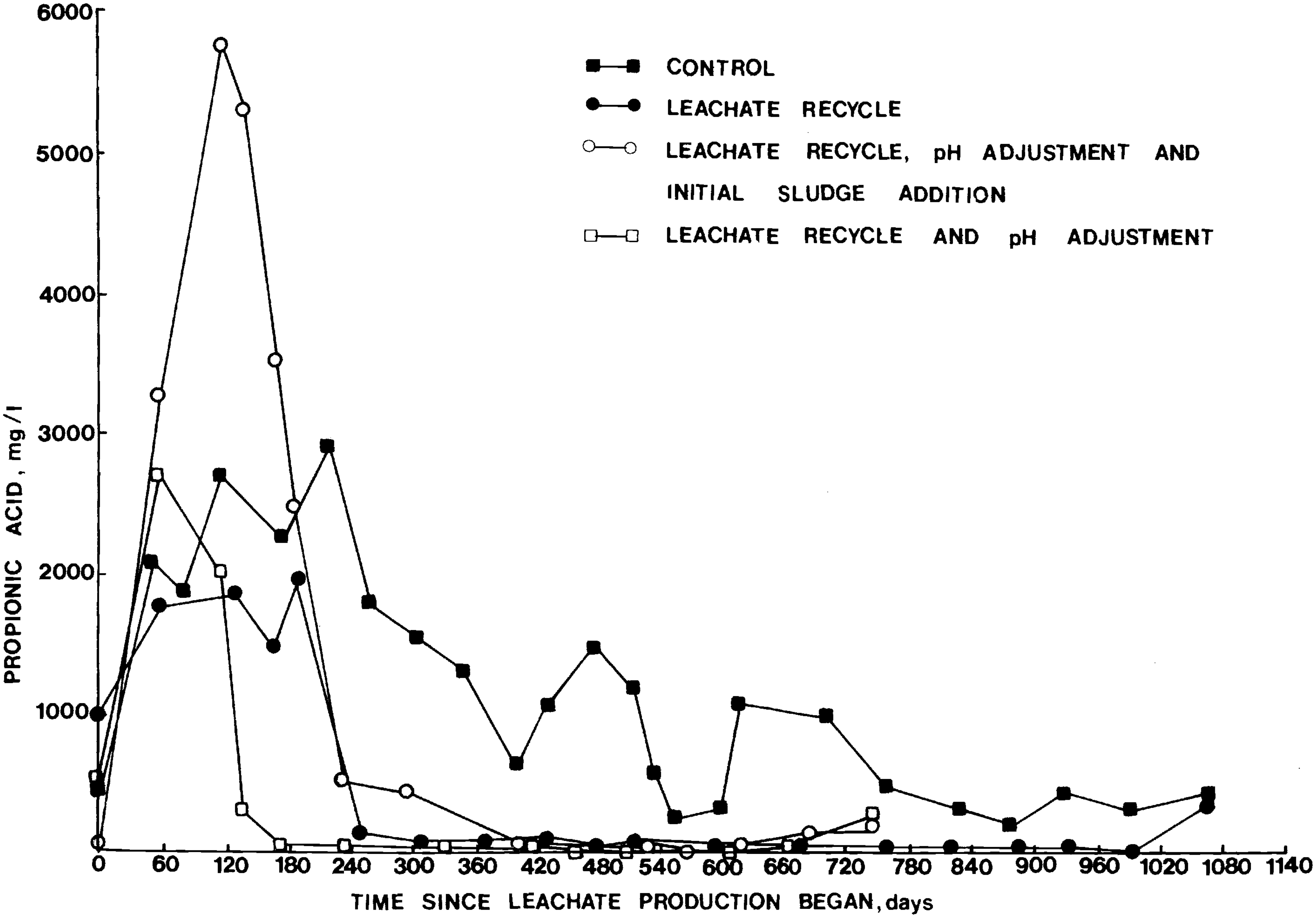


FIGURE 10 PROPIONIC ACID CONCENTRATION OF LEACHATE

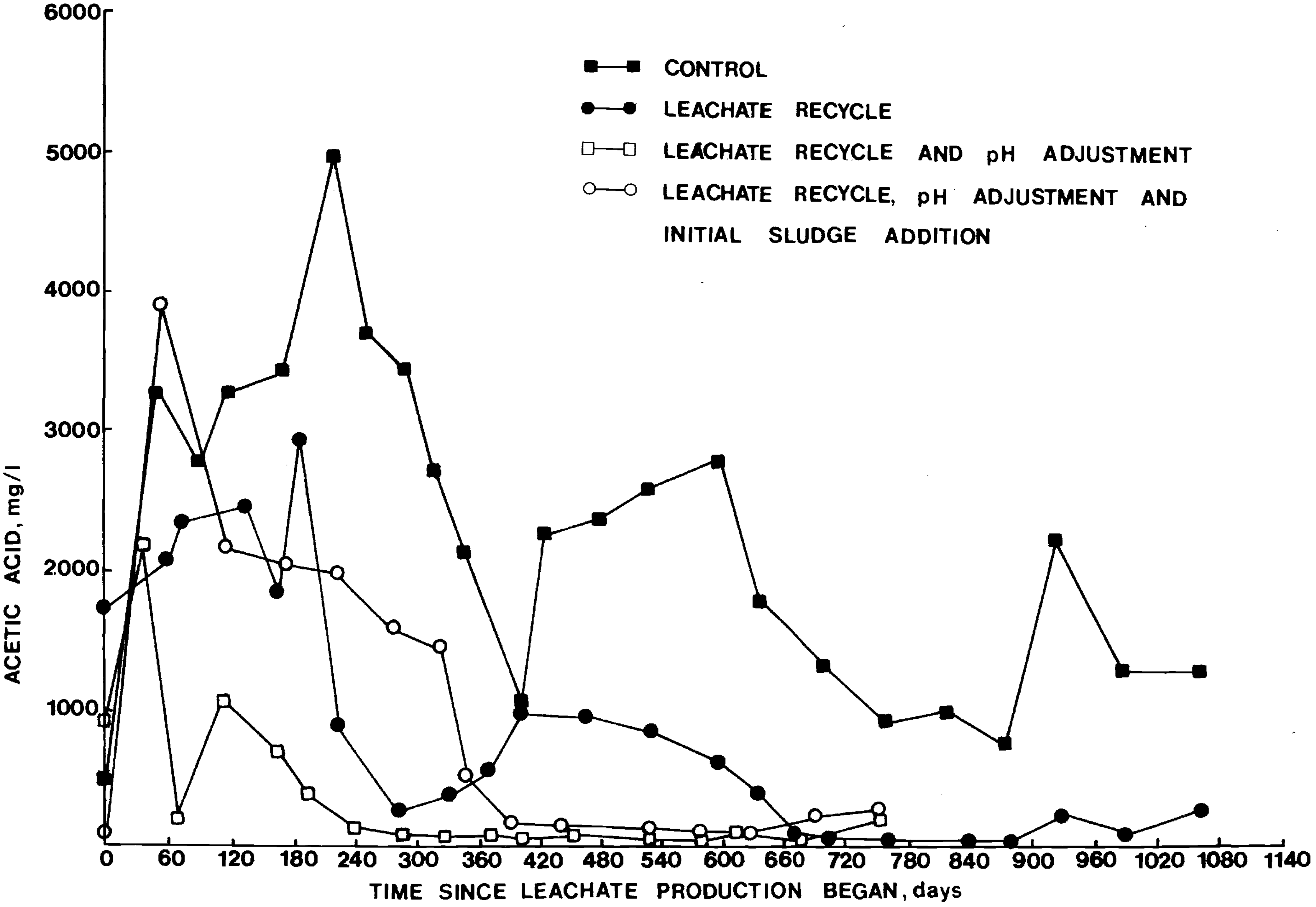


FIGURE 11 ACETIC ACID CONCENTRATION OF LEACHATE

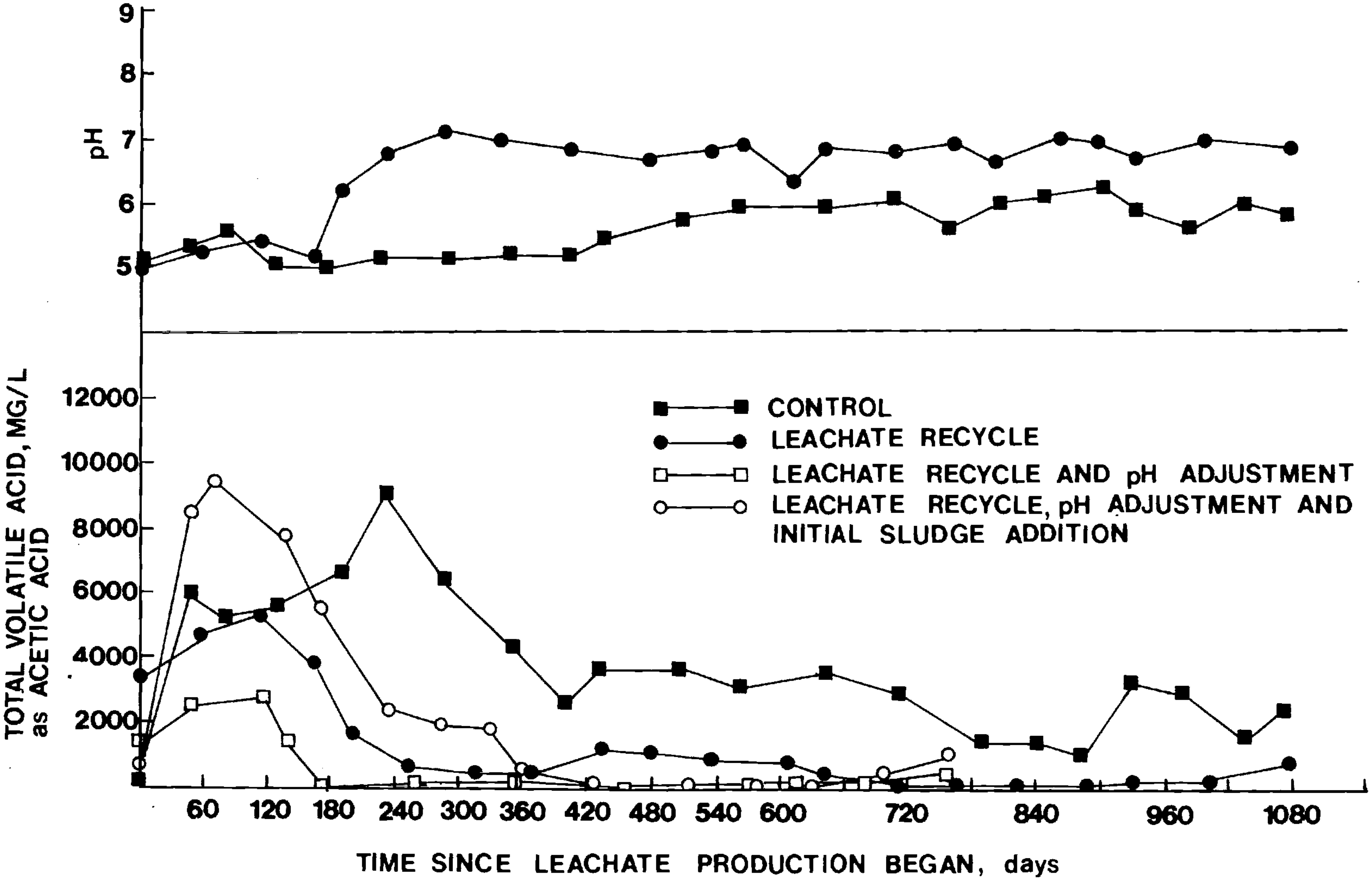


FIGURE 12 pH AND TOTAL VOLATILE ACID CONCENTRATION OF LEACHATE

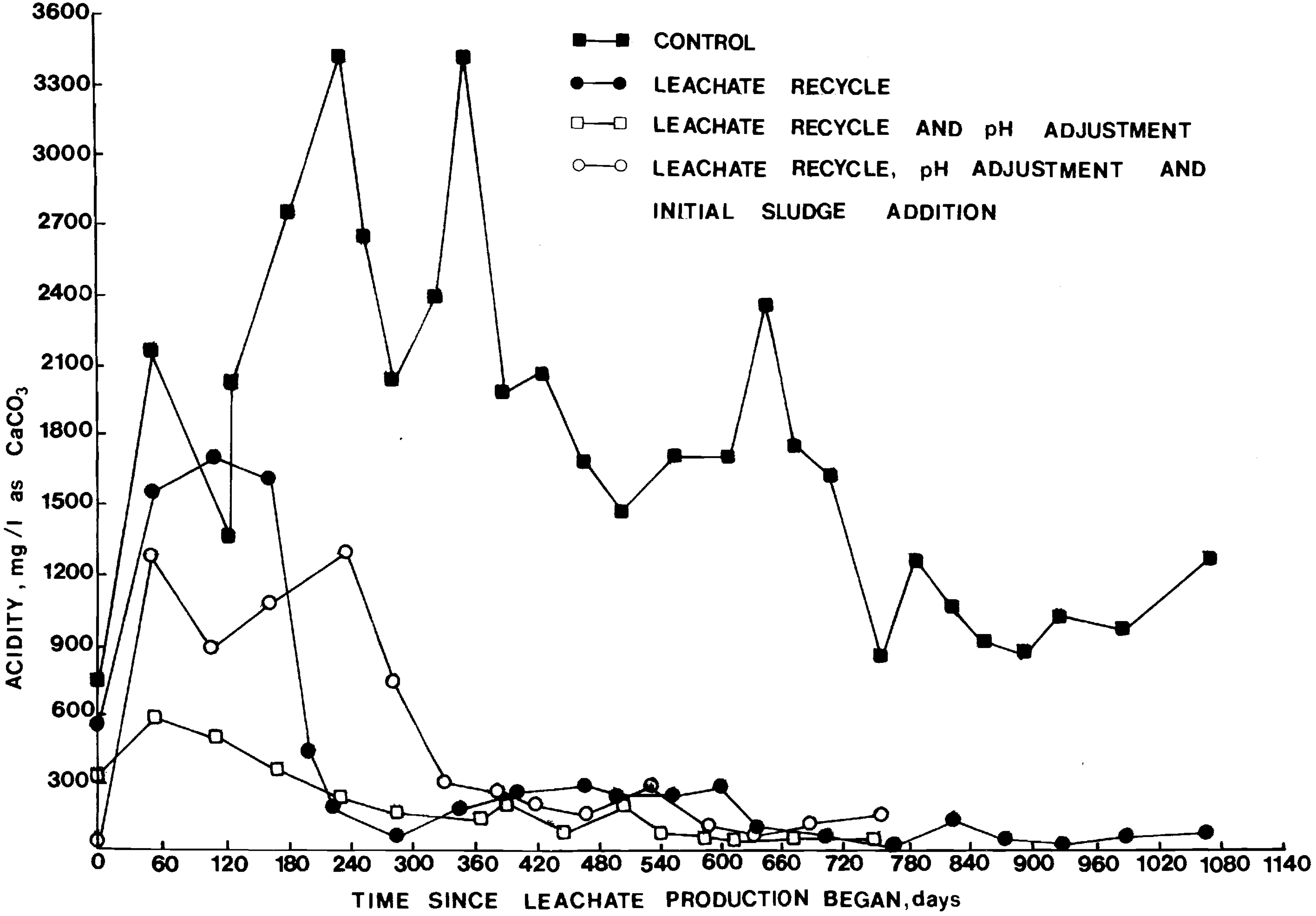


FIGURE 13 ACIDITY OF LEACHATE

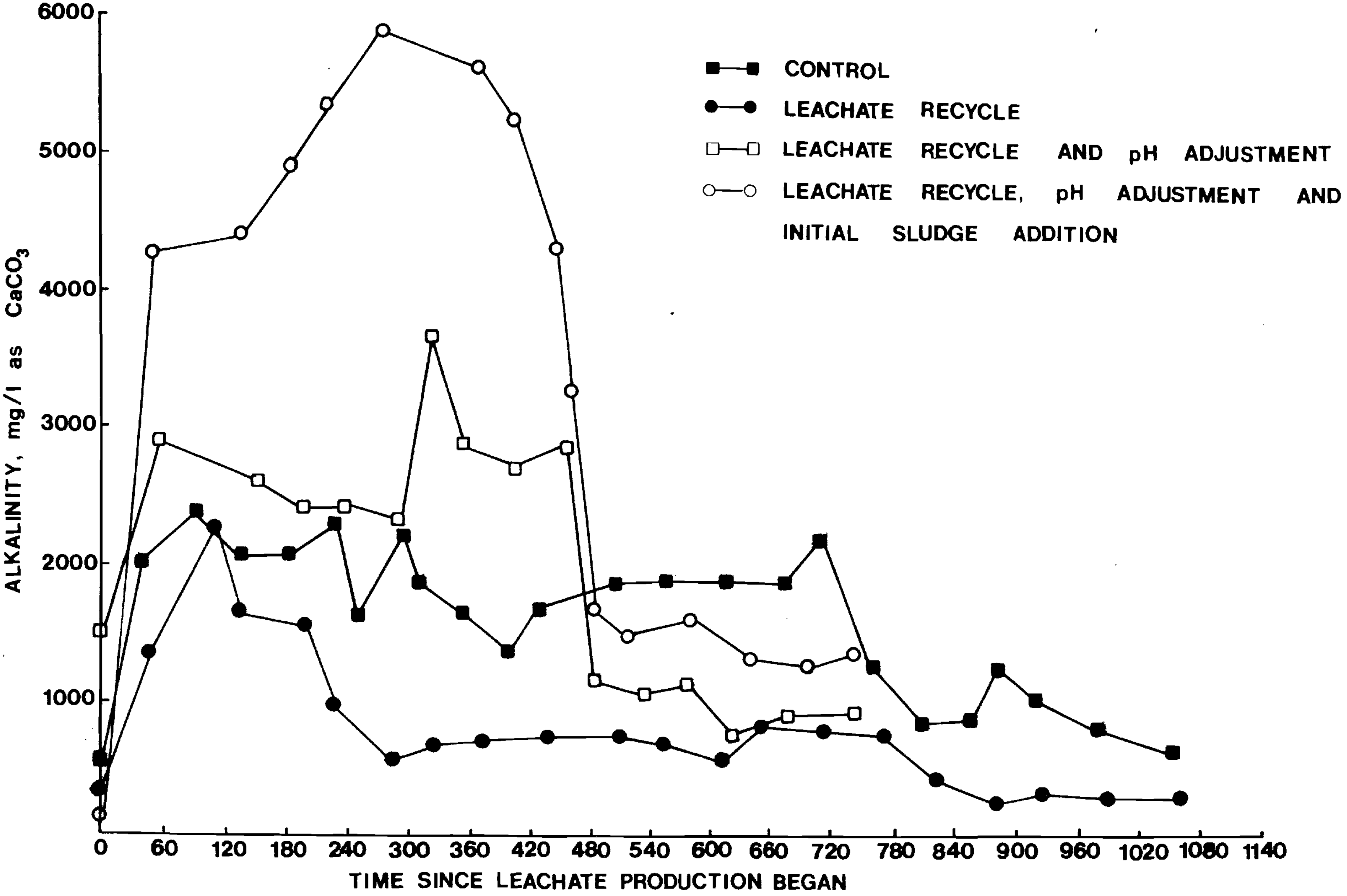


FIGURE 14 ALKALINITY OF LEACHATE

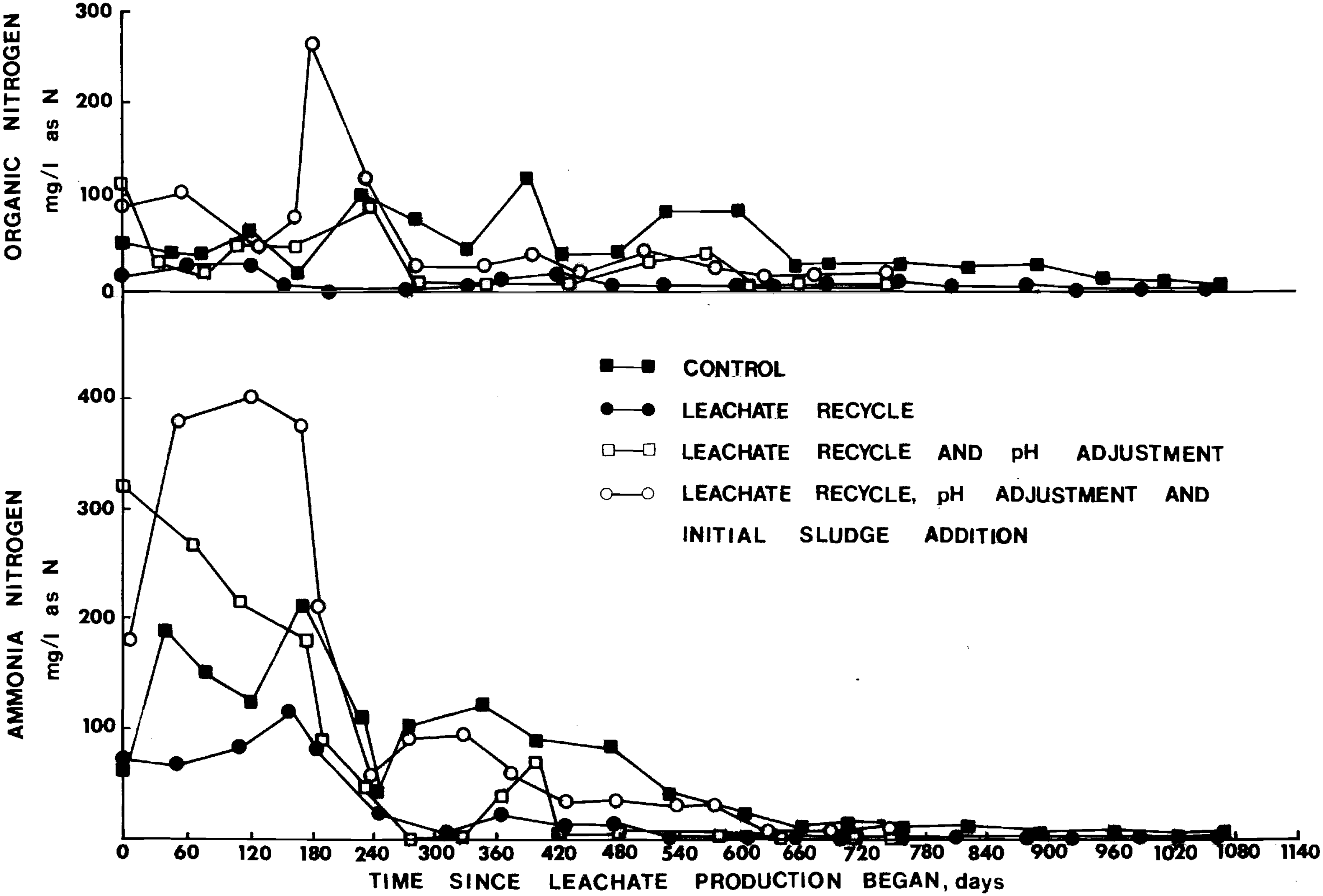


FIGURE 15 CONCENTRATIONS OF ORGANIC AND AMMONIA NITROGEN IN LEACHATE

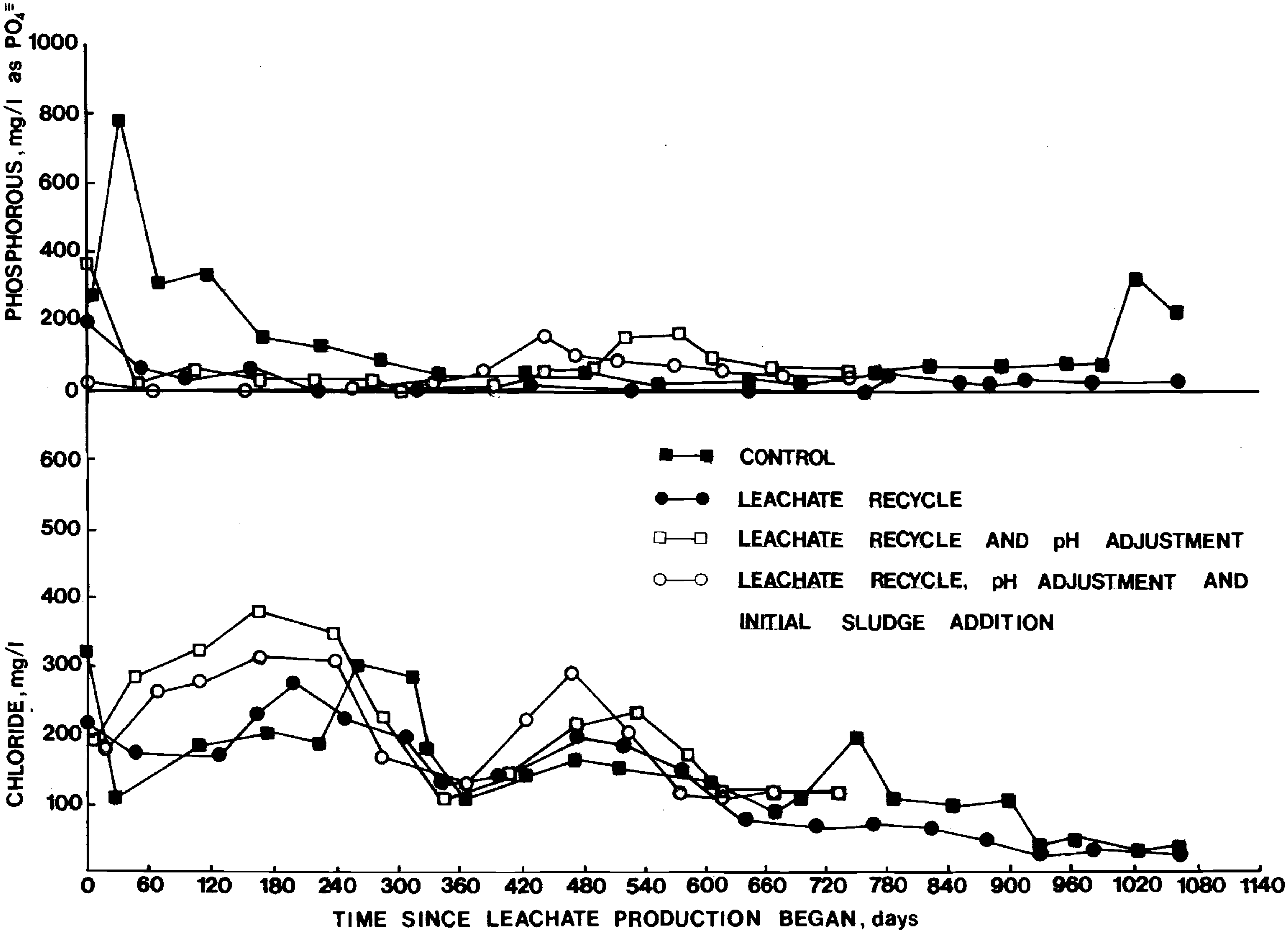


FIGURE 16 PHOSPHATE AND CHLORIDE CONCENTRATION OF LEACHATE

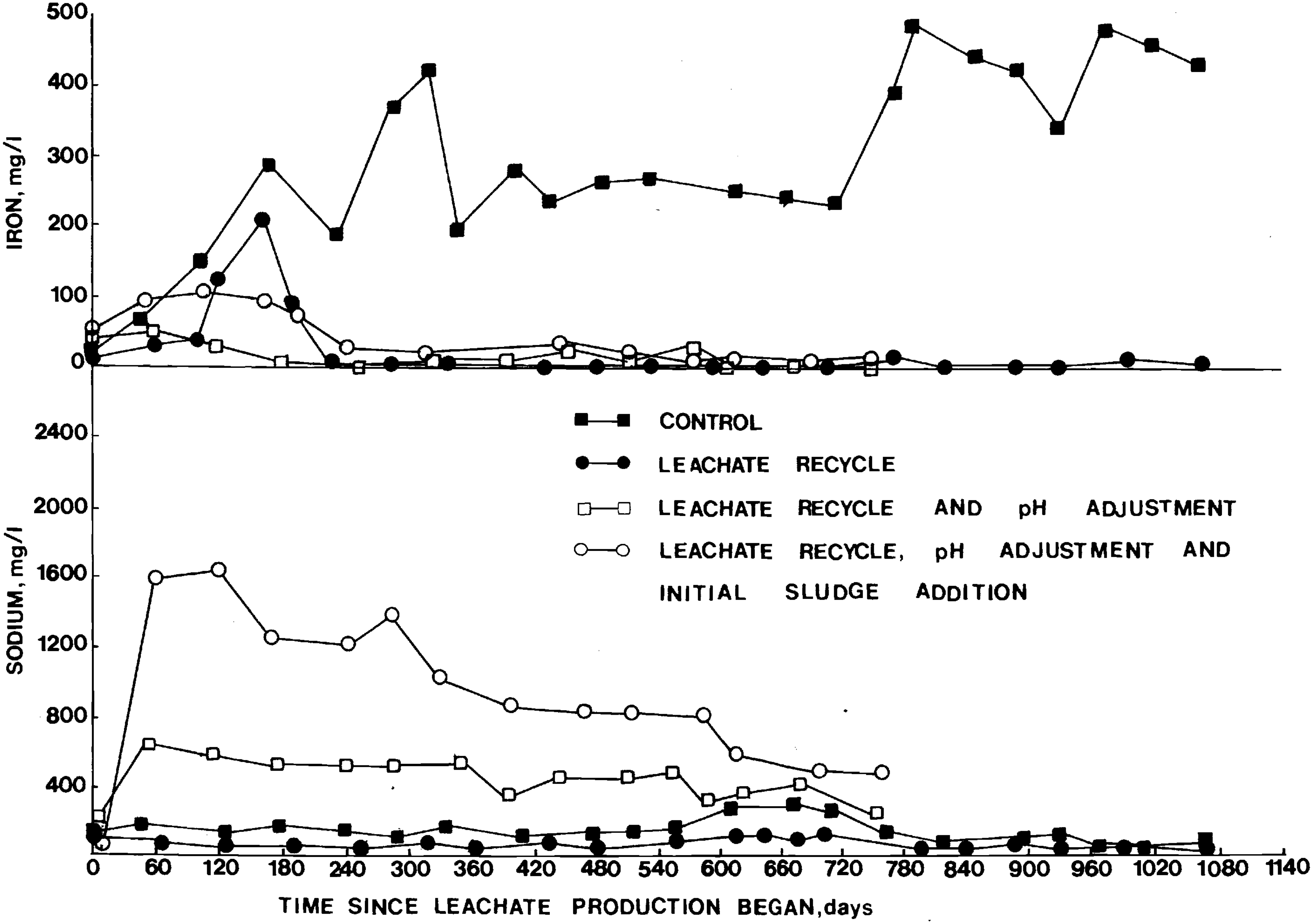


FIGURE 17 IRON AND SODIUM CONCENTRATIONS OF LEACHATE

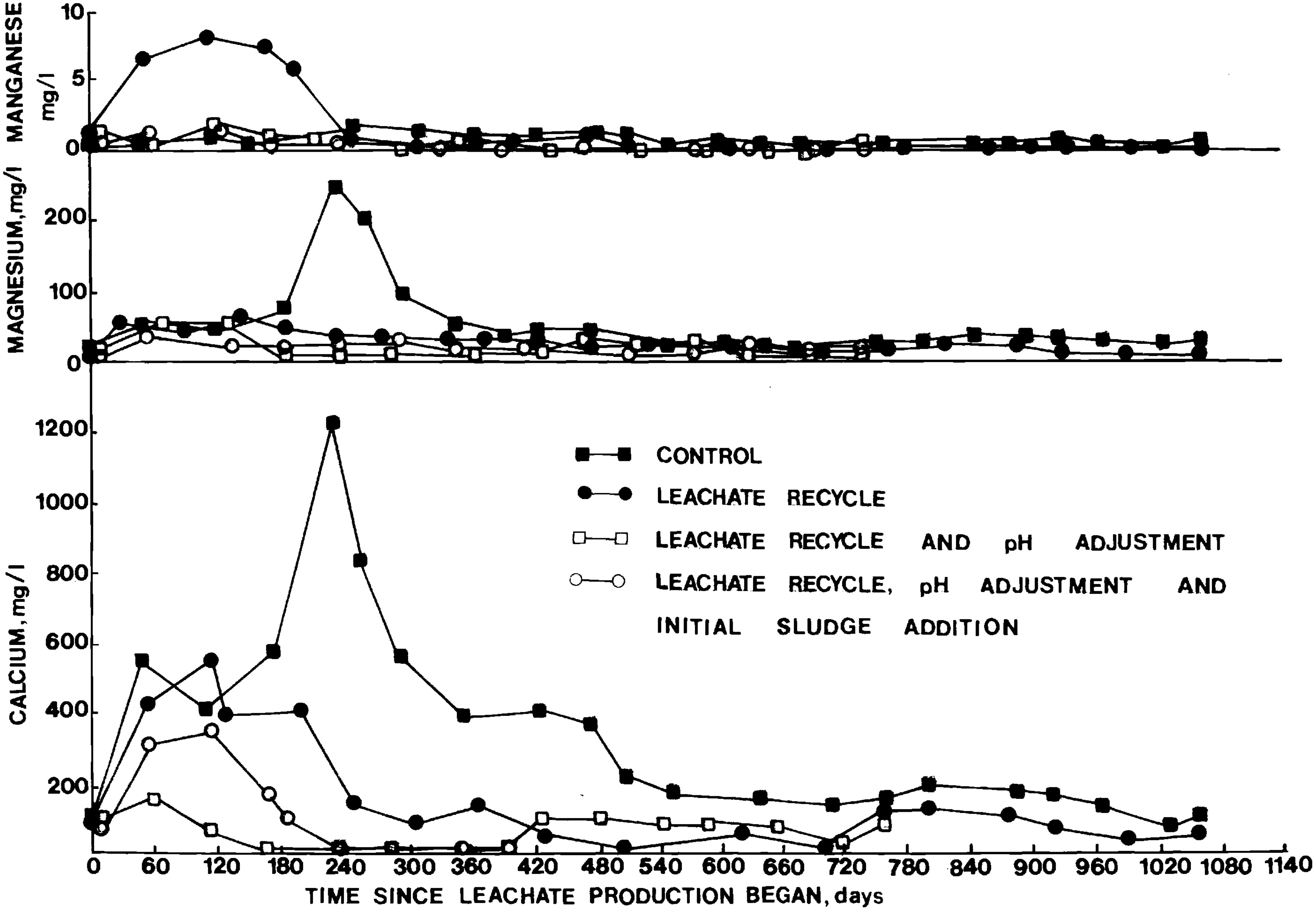


FIGURE 18 MANGANESE, MAGNESIUM AND CALCIUM CONCENTRATIONS OF LEACHATE

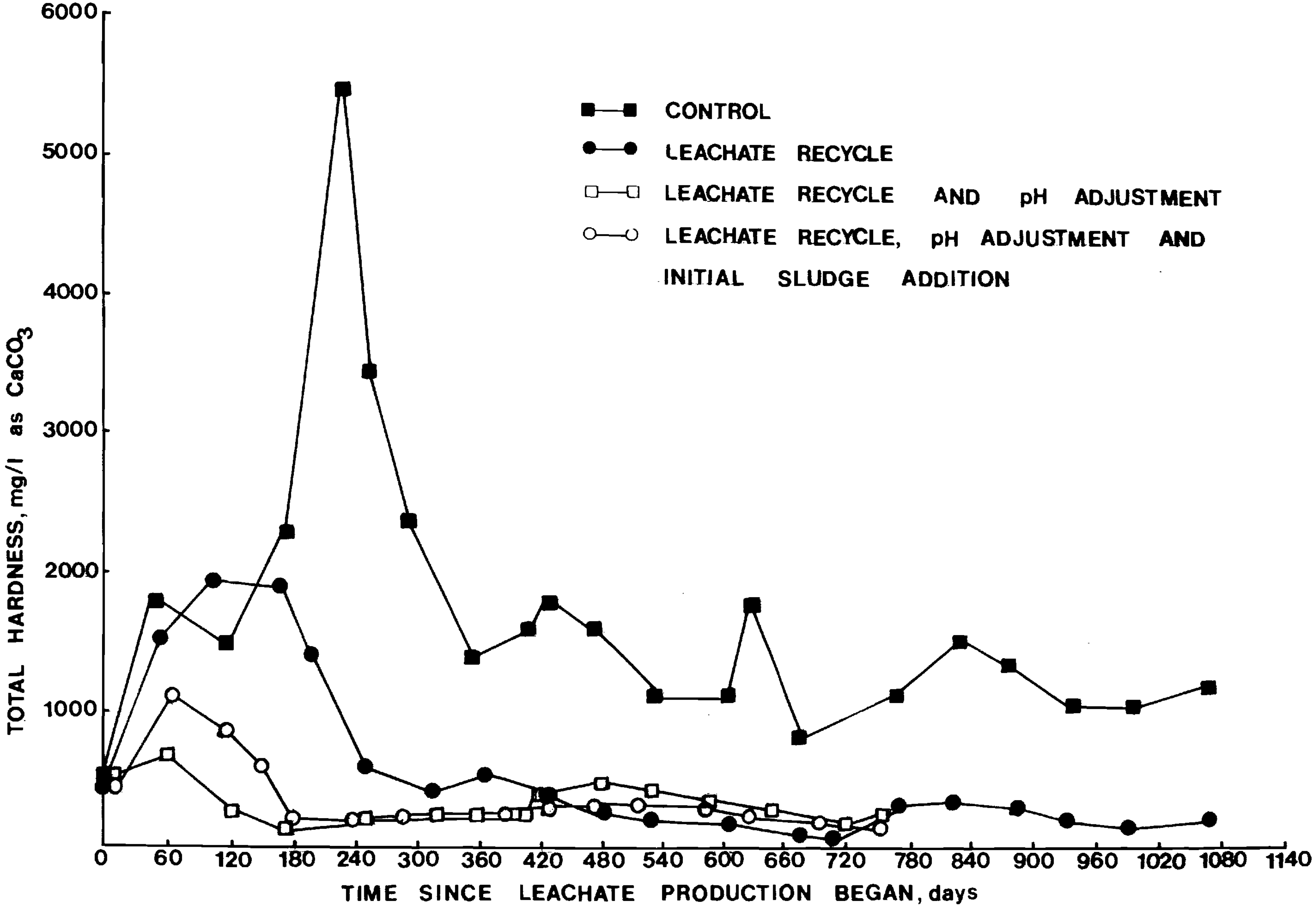


FIGURE 19 TOTAL HARDNESS OF LEACHATE

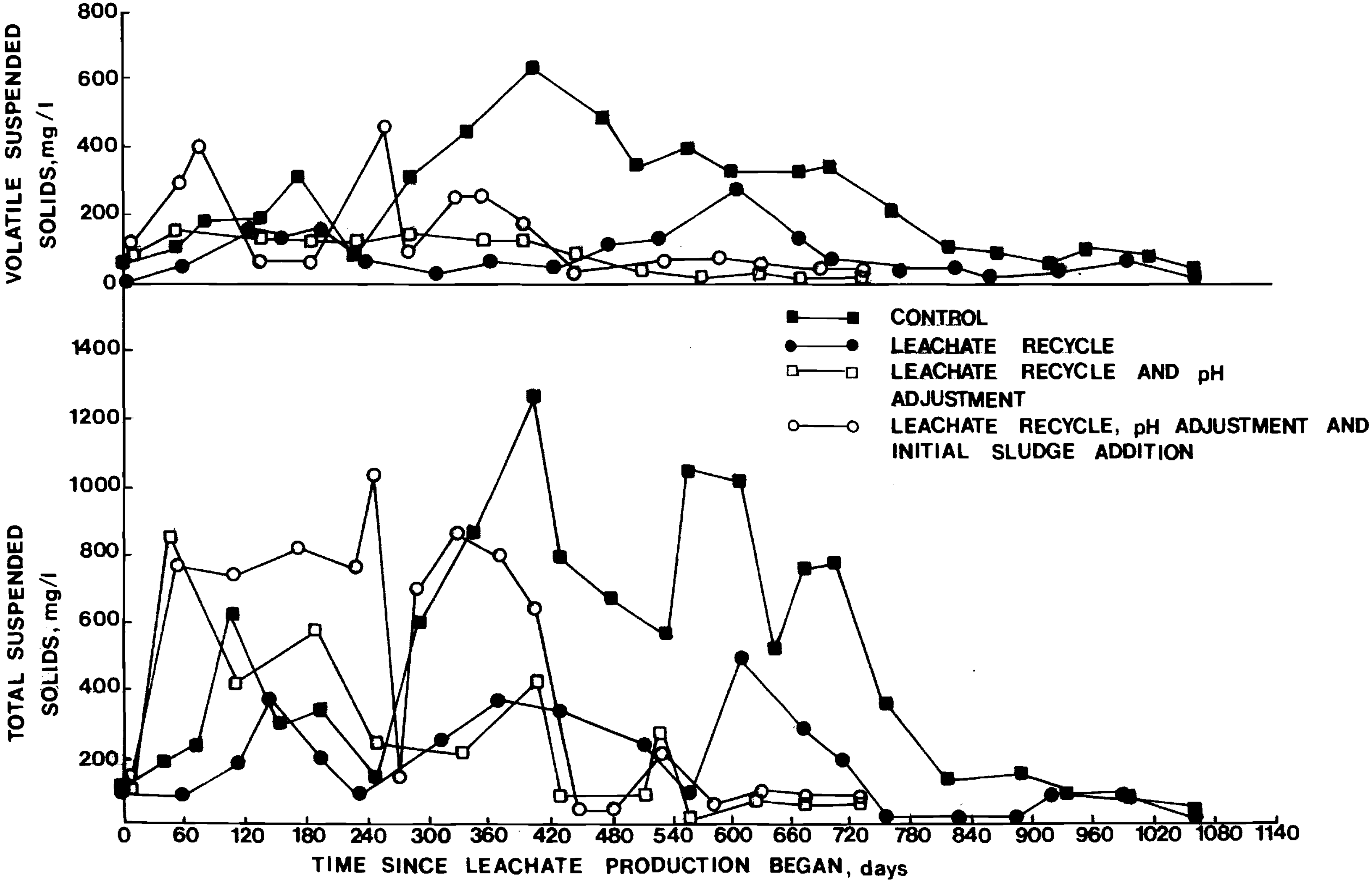


FIGURE 20 SOLIDS CONCENTRATION OF LEACHATE

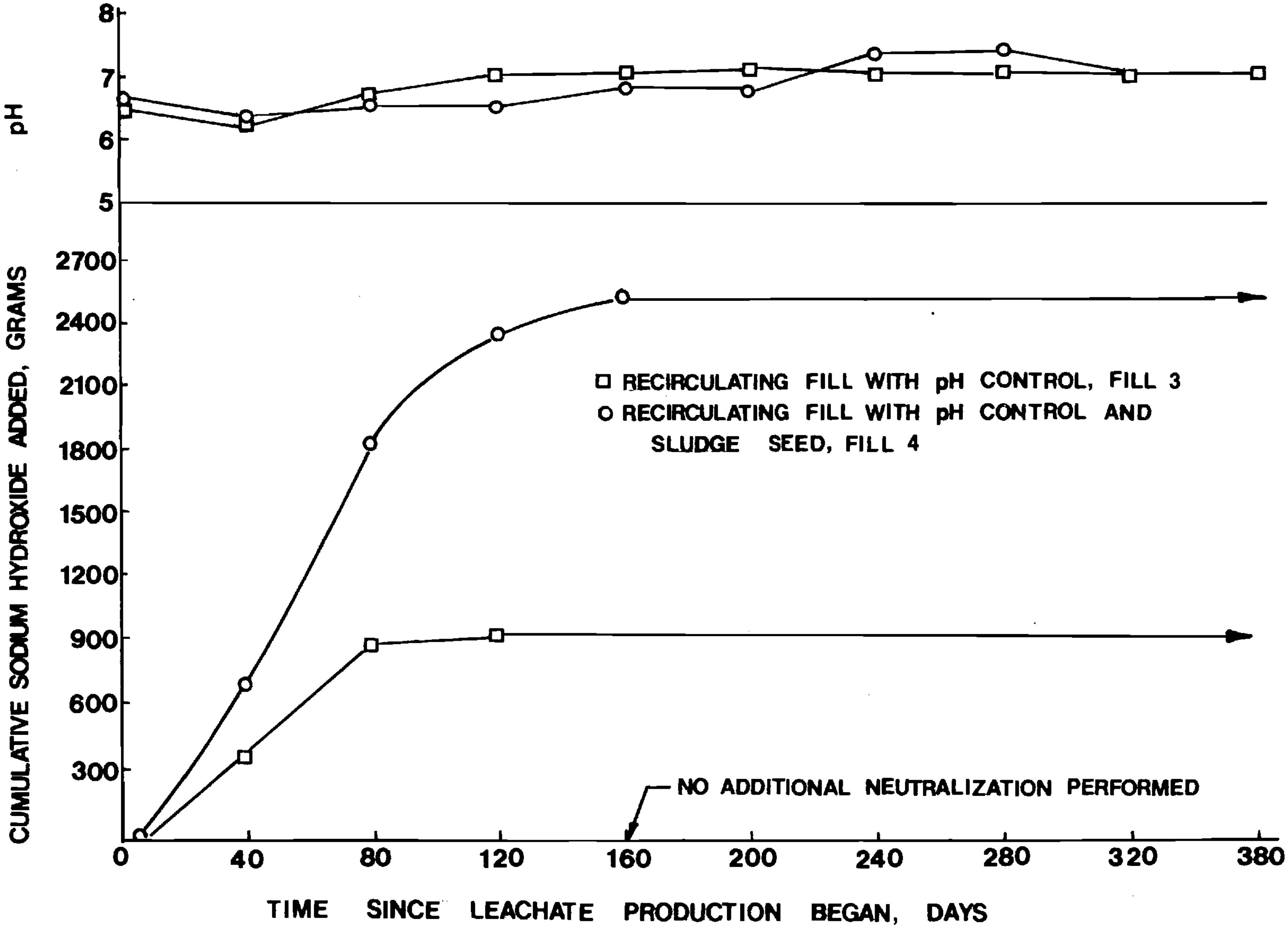


FIGURE 21 ADDITION OF NEUTRALIZING AGENT, SODIUM HYDROXIDE, DURING PHASE II

Addition of raw primary sludge to Fill 4 caused a neutralizing requirement of nearly twice that of Fill 3. Even with this two-fold increase in neutralization requirement, the leachate pH of Fill 4 was generally below that of Fill 3 and only sporadically increased above pH 6.5. Conversely, the leachate pH of Fill 3 increased above 6.5 several times and after 78 days showed a general upward trend from pH 6.55 to pH 7.03 at 96 days.

GAS ANALYSIS

Data showing the relative amounts of carbon dioxide and methane in the gas collected during Phase II are displayed in Table 14. The gas from Fill 4 generally exhibited a higher methane content than the analyses indicated for Fill 3. The sampling technique used during the study precluded determination of total quantities of gas produced and only allowed for a qualitative characterization throughout the test period.

ANALYSIS OF RAW PRIMARY SLUDGE USED DURING PHASE II

Analysis on the raw primary sludge initially added to Fill 4 included; total organic carbon, total suspended solids, volatile suspended solids, total solids, hardness, volatile acids, ammonia and organic nitrogen, nitrate, chloride, phosphate, calcium, magnesium, manganese, sodium, iron, potassium, and zinc. The tabulation of the data is presented in Table 15. These tests were used to ascertain the nutrient, organic and inorganic quality as well as possible inhibitory effects of the sludge addition to Fill 4.

Table 14. COMPOSITION OF GAS PRODUCED DURING PHASE II

Week of test period	Fill 3 Composition, % by volume CO_2	Fill 3 Composition, % by volume CH_4	Fill 4 Composition, % by volume CO_2	Fill 4 Composition, % by volume CH_4
7	100.0	0.0	53.0	47.0
12	50.3	49.7	41.5	58.5
32	50.0	50.0	21.4	78.6
44	23.7	76.3	18.2	81.8
58	28.6	71.4	50.0	50.0
67	----	----	42.3	57.7
76	34.1	65.9	35.1	64.9
84	----	----	40.0	60.0
99	41.5	58.5	30.7	69.3
108	28.5	71.5	41.4	58.6

Table 15. ANALYSIS OF RAW PRIMARY SLUDGE ADDED TO FILL 4 IN PHASE II

Sludge constituent	Concentration	Sludge constituent	Concentration
Total organic carbon, mg/l	3,300	Organic nitrogen, mg/l as N	14.0
Total suspended solids, mg/l	57,850	Nitrate, mg/l as NO_3	0.91
Volatile suspended solids, mg/l	33,400	Chlorides, mg/l	27.6
Total solids, mg/l	63,100	Phosphorous, mg/l as PO_4	7.0
Total hardness, mg/l as $CaCO_3$	582	Calcium, mg/l	138
Volatile acids:		Magnesium, mg/l	25
Acetic acid, mg/l	6,830	Manganese, mg/l	0.0
Propionic acid, mg/l	815	Sodium, mg/l	50
Butyric acid, mg/l	600	Iron, mg/l	75
Valeric acid, mg/l	290	Potassium, mg/l	132
Ammonia nitrogen, mg/l as N	361	Zinc, mg/l	0.05

SECTION VI

DISCUSSION

The sanitary landfill method of solid waste disposal depends largely upon anaerobic biological activity to stabilize the decomposable fractions of refuse. The anaerobic process is considered to proceed through two identifiable phases with conversion of the larger organic molecules into intermediates including mainly the volatile short-chained organic acids (acid fermentation), and subsequent conversion of the short-chained acids to carbon dioxide and methane (methane formation).

The methane formation phase is generally considered the rate controlling step in the anaerobic process since it proceeds at a much slower rate and is more sensitive to environmental stresses than acid fermentation. Methane forming organisms generally require strict anaerobic conditions, a near neutral pH and absence of inhibitory substances. If acid production exceeds the rate of methane formation to an extent greater than the capacity of the system to buffer the acids produced, the pH will fall below the level at which the methane producing organisms can survive and the methane forming phase of the process will cease to function efficiently. In an efficiently operating anaerobic system, however, volatile acids concentration will initially rise to a peak value and then decrease with concurrent changes in the concentration of the individual volatile acids. The pH of the system may decrease during the increase in volatile acids and will then rise steadily while the volatile acids diminish as a consequence of conversion to methane and carbon dioxide.

The effect of leachate recycle on the stabilization processes occurring within a sanitary landfill was examined for 1063 days during Phase I and for 747 days during Phase II of the experimental studies. Whereas the landfill environment was not adjusted except by leachate recirculation during Phase I, more favorable conditions for anaerobic digestion were induced during Phase II by maintaining the pH in both fills near neutral and also by adding primary sewage sludge to Fill 4. The significance of trends observed in leachate quality and landfill stabilization are discussed as they relate to landfill practices and possible remedy for potential environmental pollution problems.

CHANGES IN LEACHATE QUALITY WITH RECYCLE

The data obtained during the experimental studies have demonstrated that leachate recycle markedly reduced the concentrations of readily decomposable pollutants emitted in the leachate from a simulated landfill containing materials characteristic of residential refuse. In addition to the comparison of simple leachate recycle, the relative benefits of pH control on waste stabilization were ascertained together with the effects of initial raw sludge additions. In general, leachate recycle with initial neutralization promoted a more rapid development of methane formers with a concomitant increase in rate of stabilization and removal of pollutant concentrations from the leachate. Seeding with raw primary sludge further accelerated the biological stabilization processes initially with a more rapid and larger production of volatile acids and organic pollutants in the leachate but also with an eventual reduction in stabilization time for the readily decomposed organic materials in the leachate when compared to the fill without recycle.

Volatile Acids and pH

When dealing with an anaerobic system such as the environment within a sanitary landfill, the concentration of volatile acids and pH can be most important indicator parameters. The low molecular weight fatty acids (acetic, propionic, butyric, and valeric) are very diagnostic of the stage and degree of stability of the anaerobic process. Figures 9 through 11 reflect the behavior of the individual volatile acids during both Phase I and Phase II of the study and Figure 12 demonstrates their impact on pH when external neutralization was not used.

Phase I -

During Phase I there was an early rise in volatile acids concentrations in both Fill 1 and Fill 2 with acetic acid being the most abundant acid. A reduction in acetic and propionic acids began at about 160 days preceded by butyric and valeric acids at about 100 days in Fill 2. This decrease in volatile acids was accompanied by an increase in pH from 5.3 to 6.2 at about 160 days. The reduction in volatile acids in Fill 1 began at about 280 days after which time the acids decreased steadily but without a corresponding increase in pH.

The butyric and valeric acid concentrations in Fill 2 had decreased dramatically at about 240 days followed by acetic and propionic acids at about 280 days. The low volatile acids concentrations at this time resulted in an increase in pH to 7.1. The total volatile acids in Fill 1 decreased gradually during the 1063-day study period from a maximum of 9300 mg/l at 228 days to 2135 mg/l at the end of the test period; Fill 2 concentrations decreased from a maximum of 5818 mg/l at 96 days to a minimum of 60 mg/l and a final concentration of 733 mg/l at the end of the test period. This change was considered indicative of the removal of readily available organic pollutants from the refuse and leachate with an eventual attack on more resistant materials in the refuse and the appearance in the leachate of their volatile acid conversion products. Additional monitoring has indicated a trend toward decrease in these volatile acid residuals. A similar trend has not yet been observed for the control although there appeared to be a less dramatic decrease in volatile acids concentration followed by an increase which may also have been somewhat indicative of the readily decomposable--resistant materials conversion pattern.

Phase II -

After an initial peak at about 40-80 days, the volatile acids concentrations in Fill 3 decreased rapidly to consistently low values with the higher homologues preceding the shorter chain acids in reaching stability in concentration. When the pH in Fill 3 had been adjusted to 6.81 at 52 days, addition of NaOH for pH control was terminated. Thereafter, the total volatile acids concentration decreased from 5105 mg/l at 45 days to 130 mg/l at 221 days at a more rapid pace and in less time than indicated previously for Fill 2. Thereafter, total volatile acids concentration varied from negligible to 480 mg/l for the remainder of the test period. The pH control provided by external neutralization apparently created a more favorable environment for rapid conversion of the volatile acids to methane and carbon dioxide with an increased rate of stabilization of the organic components of the refuse.

For Fill 4, the total volatile acids concentration peaked at about 120 days after which time the acids steadily decreased to low levels similar to the other fills with leachate recycle. The maximum total volatile acid concentration in Fill 4 was 9560 mg/l or higher than experienced in Fill 3 thereby indicating that the addition of raw primary sewage sludge accelerated acid fermentation and probably also added to the reservoir of readily available organic material in the fill. As a consequence, pH adjustment was required for about 160 days to achieve a pH of 6.65. Accordingly, about 2520 grams of sodium hydroxide were added to Fill 4 as compared to 1020 grams to Fill 3.

As observed for Fills 1 and 2, the concentrations of butyric and valeric acids in Fill 3 decreased to low levels (at about 80 days) again prior to propionic (at about 160 days) and acetic (at about 300 days) thereby indicating the sequential pattern of conversion. Similarly, butyric and valeric acids decreased to their low levels in Fill 4 in about 320 days followed by propionic and acetic acids at about 360 and 400 days respectively. In addition, reductions in volatile acids to a minimum concentration followed by a gradual increase suggested conversion of readily available organic with subsequent attack on the more resistant materials in the refuse.

Comparison of the results for the four fills indicated that leachate recycle was beneficial to the removal and conversion of readily available organics in the refuse through volatile acids in the leachate to methane and carbon dioxide and that in the absence of such a procedure, the leachate continued to contain relatively high volatile acids concentrations even after 1063 days of study. Increases in residual volatile acids concentrations in all fills suggested an attack on the more resistant materials in the refuse and the possible need for continued monitoring and/or treatment.

Organic Pollutant Parameters (BOD, COD and TOC)

As could be expected, BOD, COD and TOC followed the same removal trend as the volatile acids. In each fill, the peak concentrations occurred at approximately the same time and decreased correspondingly.

Phase I -

The concentration of BOD, COD and TOC for Fill 2 decreased to relatively low constant values in about 300 days whereas in Fill 1, after reaching a maximum, these parameters decreased only gradually. The BOD, COD and TOC maxima were 13,400 mg/l, 18,100 mg/l and 5000 mg/l versus 10,100 mg/l, 10,500 mg/l and 2798 mg/l for Fills 1 and 2, respectively. Residual concentrations again remained to be considered in terms of ultimate discharge requirements.

Phase II -

Leachate recycle with pH adjustment again resulted in a more rapid decrease in pollutional characteristics and as measured by BOD, COD and TOC, reached consistently low levels at about 130 and 400 days for Fills 3 and 4, respectively. The delay in neutralization for pH control after raw sludge seeding for about two weeks apparently caused a temporary promotion of acid conditions in Fill 4 which delayed the desired production of methane from the volatile acids. However, once pH control had become effective, a dramatic reduction in all pollutional parameters occurred. As with the Phase I fills, residual concentrations remained at the end of the test period.

Acidity and Alkalinity

During the experimental investigations, the predominant source of acidity was the volatile acids so that acidity increased or decreased as the volatile acids increased or decreased unless otherwise moderated by addition of NaOH for neutralization. Likewise, the alkalinity was reflected by the association of cations and anions present in the system which under normal operation would include the carbon dioxide-bicarbonate-carbonate buffer system at neutral pH and the volatile acids buffer system at low pH. Therefore, direct relationships could be anticipated between the acid-base constituents present, i.e., volatile acids, ammonium, calcium (and magnesium), and sodium particularly when added for pH control.

Phase I -

The acidity of the leachate from Fill 2 decreased dramatically at about 200 days and corresponded to decreases in volatile acids, BOD, COD and TOC. At the end of the study period, the acidity of Fill 1 remained high at 1290 mg/l while that of Fill 2 was only 110 mg/l.

The alkalinity in the leachate from Fill 1 remained relatively constant during a considerable portion of the study period at about 2200 mg/l. However, it decreased consistently after about 700 days to a final concentration of 760 mg/l. The alkalinity in the leachate from Fill 2 also decreased gradually with time as a consequence of dilution and the impact of other reactions within the fill. The alkalinity in the leachate from both Fills 1 and 2 generally reflected the magnitude of the buffer capacity established at either acid or neutral pH.

Phase II -

The acidity in the leachate of Fills 3 and 4 changed as expected with changes in organic pollutant concentrations in the leachate. The impact of the initial raw sludge addition on acid production was reflected in the increase in acidity for Fill 4. The initial acidity in leachate from Fills 3 and 4 was generally less than that of Fills 1 and 2 due to the addition of NaOH for neutralization after two weeks.

The alkalinity in the leachate from Fills 3 and 4 indicated the influence of base additions for pH control and thus were of greater magnitude than for Fills 1 and 2. Some fluctuation was noted as is also illustrated in similar changes in sodium concentration (Figure 17). The concentration of sodium remained less than the concentration of this cation reported as toxic to the anaerobic stabilization process and therefore toxic effects were not considered as an issue during data analysis.

Nitrogen and Phosphate

Phase I -

The concentrations of organic and ammonia nitrogen were lower in the leachate from Fill 2 than in the leachate from Fill 1. The organic nitrogen decrease tended to precede the decrease in ammonia nitrogen as a consequence of sequential conversion, however, the concentrations were probably also changed as a consequence of biological utilization and/or dilution. Whereas the organic and ammonia nitrogen concentrations in the leachate from Fill 1 were 14 mg/l and 2 mg/l respectively at the end of 1063 days, measured concentrations for Fill 2 decreased to zero on several occasions and were practically nil at the end of the test period.

The initial phosphate concentrations were relatively high in the leachate from both fills as soluble phosphate was leached by the initial addition of water. The ensuing concentrations reflected higher values for Fill 1 than Fill 2 probably as a consequence of greater biological utilization and/or dilution in the latter.

Phase II -

After initial high concentrations of both organic and ammonia nitrogen, a gradual decrease occurred in the concentrations in Fill 3 whereas, in Fill 4 they did not decrease until about 200 days had elapsed. The initial raw sludge addition to Fill 4 again had its impact on the nitrogen content with greater initial concentrations in the leachate from Fill 4 than in that from Fill 3. However, with time these concentrations decreased to values of similar magnitude.

Both Fills 3 and 4 seemed to be utilizing the phosphate present and more rapidly than indicated for Fills 1 and 2. This again supported the likelihood that Fills 1 and 2 initially were less biologically active with respect to complete conversion of readily available organic materials than Fills 3 and 4 because of the absence of pH adjustment and/or sludge seeding.

Metals and Hardness

Phase I -

For the first 160 days, the concentration of iron was similar and increased steadily in both Fill 1 and Fill 2 probably as a consequence of the emergence of acid conditions (some corrosion of metal fixtures) and a more reducing condition in the fills. However, after 160 days, the iron concentration in the leachate from Fill 2 decreased sharply as the pH increased from about 5.2 to 7.2.

It was concluded that as the pollutants were removed from the leachate of Fill 2, the environment became less reducing, permitting the oxidation and precipitation of iron from the leachate. Such a possibility was evidenced by a brownish color in the recycled leachate from Fill 2 at that time as compared to the corresponding greenish color of the leachate from Fill 1. At about 430 days, the iron concentration was essentially zero in the leachate from Fill 2 whereas the iron concentration in the leachate from Fill 1 remained high and above 400 mg/l at the end of the 1063-day study period.

In the early stages of the study, the manganese concentration was higher in the leachate from Fill 2 which may also have reflected a more reducing environment than in Fill 1 with the insoluble manganese being reduced to the soluble manganous form. In fact, the leachate from Fill 1 never reached a manganese concentration above 20 mg/l throughout the 1063 days of the study while a maximum of 93 mg/l was obtained for Fill 2 at 140 days. As with iron, the concentration of manganese in the leachate from Fill 2 began to decrease as the pH rose and thereafter reached a relatively low value of 10 mg/l at 249 days. However, unlike iron, manganese is relatively soluble up to pH 9 and thus soluble throughout the pH range established during the study. As a consequence, it was possible that the decrease in soluble manganese might have been due to a lessening of the reducing conditions within Fill 2 as stabilization progressed. At 1063 days, the manganese concentration in the leachate from Fill 1 was 5.4 mg/l while it was essentially zero at about 500 days in Fill 2.

Sodium concentrations in the leachate from both fills were low throughout Phase I. Concentrations of 15 mg/l and 16 mg/l were recorded for Fills 1 and 2, respectively, at the end of the study period. In contrast, the concentrations of calcium and magnesium, although similar for about the first 200 days, became somewhat dissimilar thereafter probably as a consequence of operational modes and the influence of rainfall. The relatively intense rainfall between 200 and 220 days of the study period washed out a considerable concentration which appeared subsequently as a slug in the leachate from Fill 1. This rainfall also subsequently caused some dilution of concentration in the leachate from Fill 2. In addition, it is possible that reductions in concentration might have been due to the opportunity for ion exchange and the formation of organometallic complexes which would have been more possible in Fill 2 than in Fill 1. This exchange or complexation being pH-Eh dependent would be difficult to predict because of the differences in operation and degrees or state of stabilization at any one period of analysis.

Phase II -

The iron concentration in the leachate varied considerably between Fills 3 and 4 after an initial period of 45 days. However, the concentration in the leachate from Fill 3 decreased to very low values after 80 days when the pH increased from 6.2 to 7.05 as a consequence of neutralization and/or effective biological stabilization. The iron in the leachate from Fill 4 did not decrease to low values until about 240 days had elapsed and when the pH increased from 6.7 to 7.4. At these times, there was a noticeable change in leachate color from greenish-brown to light brown. Therefore, it is likely that with the decrease in volatile acids and increase in pH, a more oxidizing environment prevailed with a concomitant conversion of the ferrous to the ferric form of iron.

Although manganese has similar chemical characteristics as iron, it appeared that little soluble manganese was present in the leachate from either Fill 3 or Fill 4 during the study period with recorded concentrations less than 25 mg/l. Similarly, the concentrations of magnesium in the leachate from both fills were low and generally ranged between 12 and 15 mg/l. Recycle of the leachate tended to maintain relatively constant concentrations of both manganese and magnesium.

Calcium concentrations in the leachate from Fill 3 were lower than in that from Fill 4 during the initial 200 days after which time the concentrations were low and essentially constant. Compared to the analyses from Phase I, concentrations in the leachate from the Phase II fills decreased much more rapidly which again may have been a consequence of the neutralization procedures employed and possible ion exchange or complex formation. Neutralization also increased the sodium level in Fills 3 and 4 in accordance with the amount of caustic soda added for pH control (Figure 21). Accordingly, Fill 4 received and maintained larger concentrations; the maximum of 2300 mg/l at about 90 days was not considered sufficient to impart a toxic effect on the biological processes occurring in the fills.

Screening analyses for copper, zinc, nickel, lead and chromium were also conducted during each phase of the study. Except for measurable concentrations of zinc, these metals appeared only in trace quantities. A concentration of 42.5 mg/l zinc was detected at 556 days in Fill 1 which decreased to 18.7 mg/l at the end of the study period. The zinc concentration in Fill 4 reached its peak of 22 mg/l at 73 days and then gradually decreased to zero at 200 days. It is possible that the behavior and delayed appearance of zinc was a consequence of its initial precipitation in the fills with sulfides and later release in the leachate as the environment became less reducing and the sulfides were oxidized.

The total hardness in the leachate from each fill reflected the pattern of divalent cations present. Of particular significance was the change in calcium concentration which correspondingly determined the change in hardness during both phases of the study.

Solids

Phase I -

Although it was difficult to attach meaningful interpretation to the solids data because of the interdependence of the various physical and chemical processes occurring in the fills at any one time, the total solids concentration in the leachate from Fill 2 was reduced to 700 mg/l as compared to 2100 mg/l for Fill 1 after 720 days. As supported by the greater reduction in pollutional content, the solids concentration could also be considered indicative of a greater degree of stabilization with leachate recirculation although mechanical filtration was also operative as the leachate passed through the fill.

Phase II -

Solids data on the Phase II fills were less conclusive except to reflect the contribution of caustic soda used for neutralization to the total solids and a seemingly more rapid decrease with time when compared with Fills 1 and 2. Again, interpretive analysis was curtailed by the mode of operation and limitations on obtaining truly representative and meaningful samples.

EFFECTS OF pH CONTROL ON LANDFILL STABILIZATION

The more rapid improvement in quality of the leachate from the fills with leachate recycle with or without pH adjustment emphasized the beneficial effect of the development of a more active anaerobic biological system in these fills. This was especially apparent when the leachate analyses from Fill 1 were compared to those from Fills 2 and 3. However, the fill with leachate recycle, pH control, and the initial addition of primary sludge (Fill 4) was not initially as effective in improving the quality of leachate due to the apparent conflict between pH control which would abet efficient anaerobic digestion and conversion of pollutants, and the primary sewage sludge which would and did create an environment most beneficial to rapid formation of volatile acids and therefore initially unfavorable to methane forming bacteria because of detrimental increases in volatile acid concentrations. Therefore, raw sludge seeding did not initially aid in the total anaerobic stabilization process, and in fact caused it to be delayed as a consequence of a time lapse between seeding the fills with raw primary sludge and initiating the neutralization process; a delay of approximately two weeks. However, once neutralization became effective, similar results were obtained between the Phase II fills.

Refuse Composition

Except for the analyses performed on the refuse initially added to the simulated landfills, representative samples of the refuse from the landfill columns were very difficult to obtain. The sampling ports were considered too small for convenient removal of materials in quantity necessary to assure reliability of analysis. The samples from the Phase I fills were taken from near the surface of the fills and probably were less representative than the samples from the Phase II fills which were removed from near the center of each fill.

In spite of these difficulties, the analyses presented in Table 5 generally support the contention that anaerobic biological stabilization of the organic fraction of the refuse proceeded further in the fills with leachate recycle than in the control fill of Phase I. The relatively high carbon content in the refuse samples at the end of the test periods probably reflected the remaining paper fraction with less carbon generally detected in the refuse of the fills with leachate recycle where greater stabilization had occurred. Reductions in volatile solids with time, particularly in the fills with leachate recycle, were further evidence of removal of organic materials with a greater reduction being exhibited for the longer test period in Phase I. Finally, changes in nitrogen content were also anticipated as the nitrogen contributed to the nutrient requirements of the biological stabilization process. The rather erratic results were again attributed to difficulties in obtaining truly representative samples and the distribution of nitrogen with time as leachate recycle became effective.

Gas Composition

Gas analyses performed during the study period of Phase II (Table 14) indicated that there was early development of methane formers particularly in Fill 4 with a generally increasing predominance of the methane fraction of the gas produced. It is likely that the addition of sewage sludge to Fill 4 enhanced methane formation by providing a biological seed of requisite organisms. Because of the physical configuration of the fills and the sampling technique utilized during the studies, no quantitative measurement of total gas production could be made. However, even after the readily available organics in the refuse had been removed, methane was detected although the quantity of gas available for sampling was exceedingly small. As a consequence, gas sampling and analysis were terminated when sampling difficulties became prohibitive.

Admittedly, the measurement of gas production and its composition was curtailed by techniques employed but were considered to be sufficient to reflect relative activity within the fills and to provide some support concerning the intrinsic roles of acid and methane formers during the course of anaerobic stabilization. Although not measured during Phase I, a similar response in gas production and quality could be presumed to have occurred at least in the fill with leachate recycle.

VOLATILE ACIDS, pH AND BOD AS MEASURES OF LANDFILL STABILIZATION

Phase I

As discussed previously, the volatile acid concentrations in the recycled leachate of Fill 2 during Phase I decreased dramatically after 200 days of recirculation. The rapid decline in volatile acids caused a concomitant rise in pH. The pH rose rapidly from 5.2 to 6.6 and then rose steadily to a maximum of 7.4. Thus the pH of the system stabilized within the optimum range (6.6-7.4) for the pH-sensitive methane forming bacteria. As the methane forming phase became established, a stable anaerobic system was also established within the fill with leachate recycle. Because the stabilization of refuse in a landfill is dependent upon anaerobic biological action, the development of a stable anaerobic system in the fill with leachate recycle simultaneously promoted an efficient stabilization process. In contrast, the environment within the control fill (Fill 1) never exhibited a pH in the optimum range for the establishment of a viable methane forming population and thus, during the study period of 1063 days, the leachate from the control fill never became stabilized to the extent of the fill with leachate recycle.

The dramatic reduction in BOD of the leachate from the fill with leachate recycle during Phase I supported the conclusion that leachate recycle increased the rate of refuse stabilization. The BOD of the leachate from Fill 2 was reduced 99.9 percent from its maximum value by the end of the study period. The leachate from Fill 1 indicated only an 87 percent reduction from its maximum BOD over the same period. Thus in terms of readily biologically oxidizable organics in the refuse, the recycle of leachate produced a greater degree of stabilization as measured by the BOD of the leachate.

Phase II

During Phase II, the volatile acid concentration of Fill 3 was greatly reduced after 45 days with a corresponding increase in pH from 6.30 at 45 days to 7.00 at 87 days. The methane forming phase became established in Fill 3 as the pH was adjusted to promote an optimum pH (6.6-7.40) for the pH-sensitive methane producing bacteria. On the other hand, the fill with leachate recycle capabilities, pH control, and initial sludge addition (Fill 4) attained a favorable pH range for methane formation only after about 200 days. This delay was considered due in part to the lag time (two weeks) between sludge seeding and the initiation of neutralization.

In comparing the results from Fill 3 with Fill 2, it was apparent that the former had reached the low level of volatile acid production that the latter reached in about one-half the time. The leachate from Fill 3 also had correspondingly higher pH values. Therefore, it was concluded that Fill 3 had accomplished the same degree of refuse stabilization as Fill 2 but in half the time.

The BOD in the leachate varied greatly between Fills 3 and 4. Fill 3 showed a more rapid reduction in this parameter from its peak value of 7150 mg/l at 31 days; by the end of the study period the BOD had been reduced substantially and similar in magnitude to the BOD of the leachate from Fill 2 thereby indicating an increased rate of stabilization. The leachate from Fill 4 displayed a delayed reduction in BOD which paralleled the reduction in volatile acids but which was similar in magnitude to the BOD reduction in Fill 3 at the end of the study period.

In comparing the results from Fill 3 with those from Fill 1 and Fill 2, the degree of stabilization as characterized by BOD in the leachate indicated that Fill 3 had achieved approximately the same level in 120 days as Fill 2 had in 280 days and Fill 1 had not by the end of the 1063-day study period. Therefore, in terms of readily biologically oxidizable organics in the refuse, Fill 3 of Phase II achieved, in a shorter period of time, a higher rate of refuse stabilization than Fill 1 or Fill 2 of Phase I. Using the available data, the leachate from Fill 3 decreased in BOD to low concentrations and therefore the stabilization experienced by Fill 2 in less than half the time. This accelerated rate of BOD reduction emphasized the benefits of pH control and leachate recycle to landfill disposal practices. However, residual concentrations of BOD (as well as COD and TOC) and volatile acids possibly caused by secondary breakdown of more complex materials in the refuse focus attention on the potential need for residual monitoring and/or treatment.

Because ultimate site use is one of the primary concerns when designing a sanitary landfill for solid waste disposal, the rate of refuse stabilization is most important. The ultimate use of many landfill sites must be delayed for years because of problems with differential settling, gas release, uncertainties about leachate production, etc. However, it now appears that when leachate recycle and pH control are practiced, biological stabilization of the readily available constituents of the refuse as well as the immediate and the majority of settlement may be achieved in a much shorter period of time. Therefore, if the value of the landfill site in terms of ultimate use may be realized sooner, economic conditions may well warrant recycle and pH control on a large scale with or without residual treatment (See Section VII).

ENVIRONMENTAL IMPACT OF LEACHATE RESIDUALS

As indicated by the basic data, residual concentrations of both inorganic and organic materials remained in the leachate from both the Phase I and Phase II fills. These residuals could impose a detrimental environmental impact depending upon the nature and relative concentrations of the various leachate constituents with respect to the ultimate discharge receptor.

Based upon the results of the experimental studies with leachate recycle, pH control and sludge seeding, some estimate of the total mass of materials potentially discharged could be calculated if the total quantity of leachate produced was known. Accordingly, the fill without leachate recycle (Fill 1) would indicate the potential release of constituents without the benefits of leachate recycle and/or pH control; the other three fills could then be used to estimate the differences in the leachate quality for ultimate discharge accountable to the removal of the readily available organic fractions from the refuse. Therefore, the results from Fill 1 would yield an indication of organic pollution potential whereas the results from Fills 2, 3 and 4 would be more indicative of residual and also potential inorganic pollution.

Recognizing that the total quantity of leachate produced in the simulated landfills over the test periods was directly related to the initial moisture added to the respective fills, the intensity and duration of rainfall, the amount of evaporation, the quantity utilized during sampling and analysis, and for Fills 3 and 4, the moisture (and chemicals) added when neutralization was used, it was difficult to compute the total mass of constituents extracted and/or remaining as residuals in the leachate at any time. Moreover, as leachate accumulated throughout the test periods, some was removed and employed for the ensuing investigations on alternatives for residual treatment (Section VII) and the occasional excesses beyond the holding capacity of the landfill columns and/or collection sumps were removed and stored for future use. These latter excesses did not occur until the readily available organic materials in the leachate had been removed from Fills 2, 3 and 4; biological treatability studies were performed on accumulations of leachate from Fill 1.

To avoid the presentation of questionable and possibly atypical estimates of the total mass of pollutants released in the leachate during stabilization of refuse in the four simulated landfills, it was considered sufficient to emphasize the dramatic differences in pollutional quality of the leachates from the four fills exhibited in Tables 10 through 13 at the end of the respective test periods. Whereas the readily available organics had been essentially converted and removed for the fills with leachate recycle, a considerable concentration of pollutants remained in the single pass control fill (Fill 1) even after over 1000 days of Phase I. Considering that a rainfall/initial moisture addition equivalent of over 1000 gallons (Table 8) had passed through the control fill during this period, simple conversion of the pollutant concentrations from Table 10 would be indicative of the total mass extracted and potentially escaping to the environment for the particular refuse and operating mode used during the investigations. Accordingly, Table 16 presents an estimate of the major constituent materials extracted from Fill 1 based upon the previous considerations. A similar estimate could not be provided for the fills with leachate recycle in either Phase I or Phase II because of the uncertainties in determining total leachate accumulation at any one time.

Table 16. ESTIMATED INCREMENTAL AND TOTAL MASS (IN POUNDS) OF MATERIAL EXTRACTED FROM FILL 1 DURING PHASE I

Time since leachate production began, days	0	14	24	32	39	48	81	116	125	153	173	189	197	228	249	284	312	332	347	398	428	473	506
COD	9.450	2.710	2.470	1.510	0.883	0.861	1.015	1.485	0.431	2.700	7.240	2.650	1.720	2.660	1.440	2.260	2.860	-----	0.514	1.062	0.630	1.710	1.080
BOD_5	5.470	1.480	2.190	0.931	0.810	0.604	0.971	1.411	0.320	2.450	5.410	2.210	1.020	1.970	1.160	1.630	1.820	-----	0.360	0.625	0.430	1.160	0.880
TOC	2.690	0.566	0.625	0.385	0.206	0.209	0.316	0.332	0.089	0.592	1.590	0.561	0.375	0.740	0.330	0.510	0.610	0.642	0.139	0.287	0.193	0.560	0.360
Total alkalinity as $CaCO_3$	1.220	0.477	0.460	0.282	0.168	0.155	0.276	0.390	0.078	0.520	1.240	0.457	0.194	0.365	0.145	0.413	0.400	0.396	0.080	0.177	0.116	0.390	0.270
Total acidity as $CaCO_3$	1.510	0.326	0.334	0.206	0.131	0.160	0.203	0.204	0.077	0.493	1.640	0.527	0.359	0.510	0.240	0.340	0.497	0.680	0.160	0.230	0.140	0.330	0.190
Total hardness as $CaCO_3$	0.980	0.414	0.440	0.266	0.143	0.129	0.156	0.210	0.062	0.493	1.380	0.424	0.269	0.820	0.319	0.412	0.476	0.336	0.062	0.186	0.122	0.300	0.180
Phosphate as $PO_4^{\equiv}$	0.057	0.001	0.001	0.001	nil	nil	nil	0.001	nil	0.001	0.001	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil
Organic nitrogen	0.123	0.014	0.015	0.009	0.006	0.004	0.004	0.026	0.002	0.001	0.018	0.002	0.005	0.016	0.011	0.013	0.013	0.006	0.002	0.015	0.003	0.009	0.006
Ammonia nitrogen	0.122	0.044	0.040	0.028	0.014	0.014	0.016	0.015	0.005	0.058	0.126	0.040	0.029	0.017	0.005	0.019	0.021	0.031	0.006	0.010	0.006	0.016	0.011
Nitrate nitrogen	0.029	0.009	0.021	0.012	0.008	0.001	-----	0.001	nil	-----	-----	-----	-----	-----	-----	-----	----	-----	-----	0.001	nil	nil	nil
Chloride as Cl^-	0.704	0.114	0.026	0.015	0.007	0.025	-----	0.025	0.009	0.046	0.122	0.057	0.034	0.027	0.028	0.048	0.061	0.025	0.006	0.017	0.010	0.025	0.022
Sulfate as $SO_4^{=}$	0.184	0.037	0.026	0.012	0.012	0.001	nil	0.001	nil	0.003	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Calcium as Ca	0.273	0.127	0.112	0.087	0.055	0.040	0.047	0.055	0.015	0.133	0.340	0.104	0.060	0.184	0.078	0.094	0.101	0.088	0.018	0.041	0.027	0.067	0.031
Magnesium as Mg	0.057	0.021	0.016	0.011	0.005	0.005	0.006	0.007	0.002	0.018	0.050	0.016	0.008	0.038	0.019	0.015	0.014	0.008	0.002	0.005	0.003	0.009	0.002
Manganese as Mn	0.007	0.003	0.001	0.001	0.001	0.001	0.001	0.001	nil	0.004	0.008	0.003	0.002	0.003	0.002	0.002	0.002	0.004	0.001	0.001	0.001	0.001	0.001
Sodium as Na	0.140	0.037	0.031	0.019	0.011	0.011	0.020	0.017	0.005	0.034	0.091	0.028	0.016	0.024	0.013	0.015	0.029	0.021	0.005	0.015	0.009	0.028	0.017
Iron as Fe	0.020	0.006	0.017	0.005	0.007	0.005	0.007	0.023	0.008	0.044	0.177	0.053	0.046	0.027	0.023	0.063	0.091	0.038	0.003	0.035	0.016	0.054	0.040
Zinc as Zn	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Total volatile acids as Acetic Acid	1.912	1.276	1.170	0.794	0.495	0.450	0.592	0.992	0.210	1.41	3.780	1.230	0.770	1.370	0.624	1.100	1.190	0.969	0.214	0.324	0.290	0.826	0.533

Table 16 (continued) ESTIMATED INCREMENTAL AND TOTAL MASS (IN POUNDS) OF MATERIAL EXTRACTED FROM FILL 1 DURING PHASE I

Time since leachate production began, days	530	556	606	636	672	704	758	785	820	858	874	895	899	928	949	964	972	979	993	1007	1028	1042[a]	1063[a]	Total
COD	1.550	1.140	1.400	1.830	1.480	0.370	0.900	0.340	0.610	0.190	0.270	0.530	0.050	0.720	0.830	0.056	0.081	0.077	0.480	0.120	0.320	0.190	0.150	63.030
BOD_5	0.950	0.710	0.980	1.250	1.110	0.250	0.540	0.220	0.300	0.120	0.120	0.260	0.027	0.460	0.480	0.032	0.051	0.043	0.290	0.075	0.200	0.140	0.072	43.990
TOC	0.420	0.440	0.320	0.620	0.570	0.150	0.280	0.110	0.170	0.094	0.110	0.240	0.015	0.300	0.360	0.023	0.044	0.035	0.230	0.057	0.160	0.100	0.071	17.830
Total alkalinity as $CaCO_3$	0.390	0.380	0.470	0.540	0.530	0.170	0.350	0.097	0.140	0.086	0.095	0.302	0.013	0.190	0.210	0.012	0.021	0.022	0.110	0.030	0.077	0.037	0.028	12.970
Total acidity as $CaCO_3$	0.360	0.310	0.380	0.700	0.450	0.120	0.220	0.120	0.170	0.077	0.110	0.210	0.011	0.190	0.230	0.014	0.029	0.029	0.140	0.040	0.095	0.068	0.048	13.510
Total hardness as $CaCO_3$	0.230	0.220	0.260	0.550	0.200	0.056	0.310	0.130	0.250	0.110	0.140	0.310	0.018	0.270	0.330	0.020	0.043	0.033	0.210	0.058	0.160	0.096	0.057	12.640
Phosphate as $PO_4^{=}$	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	------
Organic nitrogen	0.017	0.016	0.013	0.018	0.004	0.002	nil	0.003	0.004	0.002	0.002	0.005	nil	0.002	0.003	nil	nil	nil	0.002	nil	0.001	0.001	0.001	0.419
Ammonia nitrogen	0.007	0.005	0.004	0.002	0.002	0.001	0.003	0.001	0.002	0.001	0.001	0.002	nil	0.001	0.001	nil	nil	nil	nil	nil	nil	nil	nil	0.726
Nitrate nitrogen	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	nil	------
Chloride as Cl^-	0.032	0.037	0.031	0.040	0.022	0.008	0.051	0.011	0.017	0.007	0.009	0.021	nil	0.005	0.008	nil	0.001	0.001	0.004	0.001	0.002	0.001	0.001	1.763
Sulfate as $SO_4^{=}$	----	----	----	----	----	----	----	-----	----	-----	----	----	----	----	----	----	----	-----	----	-----	----	----	----	------
Calcium as Ca	0.039	0.032	0.035	0.042	0.028	0.011	0.039	0.015	0.035	0.015	0.019	0.041	0.002	0.035	0.035	0.002	0.002	0.002	0.013	0.003	0.006	0.004	0.004	2.629
Magnesium as Mg	0.004	0.004	0.005	0.006	0.003	0.001	0.006	0.002	0.004	0.002	0.003	0.006	nil	0.005	0.004	nil	nil	nil	0.002	0.001	0.015	0.001	0.001	0.408
Manganese as Mn	0.001	0.001	0.001	0.001	0.001	nil	0.001	nil	0.001	nil	nil	0.001	nil	0.003	0.003	nil	nil	nil	0.005	nil	nil	nil	nil	0.081
Sodium as Na	0.028	0.031	0.063	0.070	0.061	0.016	0.013	0.004	0.008	0.004	0.005	0.011	0.001	0.007	0.006	nil	nil	nil	0.003	0.001	0.002	0.001	0.001	0.972
Iron as Fe	0.055	0.050	0.062	0.075	0.063	0.018	0.100	0.048	0.081	0.038	0.048	0.100	0.004	0.060	0.085	0.006	0.013	0.010	0.063	0.018	0.053	0.033	0.016	1.937
Zinc as Zn[b]	-----	0.008	0.009	0.003	0.003	0.001	0.003	0.001	0.002	0.001	0.001	0.002	nil	0.006	0.006	nil	nil	nil	0.002	nil	0.001	nil	0.001	0.139
Total volatile acids as Acetic Acid	0.803	0.610	0.750	0.960	0.812	0.210	0.370	0.150	0.220	0.130	0.110	-----	0.020	0.580	0.510	0.032	0.056	0.041	0.250	0.061	0.120	0.074	0.079	29.470

[a] Values generated from trend in precipitation data for days 1060 to 1093 (day 0 for leachate production corresponds to day 33 following initial refuse placement-refer to Table 8).

[b] Values for Zinc not determined until 556 days after leachate production began.

Inspection of the estimated masses of materials indicated in Table 16 for the fill without leachate recycle emphasizes the probable need for some type of attenuation of these constituents if leachate production occurs and threatens the surrounding environment. The attenuation provided by leachate recycle during these studies was considered sufficient and also predictable with respect to the readily available organic materials, however, depending upon prevailing circumstances, organic and inorganic residuals and possibly secondary conversion of more resistant organics may require additional consideration.

SECTION VII

SEPARATE TREATMENT OF LEACHATE AND LEACHATE RESIDUALS

INTRODUCTION

In many areas where ground or surface waters are used for domestic or industrial purposes, the landfill method of solid waste disposal has been discouraged because of possible production and uncontrolled release of leachate. Since leachate may be extremely high in BOD and other pollutants, even if it were contained and collected, some questions would arise concerning its treatability by either conventional or special treatment methods. The studies described heretofore have demonstrated the changes in leachate quality which may occur with time and also the benefits derived from on-site treatment of the leachate by recycle through the landfill. The major benefits so derived include more rapid and predictable stabilization of the readily available organic refuse constituents as well as a dramatic reduction in pollutant strength in the leachate to levels such that the leachate could be amenable for discharge or for release for additional treatment within a more acceptable time frame. This stabilization and/or reduction in pollutional characteristics of the leachate could be greatly facilitated by initial neutralization during recycle of the leachate in order to control the pH of the environment within an acceptable range for the immediate development of the methane forming organisms. In essence, the landfill itself is thereby used as a controlled anaerobic treatment system much analogous to an anaerobic trickling filter.

Assuming that the results from the simulated landfills used during the experimental studies can be related to large-scale landfill operations, it appears that recycled leachate can reach, in a reasonable length of time, a quality suitable for consideration for ultimate release into noncritical receiving waters. In addition, this study has indicated that the length of time required to reach the desired quality of leachate can be lessened by initial neutralization of the recycled leachate. Whether residual organics or such inorganic pollutant residuals as hardness, chloride, calcium, etc. require additional treatment will depend upon the condition of the receiving waters and/or regulatory requirements.

It would also seem plausible to use leachate recycle (with or without pH control) in combination with external treatment. Since most landfill sites are not near municipal wastewater collection and treatment systems, a logical receptor for ultimate discharge, it might be advantageous to use portable package-type waste treatment facilities in conjunction with leachate recycle at the site. Leachate recycle through the landfill and the treatment facility would then be beneficial both in maintaining a constant flow and in providing removal of specific pollutant constituents. The effluent could eventually be discharged intermittently to the receiving waters at the most advantageous and least detrimental times. When the refuse constituents in the landfill had been stabilized and the leachate quality had reached an acceptable level for discharge, the portable plant could be then moved to another location. Such a stabilization/leachate treatment scheme working in consort may well prove to be the most reliable and economical approach to controlled landfill operation with environmental quality protection.

Because of the need for screening and determining the relative applicability of separate and/or combined treatment schemes for raw leachate or leachate residuals, separate biological and physical-chemical leachate treatment studies were initiated. The alternatives selected and presented hereafter were based upon the premise that a relatively fresh and usually strong leachate with high organic pollutant characteristics would best be treated by biological methods possibly followed by physical-chemical methods for removal of residual organics and/or inorganics, color, odor and various biological impurities. Physical-chemical methods would also be most applicable for an older leachate devoid of all but residual organic pollutants but containing certain possibly detrimental inorganic constituents. The systems used during the separate treatability studies were chosen to simulate conventional biological and physical-chemical treatment methods and the accumulated data were analyzed in accordance with accepted techniques and the analytical procedures presented previously in SECTION IV.

SEPARATE BIOLOGICAL LEACHATE TREATMENT

Separate studies of both anaerobic and aerobic biological treatment were performed in a complete-mix reactor system similar to that indicated in Figure 22. The leachate used in both studies was a mixture of leachate from the control column of Phase I (Fill 1) and a local landfill. The average characteristics of the two leachate samples employed during the studies are indicated in Table 17.

Table 17. CHARACTERISTICS OF LEACHATE USED DURING SEPARATE BIOLOGICAL TREATMENT

Leachate characteristic	Anaerobic treatment	Aerobic treatment
pH	5.1	7.0
COD, mg/l	6,000	500
BOD_5, mg/l	3,700	260
TOC, mg/l	2,100	320
Suspended solids		
Total, mg/l	1,100	625
Volatile, mg/l	300	160
Calcium, mg/l	200	100
Magnesium, mg/l	64	35
Potassium, mg/l	348	204
Sodium, mg/l	313	425
Phosphate, mg/l $PO_4^{\equiv}$	-	0.7
Total volatile acids, mg/l as acetic acid	2,700	410

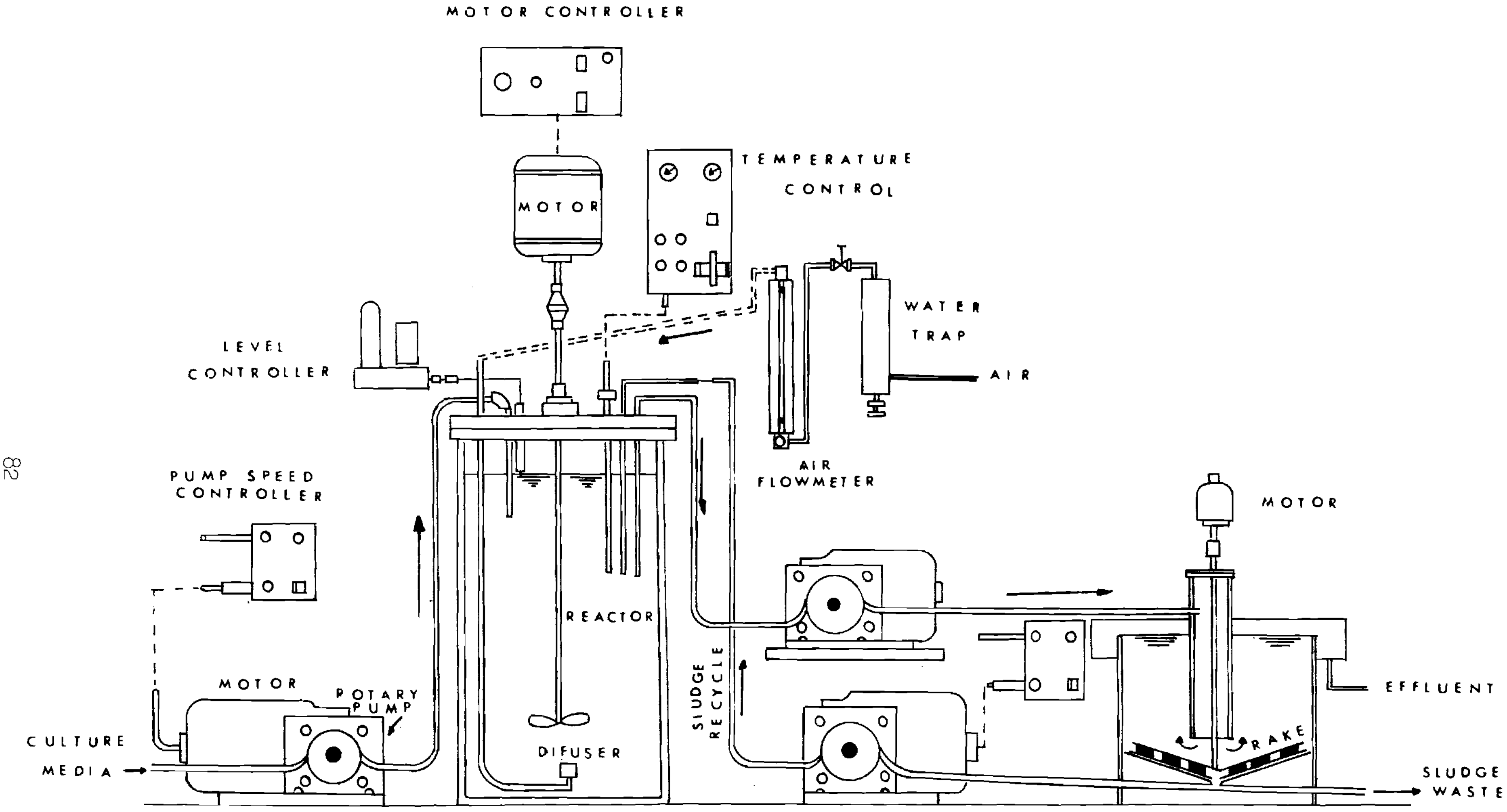


FIGURE 22 COMPLETELY MIXED, CONTINUOUS FLOW REACTOR SYSTEM

A more concentrated leachate representative of a landfill undergoing initial biological stabilization with the production of high volatile acids concentrations was intentionally used during the anaerobic treatability studies, partially to emphasize the logic of choice of treatment method for such a leachate and also to provide some confirmation of the results obtained during Phase I and Phase II of the leachate recycle studies. A less concentrated and more characteristic of an older or at least partially treated leachate was intentionally chosen for the aerobic treatability studies since aerobic treatment would normally be more logically applied under such circumstances.

The data from the anaerobic treatability studies are included in Table 18 and Figure 23. Corresponding data from the aerobic treatability studies are included in Table 19 and Figure 24. In either case, the data indicated good removals of the pollutant components of the leachate as measured by COD, BOD_5, TOC and volatile acids with acceptable correlations between these parameters.

The graphical displays of the data (Figures 23 and 24) also include the kinetic parameters developed by application of continous culture theory analysis. The results are typical of results expected when the anaerobic and arobic treatment processes applied to a biologically degradable substrates are compared. Accordingly, washout occurred in 1.3 days and 1.8 hours respectively in the anaerobic and aerobic systems; a reflection of the relative differences in generation times between anaerobic and aerobic organisms. Similarly, biological solids yield for the anaerobic system was half of the corresponding yield for the aerobic system; a consequence of less conversion of substrate to biomass in the former process.

During the anaerobic treatability studies, the pH ranged between 6.9 and 7.6 which was considered satisfactory for good conversion of the volatile acids to methane and carbon dioxide. Once active anaerobic decomposition had been established, gas production ranged between about 9 and 17.4 cu. ft. per pound of BOD_5 destroyed (about 6 to 11 cu. ft. per pound of COD destroyed) which was in agreement with the results of Boyle and Ham[38]. Total alkalinity varied between 680 and 2800 mg/l as $CaCO_3$ which was also considered sufficient to counteract the pH-depressing influence of the volatile acids throughout the study period.

In general, the gas produced during the anaerobic biological treatability studies was higher in methane content than normally reported for anaerobic sludge digestion. Therefore, assuming the studies were a reasonable representation of expected gas yields, energy recovery from the gas produced during conversion of the leachate would be an attractive possibility. The relative abundance of methane in the gas was probably accountable in part to the nature of the individual volatile acids which made up the primary available organic constituent of the leachate. Normally the total volatile acids consisted of 33, 40, 17 and 10 percent acetic, propionic, butyric and valeric acids, respectively. In addition, as the pH increased, a greater carbon dioxide content and alkalinity existed in the aqueous phase of the system thereby seemingly increasing the proportion of methane in the gas.

Table 18. RESULTS OF SEPARATE ANAEROBIC BIOLOGICAL LEACHATE TREATMENT IN CONTINUOUS CULTURE WITHOUT SOLIDS RECYCLE

Effluent analyses

Liquid retention time, days	COD, mg/l[a]	BOD_5, mg/l[a]	Total volatile acids, mg/l as CH_3COOH[a]	Volatile suspended solids, mg/l	pH	Gas production	
						cu.ft./lb. BOD removed	% CH_4
0[b]	6000	3700	2700	300	5.1	---	----
0.10	6010	3410	2600	260	6.9	nil	----
0.16	5990	3400	2682	294	7.0	0.9	80.2
0.33	5400	4100	2915	315	7.3	0.7	82.5
1.0	4020	2600	1206	450	7.4	4.6	----
5.0	1090	470	187	700	7.5	9.9	82.1
10.0	670	80	109	400	7.6	9.3	83.2
15.0	140	75	63	490	7.1	17.4	74.6

[a] Filtered sample

[b] Average influent concentration for all retention times.

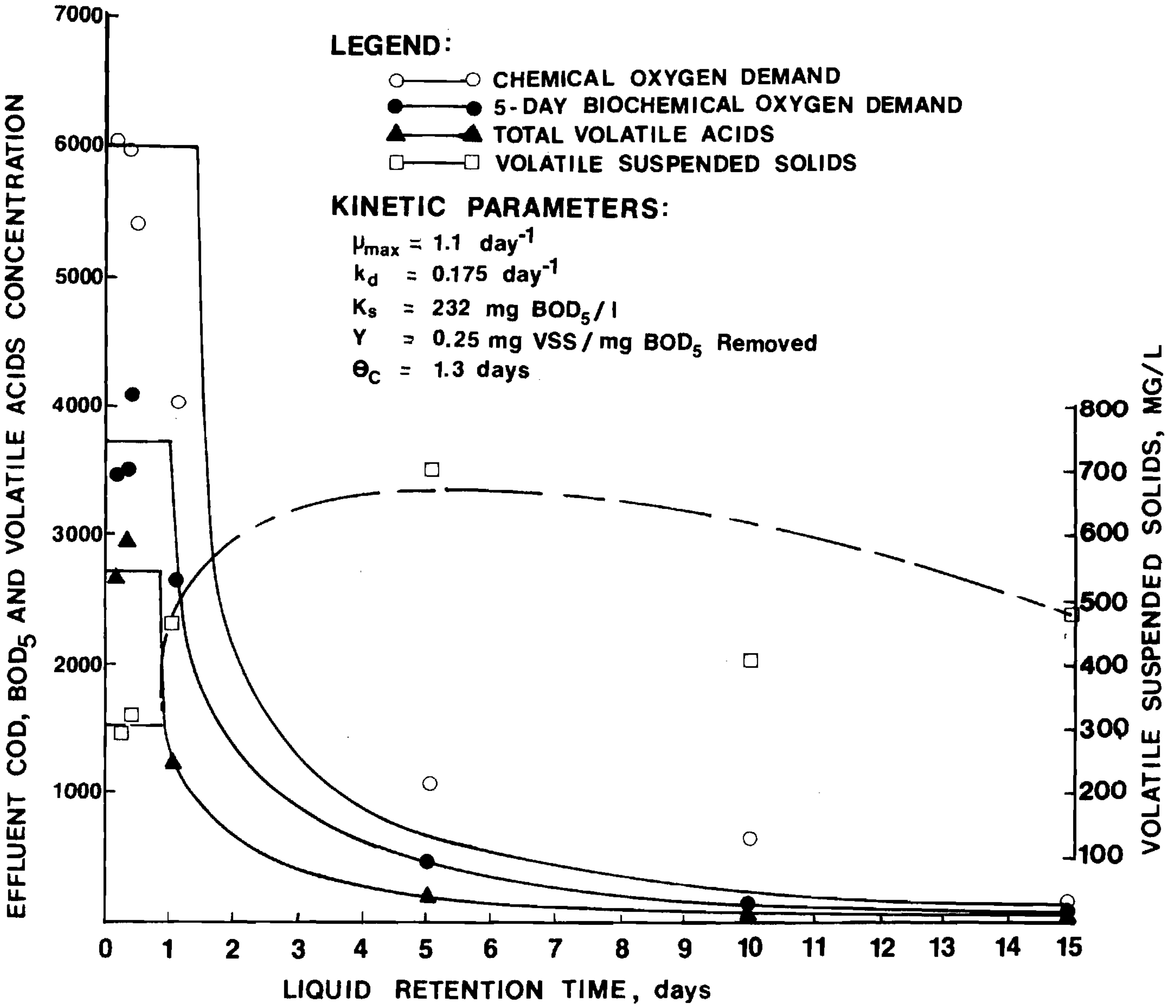


FIGURE 23 ANAEROBIC BIOLOGICAL TREATMENT OF LEACHATE IN CONTINUOUS CULTURE

Table 19. RESULTS OF SEPARATE AEROBIC BIOLOGICAL LEACHATE TREATMENT IN CONTINUOUS CULTURE WITHOUT SOLIDS RECYCLE

	Effluent analyses										
Liquid retention time, days	COD, mg/l	BOD_5 mg/l	TOC, mg/l	Suspended solids		pH	Calcium, mg/l	Magnesium, mg/l	Potassium, mg/l	Sodium, mg/l
				Total, mg/l	Volatile, mg/l					
0[a]	500	260	320	625	160	7.0	100	35	204	425
2.3	290	75	240	975	215	8.0	34	31	144	425
3.0	250	42	200	1000	250	8.1	29	34	164	---
5.5	205	36	140	930	300	8.2	25	30	140	425
8.0	210	30	150	870	310	8.3	25	32	164	---

[a] Average influent concentration for all retention times.

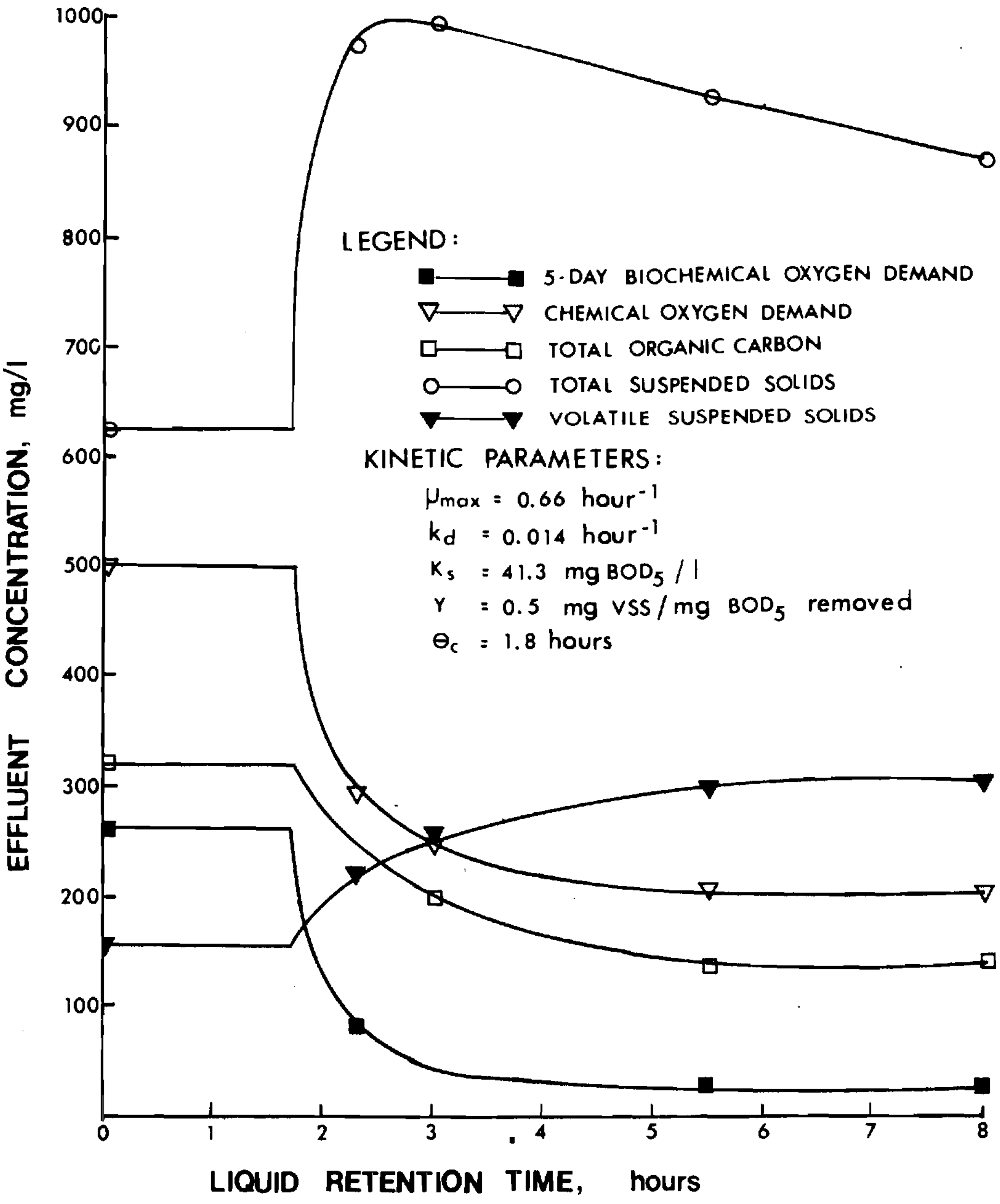


FIGURE 24 AEROBIC BIOLOGICAL TREATMENT OF LEACHATE IN CONTINUOUS CULTURES

PHYSICAL-CHEMICAL LEACHATE TREATMENT

The efforts of several investigators[39-41] have indicated that chemical coagulation and oxidation are not effective procedures for removing dissolved and particularly organic pollutants from leachate. These observations were further confirmed by Karr[42] and Mingledorff[43] using lime and alum supplemented with a non-ionic polyelectrolyte (PURIFLOC N-17). Removals of BOD and COD were generally less than 25 percent. Chemical oxidation with chlorine and permanganate required very high dosages (1000-1200 mg/l) to effect similar removals[39, 42] as was further demonstrated by Boyle and Ham[38]. Therefore, high oxidant requirements coupled with the vast quantities of solids produced during chemical coagulation and in need of further treatment and/or disposal precluded consideration of these methods for treatment of high organic strength leachates.

Separate Treatment of Leachate Residuals

Since inspection of the quality data for effluents from the leachate recycle and/or separate biological treatability studies indicated organic and inorganic residuals which may be unacceptable for ultimate discharge, adjunct investigations on other physical-chemical treatment alternatives for residuals treatment were initiated. The alternatives were narrowed to treatment for organic and inorganic residuals and therefore ion exchange and adsorption seemed plausible choices.

Cation Exchange Treatment of Leachate Residuals -

To ascertain the effectiveness of ion exchange treatment of leachate residuals, some of the effluent from the separate aerobic biological leachate treatment studies was collected and subjected to batch treatment with increasing dosages of cation exchange resin (DOWEX, 50W x 8, H^+ form). As indicated in Table 20 and Figure 25, excellent cation removal was achieved with the divalent

Table 20. CATION EXCHANGE TREATMENT OF LEACHATE RESIDUALS

Effluent analysis	Resin dosage, g/l[a]					
	0	1.3	2.0	5.0	10.0	25.0
pH	8.1	7.6	7.3	6.9	2.9	2.5
Alkalinity, mg/l $CaCO_3$	560	500	430	130	---	---
TDS, mg/l	1040	944	838	734	352	254
Specific conductance µmho/cm	2100	1920	1790	890	960	1360
Calcium, mg/l	29	20	7.4	4.9	4.4	1.0
Magnesium, mg/l	18.8	9.2	4.5	0.2	0.1	---
Potassium, mg/l	100	93	86	32	8.8	2.6
Sodium, mg/l	260	262	240	130	40	15.0
Acidity, mg/l $CaCO_3$	0	105	120	210	400	470
COD, mg/l	185	166	166	---	150	166

[a] DOWEX 50W x 8, H^+ form; one hour exposure time.

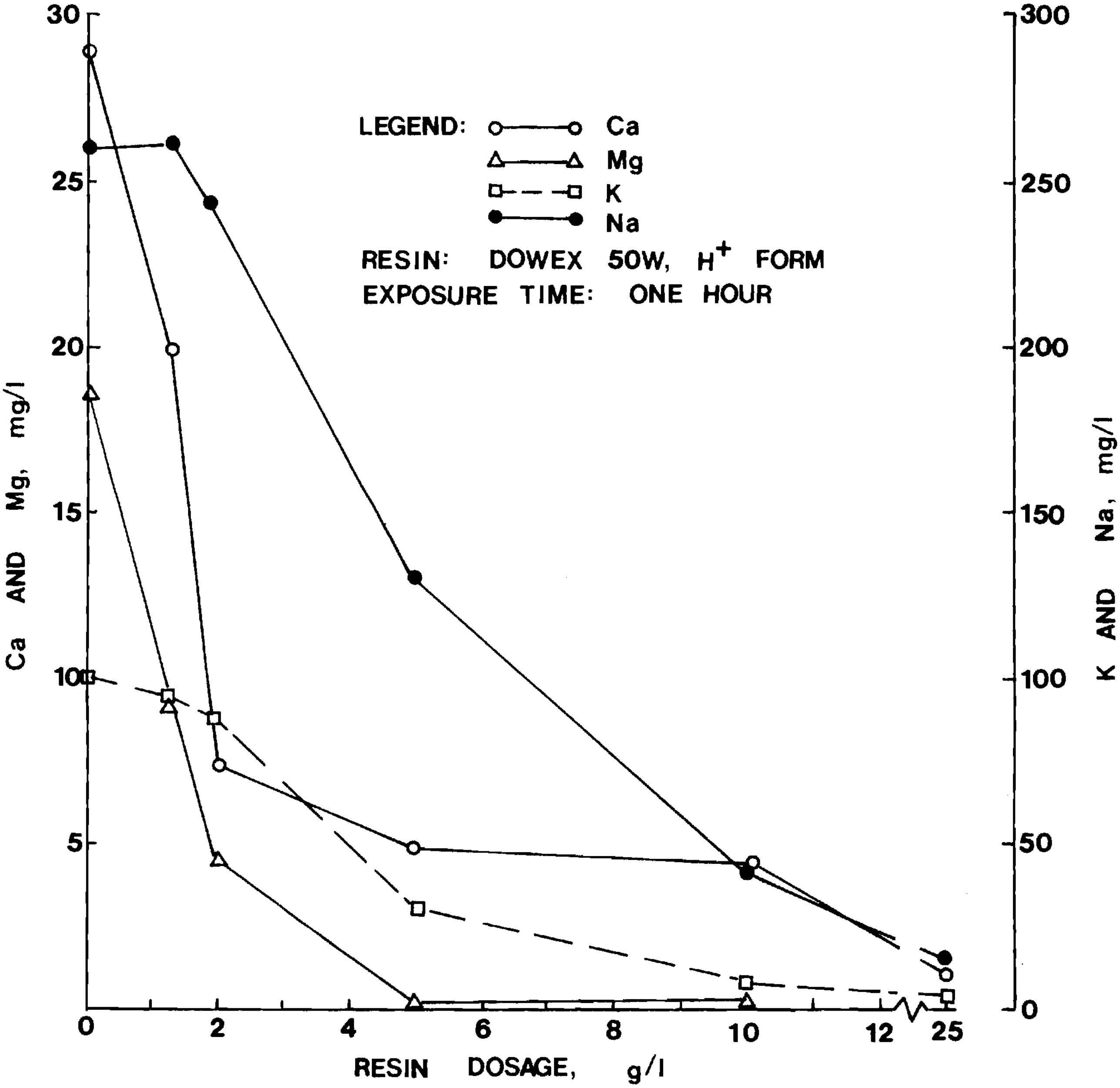


FIGURE 25 REMOVAL OF METALS FROM AEROBIC BIOLOGICAL LEACHATE TREATMENT EFFLUENT BY CATION EXCHANGE

calcium and magnesium preceeding the removal of monovalent sodium and potassium.

In an attempt to monitor overall removal performance, several common parameters were used including total dissolved solids (TDS), pH, alkalinity or acidity, specific conductance and COD. Changes in these parameters are also included in Table 20 and some of these data are displayed graphically on Figures 26 and 27. Analysis of these data indicated that neither alkalinity or specific conductance were good monitors at high resin dosages where the pH had decreased and the acidity increased during exchange as the hydrogen ions were released from the resin. Indeed, specific conductance actually increased despite a steady decrease in total dissolved solids. Therefore, TDS concentration was considered the only acceptable overall cation removal indicator parameter reflecting a 75 percent removal by cation exchange alone. The remaining solids (and COD) indicated a possible need for additional treatment for removal of anions and oxygen demanding constituents.

Mixed Resin Ion Exchange Treatment of Leachate Residuals -

Since anion residuals appeared after the cation exchange studies, additional batch investigations with increasing dosages of both anion and cation exchange resins (equal amounts of DOWEX 50W x 8, H^+ form and DOWEX 1 x 8, OH^- form) were conducted also on some of the effluent from the separate aerobic biological leachate treatment studies. The results of these investigations are included in Table 21 and Figues 28 and 29.

Table 21. MIXED RESIN TREATMENT OF LEACHATE RESIDUALS

Effluent analysis	Resin dosage, g/l[a]					
	0	1.3	2.0	5.0	10.0	25.0
pH	8.5	8.1	7.7	7.5	5.0	5.5
Alkalinity, mg/l $CaCO_3$	520	405	260	100	<5	<5
TDS, mg/l	926	728	613	336	118	82
Specific conductance, µmho/cm	1460	1350	1045	480	13	3
Calcium, mg/l	13.2	6.6	2.5	0	1.2	0
Potassium, mg/l	12.6	6.0	1.1	0.08	0.05	0.05
Sodium, mg/l	198	178	142	46	0.35	0.35
Chloride, mg/l	130	105	95	62	5	<5
Sulfate, mg/l $SO_4^=$	4.0	nil	---	---	---	---
Niltrate, mg/l N	0.4	nil	nil	nil	nil	nil
Total Phosphate, mg/l P	0.1	---	---	---	---	---
COD, mg/l	120	68	---	50	---	---

[a] Equal amounts of DOWEX 50 x 8, H^+ form and DOWEX 1 x 8, OH^- form; one hour exposure time.

The data indicate that all measured ionic impurities were removed, again in order of resin selectivity. The decrease in pH was not as dramatic with the anion resin present and both TDS and specific conductance could be used as a measure of overall performance. However, since some impurities still remained,

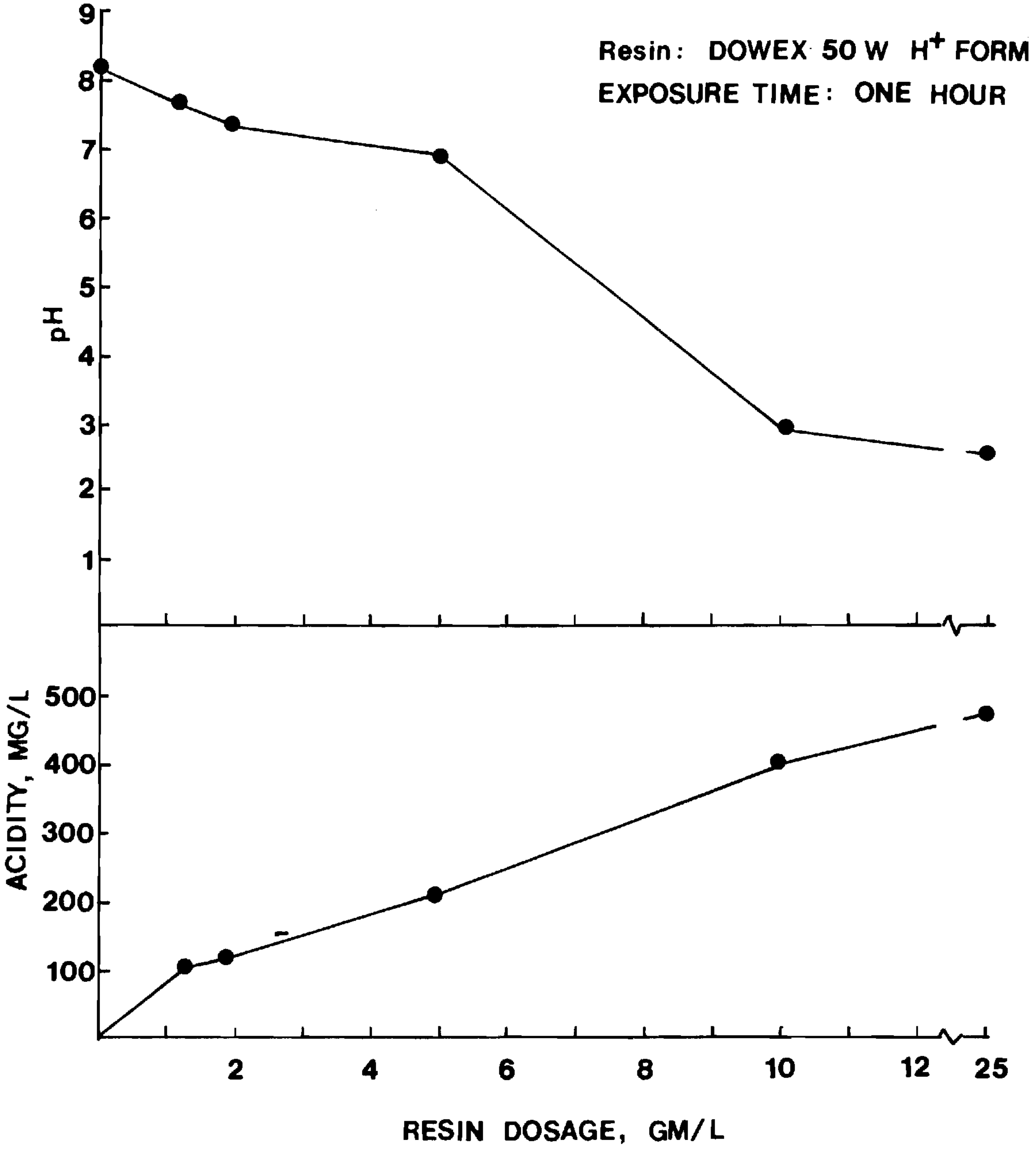


FIGURE 26 EFFECT OF CATION EXCHANGE ON pH AND ACIDITY OF EFFLUENTS FROM AEROBIC BIOLOGICAL TREATMENT OF LEACHATE

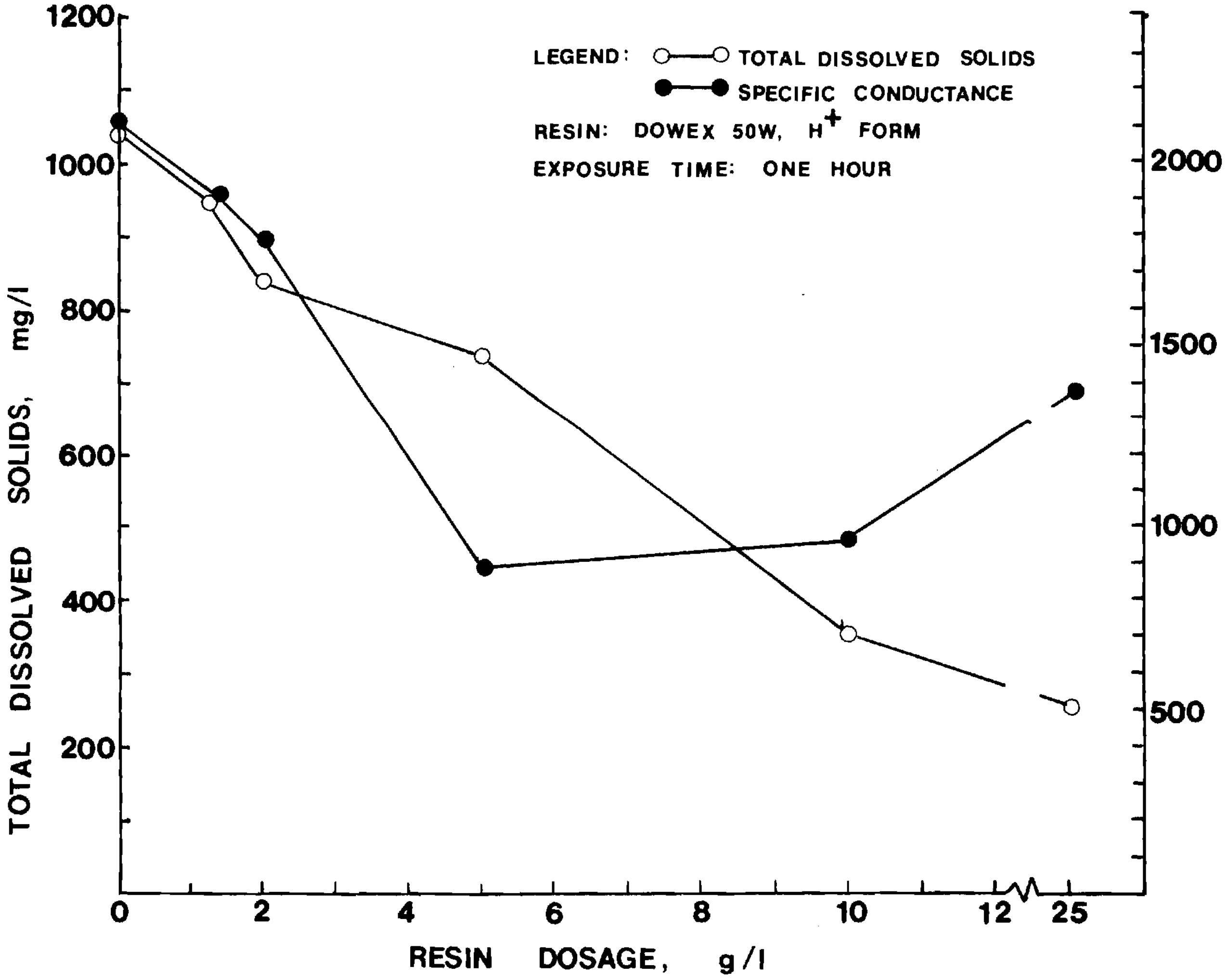


FIGURE 27 EFFECT OF CATION EXCHANGE ON TOTAL DISSOLVED SOLIDS AND SPECIFIC CONDUCTANCE OF EFFLUENT FROM AEROBIC BIOLOGICAL TREATMENT OF LEACHATE

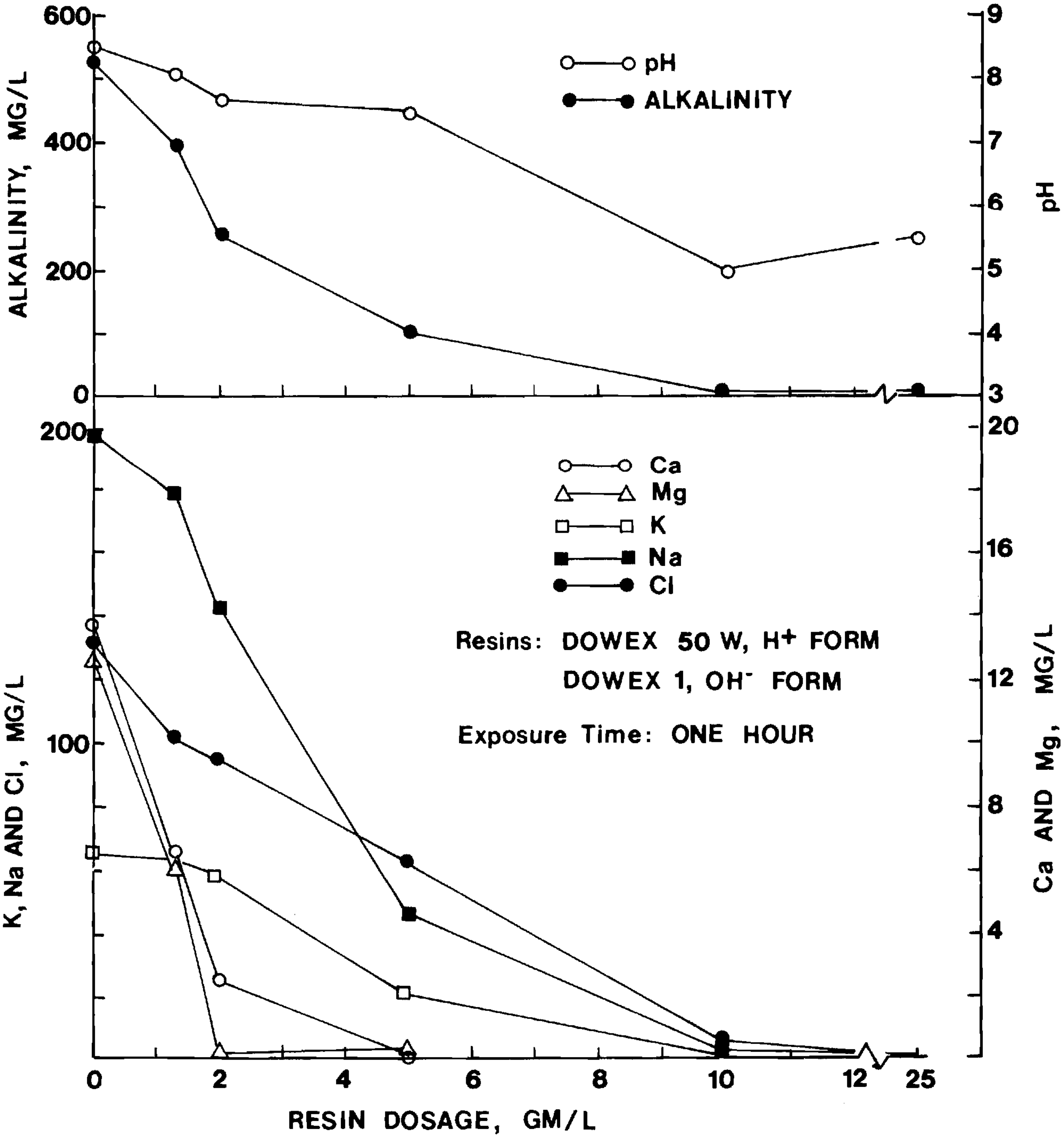


FIGURE 28 MIXED RESIN ION EXCHANGE TREATMENT OF EFFLUENT FROM AEROBIC BIOLOGICAL TREATMENT OF LEACHATE

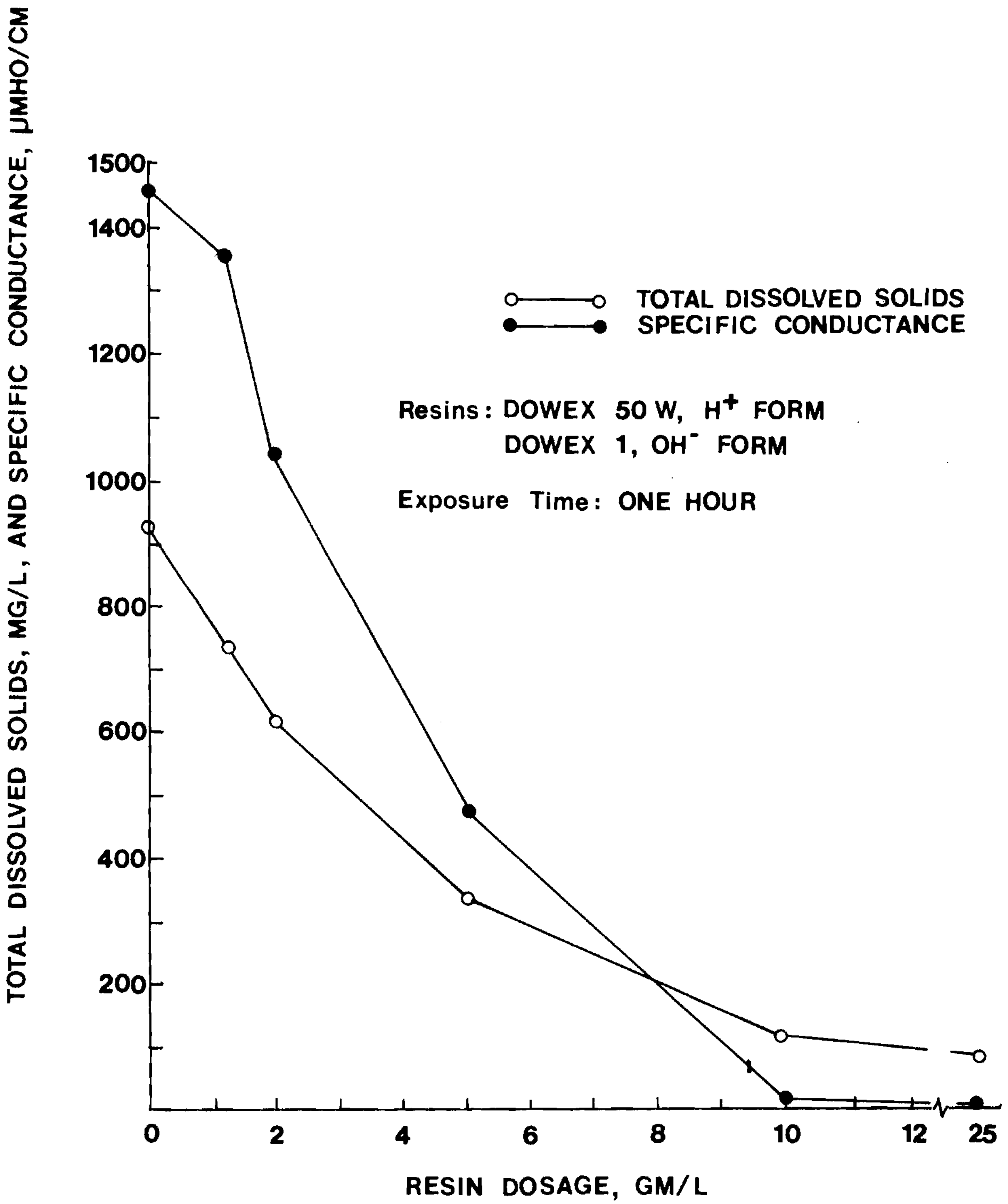


FIGURE 29 EFFECT OF MIXED RESIN ION EXCHANGE ON DISSOLVED SOLIDS AND SPECIFIC CONDUCTANCE OF EFFLUENT FROM AEROBIC BIOLOGICAL TREATMENT OF LEACHATE

TDS was probably the more indicative parameter of actual effluent quality reflecting both ionic and organic residuals. To be used as a predictive parameter, ion exchange could be considered a form of sorption from solution and the equilibrium distribution of ions between resin and solution phases could be expressed by conventional isotherm analysis as used for carbon adsorption in the succeeding section.

Carbon Treatment of Leachate Residuals -

Since organic residuals remained in the effluents from biological leachate treatment, some of the effluent from the separate aerobic biological leachate treatment was also subjected to batch treatment with powdered activated carbon (NUCHAR C-190-N). Predetermined dosages of carbon were added to the effluent, mixed for 30 minutes and then removed by filtration through Whatman No. 2 filter paper. Filtrate analyses yielded the data included in Table 22.

Table 22. CARBON TREATMENT OF LEACHATE RESIDUALS

Effluent analysis	Carbon dosage, mg/l[a] 0	500	1,000	2,000	4,000	10,000
COD, mg/l	184	92	64	55	18.4	18.4
TDS, mg/l	976	850	886	916	980	1160
Specific conductance, µmho/cm	1310	1250	1390	1440	1535	1770

[a] Westvaco NUCHAR C-190-N; 30 minutes exposure time.

The data in Table 22 indicated that COD removals were very good and a Freundlich isotherm and predictive equation could be developed as shown on Figure 30. At initial contact with the effluent, each gram of carbon adsorbed 540 mg of COD. However, as indicated in Table 22, both specific conductance and TDS increased as carbon dosages increased. These increases were attributed to leaching from the carbon and were considered of sufficient significance to warrant additional scrutiny as demonstrated in the following section.

Carbon Treatment After Mixed Ion Exchange Treatment of Leachate Residuals -

To confirm the causes of problems with leaching of impurities during carbon adsorption, additional studies were performed on activated carbon treatment after application of mixed resin ion exchange treatment of some of the effluent from separate aerobic biological leachate treatment. The same exchange resins and carbon were employed as before and the results of these studies were tabulated and are included in Table 23.

As indicated in Table 23, dosages of ion exchange resin were varied and the carbon dosage was maintained at 4000 mg/l which was the concentration previously yielding a constant effluent COD (Table 22). The results of addition of the ion exchange resins were very similar to the previous batch studies

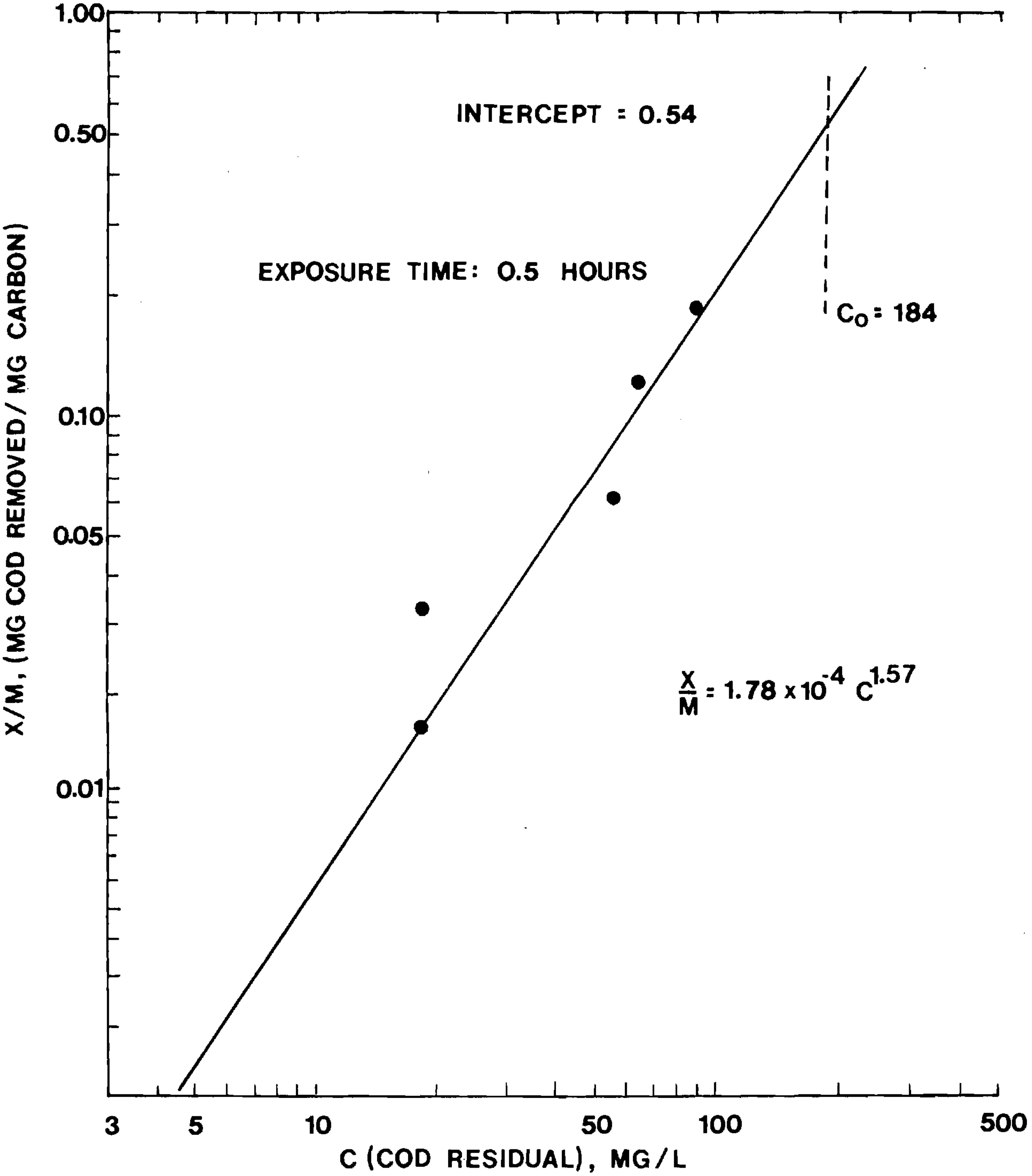


FIGURE 30 THE FREUNDLICH ISOTHERM OF CARBON ADSORPTION ON EFFLUENT OF AEROBIC BIOLOGICAL TREATMENT OF LEACHATE

Table 23. COMBINED MIXED RESIN ION EXCHANGE AND CARBON TREATMENT OF LEACHATE RESIDUALS

Effluent analysis	Resin dosage, g/l[a]					
	0	1.3	2.0	5.0	10.0	25.0
pH, Initial	8.1	8.2	7.8	7.5	4.9	4.9
Final[b]	--	8.6	8.4	8.1	7.1	6.7
COD, mg/l						
Initial	180	125	115	--	57.3	49.2
Final[b]	--	0	0	0	0	0
TDS, mg/l						
Initial	1100	912	864	576	146	64
Final[b]	--	898	862	508	164	294
Specific conductance, µmho/cm						
Initial	1800	1745	1445	768	21	5.5
Final[b]	--	1800	1650	960	274	274
Calcium, mg/l						
Initial	18.0	15.0	8.7	1.8	0.6	0.6
Final[b]	--	11.4	5.1	1.0	0.6	0.8
Magnesium, mg/l						
Initial	16.8	9.0	4.5	0.7	0.1	0
Final[b]	--	8.4	3.1	0.4	0.3	0.34
Potassium, mg/l						
Initial	104	96	84	42	0.4	0
Final[b]	--	104	86	46	8.0	6.7
Sodium, mg/l						
Initial	170	165	155	105	3.3	1.1
Final[b]	--	195	185	120	31	30
Sulfate, mg/l $SO_4^=$						
Initial	0	--	--	--	--	--
Final[b]	--	76	80	80	72	80

[a] Equal amounts of DOWEX 50W x 8, H^+ form and DOWEX 1 x 8, OH^- form; one hour exposure time.

[b] 4.0 g/l NUCHAR C-190-N; 30 minutes exposure time.

(Table 21) with respect to ion removal, a steady decrease in TDS and specific conductance, pH and COD. However, with the addition of carbon after this ion exchange treatment, the COD was removed but significant increases in TDS and specific conductance were noted. Corresponding increases in pH, sodium, potassium and sulfate were also noted together with some reduction in calcium and magnesium after carbon treatment.

Since the treatment of leachate residuals by ion exchange followed by carbon adsorption resulted in unfavorable increases of inorganic dissolved solids apparently originating from the carbon, these studies indicated that if residual treatment is necessary, the treatment sequence should be reversed with carbon adsorption preceding ion exchange. Accordingly, Figure 31 suggests a possible scheme for on-site treatment of leachate from sanitary landfills including both biological and physical-chemical processes. Leachate recycle with possible facilities for neutralization could be substituted in the indicated treatment scheme for separate biological treatment. The ultimate choice and extent of treatment as well as its period of application would be a function of the nature of the leachate and the environmental considerations. With the proposed scheme, effluent of any desired inorganic or organic quality could be achieved simply by manipulating the treatment methods.

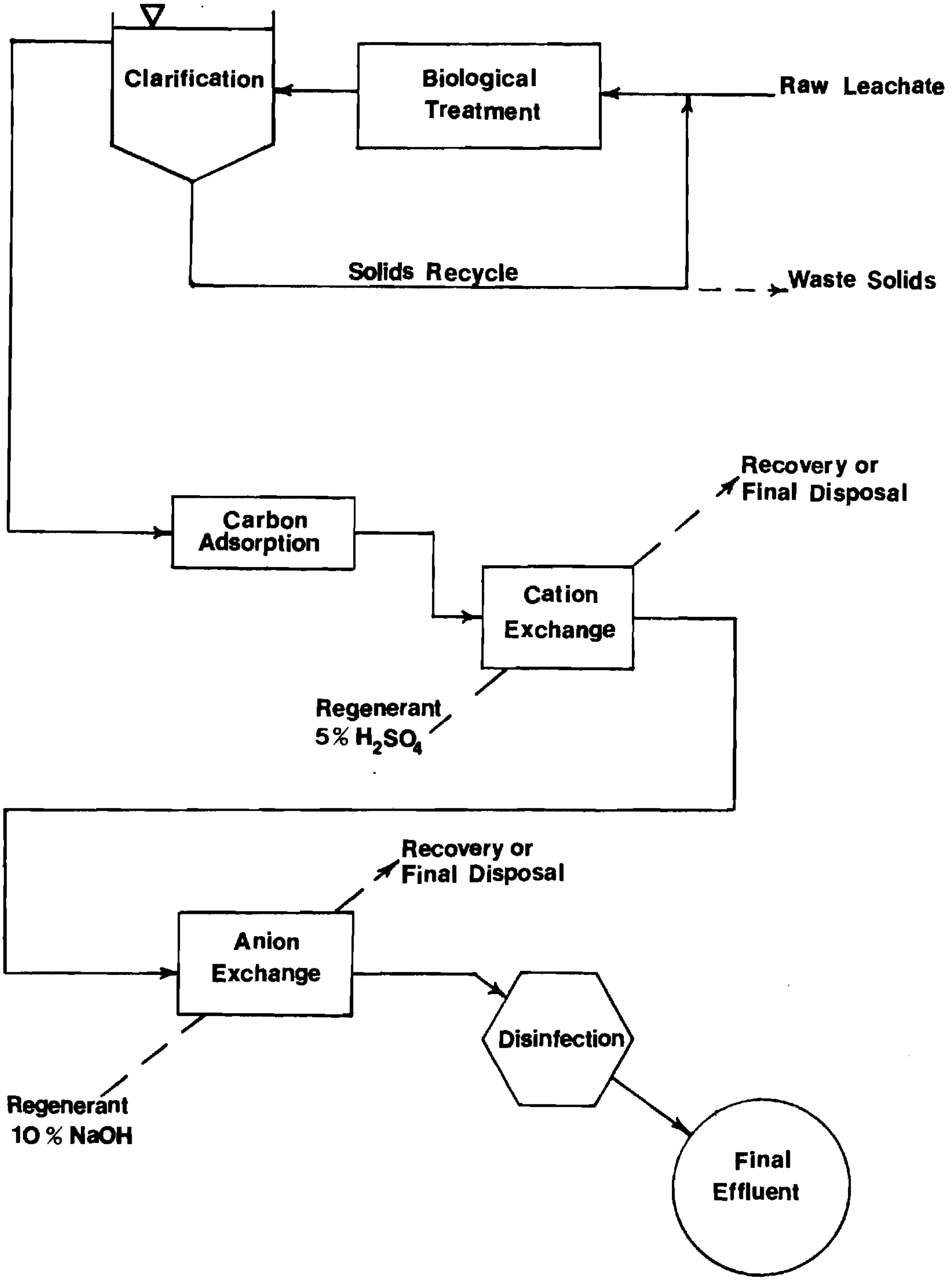


FIGURE 31 POSSIBLE SCHEME FOR ON-SITE TREATMENT OF NON-RECYCLED LEACHATE

SECTION VIII

REFERENCES

1. Fungaroli, A. A., "Hydrologic Considerations in Sanitary Landfill Design and Operation," In: Proceedings of National Solid Wastes Management Conference, University of Houston, 1970, p. 208-217.

2. Proceedings of the Symposium on Ground Water Contamination, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio, Tech. Report W61-5, Public Health Service, U. S. Dept. of Health, Education, and Welfare, 1961.

3. Anderson, J. R., and J. N. Dornbush, "Influence of Sanitary Landfill on Ground Water Quality," Jour. Amer. Water Works Assn., 59, No. 4, p. 457-470 (1967).

4. Hughes, G. M., R. A. Landon, and R. N. Farvolden, "Summary of Findings on Solid Waste Disposal Sites in Northeastern Illinois," Illinois Geol. Survey, Envir. Geology Notes, 45, 25 p. (1971).

5. Hughes, G. M., R. A. Landon, and R. N. Farvolden, "Hydrogeologic Data from Four Landfills in Northeastern Illinois," Illinois Geol. Survey, Envir. Geology Notes, 26, 42 p. (1969).

6. Hughes, G. M., "Selection of Refuse Disposal Sites in Northeastern Illinois," Illinois Geol. Survey, Envir. Geology Notes, 17, 15 p. (1967).

7. Hughes, G. M., R. N. Farvolden, and R. A. Landon, "Hydrogeology and Water Quality at a Solid Waste Disposal Site," Illinois State Geological Survey, Naperville, Illinois, Special Report, 15 p. (1969).

8. Hughes, G. M., R. N. Farvolden, and R. A. Landon, "Hydrogeology of Solid Waste Disposal Sites in Northeastern Illinois," Interim Report to USPHS, 137 p. (1969).

9. Coe, J. J., "Effect of Solid Waste Disposal on Ground Water Quality," Jour. Amer. Water Works Assn., 62, No. 12, p. 776-783 (1970).

10. Calvert, C., "Contamination of Ground Water by Impounded Garbage Water," Jour. Amer. Water Works Assn., 24, No. 2, p. 266-270 (1932).

11. Carpenter, L. V., and L. R. Setter, "Some Notes on Sanitary Landfills," Amer. Jour. Pub. Health, 30, No. 4, p. 385-393 (1940).

12. Davison, A. S., "The Effect of Tipped Domestic Refuse on Ground Water Quality," Jour. Soc. Water Treatment and Examination, 18, Part 1, p. 35-41 (1969).

13. Hopkins, G. J., and J. R. Popalisky, "Influence of an Industrial Waste Landfill Operation on a Public Water Supply," Jour. Water Poll. Control Fed., 42, No. 3, p. 431-436 (1970).

14. Merz, R. C., and R. Stone, "Special Studies of a Sanitary Landfill," Final Summary Report and Third Progress Report to USPHS, 51 p. (1968).

15. Remson, J., A. A. Fungaroli, and A. W. Lawrence, "Water Movement in an Unsaturated Sanitary Landfill," *Jour. San. Engr. Div.*, *Amer. Soc. Civil Engineers*, *94*, SA2, p. 307-317 (1968).

16. Qasim, S. R., and J. C. Burchinal, "Leaching from Simulated Landfills," *Jour. Water Poll. Control Fed.*, *42*, No. 3, p. 371-379 (1970).

17. Qasim, S. R., and J. C. Burchinal, "Leaching Pollutants from Refuse Beds," *Jour. San. Engr. Div.*, *Amer. Soc. Civil Engineers*, SA1, p. 49-58 (1970).

18. Fungaroli, A. A., and R. L. Steiner, "Laboratory Study of the Behavior of a Sanitary Landfill," *Jour. Water Poll. Control Fed.*, *43*, No. 2, p. 252-267 (1971).

19. "Report on the Investigation of Leaching of a Sanitary Landfill," Calif. Water Poll. Control Board, Publication No. 10, 91 p. (1954).

20. Eliassen, R., "Decomposition of Landfills," *Amer. Jour. Pub. Health*, *32*, No. 9, p. 1029-1037 (1942).

21. Salvato, J. A., W. G. Wilkie, and B. E. Mead, "Sanitary Landfill Leachate Prevention and Control," Special Report, New York State Dept. of Health 43 p.

22. Pohland, F. G., and D. E. Bloodgood, "Laboratory Studies on Mesophilic and Thermophilic Anaerobic Sludge Digestion," *Jour. Water Poll. Control Fed.*, *35*, No. 1, p. 11-42 (1963).

23. Dague, R. R., "Application of Digestion Theory to Digester Control," *Jour. Water Poll. Control Fed.*, *40*, No. 12, p. 2021-2032 (1968).

24. Pohland, F. G., General Review of Literature on Anaerobic Sewage Sludge Digestion," Purdue University, Engineering Extension Series No. 110, 1962, 44 p.

25. Pohland, F. G., and K. H. Mancy, "Use of pH and pE Measurements during Methane Biosynthesis," *Biotechnology and Bioengineering*, *XI*, p. 683-699 (1969).

26. Heukelekian, H., and B. Heinemann, "Studies on the Methane Producing Bacteria. II. Enumeration in Digesting Sewage Solids," *Sewage Works Jour.*, *11*, No. 3, p. 436-444 (1939).

27. McCarty, P. L., "Anaerobic Wastes Treatment Fundamentals, Part II. Environmental Requirements and Control," *Public Works*, *10*, p. 123-126 (1964).

28. Mylorie, R. L., and R. E. Hungate, "Experiments on the Methane Bacteria in Sludge," *Canadian Jour. Microbiology*, *1*, No. 1, p. 55-64 (1954).

29. McCarty, P. L., "Anaerobic Waste Treatment Fundamentals, Part III. Toxic Materials and their Control," Public Works, 11, p. 91-94 (1964).

30. Kugelman, I. J., and K. K. Chin, "Toxicity, Synergism and Antagonism in Anaerobic Waste Treatment Processes," In: Anaerobic Biological Treatment Processes, F. G. Pohland (ed.), American Chemical Society, Washington, D.C., Advances in Chemistry Series 105, 1971, p. 55-90.

31. Sawyer, C. N., F. S. Howard, and R. Pershe, "Scientific Basis for Liming of Digesters," Sewage and Industrial Wastes, 26, No. 8, p. 935-944 (1954).

32. Culham, W. B., and R. A. McHugh, "Leachate from Landfills may be New Pollutant," Jour. Envir. Health, 31, No. 6 p. 551-556 (1969).

33. Emrich, G. H., "Guidelines for Sanitary Landfills - Ground Water and Percolation," Compost Science, 13, No. 3, p. 12-15 (1972).

34. Cartwright, L. V., and Sherman, F. B., "Evaluating Sanitary Landfill Sites in Illinois," Illinois Geol. Survey, Envir. Geology Notes, 27, 15 p. (1969).

35. "Development of Construction and Use Criteria for Sanitary Landfills," Interim Report, U. S. Public Health Service, Grant D01-U1-00046, 1969.

36. Hughes, G. W., R. A. Landon, and R. N. Farvolden, "Hydrogeology of Solid Waste Disposal Sites in Northeastern Illinois," Final Report, U. S. Environmental Protection Agency, Publication SW-120, Washington, D.C., 1971, 154 p.

37. APWA, AWWA, APHA, "Stand. Methods for the Examination of Water and Wastewater," 13th Edition, New York, Amer. Public Health Association, 1971, 874 p.

38. Boyle, W. C., and R. K. Ham, "Treatability of Leachate from Sanitary Landfills," In: Proceedings of the 27th Industrial Waste Conference, Purdue University, Engineering Extension Series No. 141, Part 2, 1972, p. 687-704.

39. Ho, S., W. C. Boyle, and R. K. Ham, "Chemical Treatment of Leachates from Sanitary Landfills," Jour. Water Pollution Control Fed., 46, No. 7, p. 1776-1791 (1974).

40. Thornton, R. J., and Blanc, F. C., "Leachate Treatment by Coagulation and Precipitation," Jour. Environmental Engineering Div., Proc. Amer. Soc. Civil Engineers, 99, No. EE4, p. 535-544 (1973).

41. Fernandez, R. W., "The Treatability of Leachate from Shredded Refuse Columns," M. S. Report, University of Florida, 1972, 96 p.

42. Karr, P. R., "Treatment of Leachate from Sanitary Landfills," Special Research Report, Georgia Inst. of Technology, 1972, 73 p.

43. Mingledorff, F. C., "Preliminary Investigations on the Chemical Treatment of Leachate from Sanitary Landfills," Special Research Report, Georgia Inst. of Technology, 1973, 44 p.