



Project Summary

Treatment of Hazardous Landfill Leachates and Contaminated Groundwater

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The objective of this study was to assess pilot- and field-scale application of separate or combined biological and physical/chemical treatment to high-strength hazardous dump site or landfill leachates, extracted sludges and wastes, and land-spilled hazardous substances. Four types of real-world toxic, concentrated, complex wastes served as prototype waste streams: industrial landfill leachate, leachate from an industrial sludge impoundment, forced extract from impounded industrial sludge, and groundwater contaminated with a chlorinated solvent. Techniques evaluated during bench- and laboratory-scale experiments were: dispersed and fixed-film aerobic and anaerobic mixed microbial systems, flocculation/precipitation, ultrafiltration (UF), and reverse osmosis (RO). In general, some physical/chemical pretreatment (liming, floc/settle) was required to obtain high efficiency biodegradation. The biodegradation effluent could be "polished" by UF, RO, or ion exchange when required to meet National Pollutant Discharge Elimination System (NPDES) standards. Soil-based field pilot plants were

constructed and operated to demonstrate sequential aerobic/anaerobic microbial treatment for leachates from two CERCLA-NPL sites and for groundwater contaminated with 1,1,1-trichloroethane (TCA) at a third site. Even in the presence of high concentrations of inorganic salts, organic carbon reductions of 95% to 99% were achieved. The levels of chlorinated solvents extracted in subsurface waters were reduced from 5 mg/L to less than 20 µg/L (greater than 99.6%). The contaminant reductions attained are not the maximum that could be achieved but reflect pragmatic, cost effective treatment levels.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The major objective of this study was to demonstrate pilot- and field-scale treatability of high-strength dump or

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landfill leachates, extracted sludges or wastes, and land-spilled hazardous substances. Two specific treatment types were examined: biological treatment and physical/chemical treatment.

Biological investigations involved dispersed and fixed-film mixed and indigenous cultures for treating representative concentrated hazardous aqueous wastes that could contain both organic and inorganic compounds. The need for sequential process steps was recognized. At the outset, only bench-scale methodologies were undertaken. Various sources of microbial seed were used, and evidence for long-term adaptations and responses were considered of primary importance. Experiments were designed to fill a gap in existing literature that focuses on degradation of single hazardous species and binary or very simple multiple solutes in solution with water. Studies of complex—mixed organic and inorganic—solute systems have not been reported.

Physical/chemical treatment of influent to and effluent from bioreactors was identified as important, but was given a lower priority since it is less novel. Potential physical/chemical treatments included: RO, UF, flocculation/sedimentation, membrane separations, and adsorption. As with biological treatment, feed streams were mixed solutions of multiple organic species and heavy metals in water. Emphasis was placed on high-strength and complex solutions and on the need to inactivate or detoxify toxic metal species, as well as biogenic, biodegradable, and refractory organic compounds. Investigations of biological treatment techniques were marked by two concerns: (1) product water quality suitable for discharge to the environment, and (2) minimum volume and maximum strength of concentrated residues for ease of handling and/or recovery.

During the program, microbial treatment for four types of high-strength, complex aqueous wastewaters was investigated. These included: industrial landfill leachate, leachate from an industrial sludge impoundment, forced extract from impounded industrial sludge,

and groundwater contaminated with chlorinated solvent. Pretreatment by physical/chemical methods was soon shown to be essential to remove colloids and fouling agents. Ultimately, total organic carbon (TOC) reductions of 95% to 99% were achieved, even in the presence of high concentrations of inorganic salts. Acclimated, mixed microbial populations were employed in all cases; no genetically engineered or specifically cultured organisms were used. Aerobic and anaerobic regimes were developed, in sequence, in packed-bed (soil-based) bioreactors.

Biological treatment was evaluated in bench-scale experiments with laboratory column reactors. Much common ground was discovered with respect to organic carbon loading rates, nutrient requirements, buffering, and co-substrates for co-metabolism. Design criteria for scaled-up investigations were derived.

The laboratory column work progressed so well that resources were available to treat three additional hazardous waste liquors treated in pilot plants designed specifically for the purpose. Out-of-door, pilot-scale treatment of landfill leachate was first demonstrated in a pilot unit at the University. Subsequently, sludge extract solution and chlorinated solvent solution were treated in field-site pilot plants built and operated at the actual sites of contamination. In these cases, field performance matched or exceeded bioreactor performance in the laboratory. In conjunction with Enviresponse, Inc., a conceptual design for a transportable, mixed microbial, hazardous organic solute treatment system was developed. In short, the ability to treat complex, organic waste solutions has been demonstrated in the field and is available for application to numerous CERCLA sites.

Physical/chemical treatment is generally necessary for pre- and post-biological reactor processing. Unit processes of this type are required for separation of dispersed oil and particulate matter and for quantitative reductions in heavy metal and inorganic salt

concentrations. Through membrane separations and selective adsorption, it is possible to reduce solute concentrations to levels compatible with direct discharge of treated effluent. Several process technologies in this category were demonstrated to function very effectively in conjunction with biological treatment.

Methods, Discussion, and Results

Leachate Characteristics

For the initial phases of this work, leachate was obtained from a large commercial landfill receiving substantial quantities of industrial wastes. Leachate emanating from this landfill is collected in open basins or lagoons and allowed to settle by gravity. A floating oily layer is removed and stored in drums. The underflow from the collection basin is pumped to API separators for further oil removal. Bulk oil separated by gravity has been found to contain high concentrations of PCBs. The bulk aqueous phase has high residual turbidity consisting of colloids, stable emulsions, and fine particles coated with oil, which must be removed by pretreatment. After pretreatment, the clarified aqueous phase has the following range of properties:

dissolved organic carbon (DOC)	8,000 - 12,000 mg/L
chemical oxygen demand (COD)	23,000 - 30,000 mg/L
total dissolved solids (TDS @ 103°C)	15,000 - 17,000 mg/L

Other typical values include TKN, ammonia-N, and sulfate at 1,450, 1,000, and 3,400 mg/L, respectively. A large number of heavy metals, i.e., nickel, lead, chromium, copper, etc., are present at concentrations above 0.1 mg/L.

Later, effluent was obtained from natural leaching and by forced extraction of an industrial sludge disposal lagoon. Primary and secondary sludges from diverse chemical manufacturing operations had been impounded in the lagoon

for several decades. The natural leachate has the following properties:

TOC	170 - 5,000 mg/L
TDS @ 103°C	2,700 - 4,300 mg/L
TKN	25 - 820 mg/L

Extraction of the sludges with sodium hydroxide solution, at pH 10 to 11, increases these values by factors of 3 to 5. Trace metal concentrations are increased also: aluminum and zinc at 1 to 10 mg/L, and, numerous others at 0.1 to 1 mg/L.

During the period of investigation, a problem of groundwater contamination with chlorinated solvent was suggested for study. Concentrations of 1 to 15 mg/L of TCA had been encountered in otherwise high-quality groundwater. Lesser concentrations of byproduct species were also observed. Based on environmental impacts and groundwater quality criteria, this situation could be defined as involving a high-strength wastewater. A microbial remediation process comparable to the renovation processes for the very high-strength leachates described above was developed, tested in the laboratory, and operated at pilot scale in the field.

Pretreatment

Physical/chemical pretreatment of high-strength leachates with coagulating/flocculating agents produces a minimal decrease in DOC, while reducing turbidity and the level of heavy metals present in the wastewater. Lime gave the best results with the leachate sample involved in this study.

Utilizing lime to a solution equilibrium pH of 12 produced greater than 98% reduction in turbidity. Reductions in dissolved TOC and COD averaged less than 5%. Polyelectrolytes were found to increase the rate but not the final level of turbidity reduction. A pretreatment protocol was developed; it included addition of lime in sufficient quantity, approximately 6 g/L, to achieve a pH of 12 with subsequent floc settlement. The supernatant was decanted and sparged

with CO₂ until the pH was reduced to 9 or less. At this point, the supernatant was decanted and a second recarbonation step was used to decrease final pH to 7.5.

Microbial Treatment

Biochemical Process

Aerobic biological studies revealed that a dispersed mixed microbial population, acclimated to landfill leachate, degraded

80% to 90% of the organic species present in the hazardous industrial waste liquor, with or without the addition of glucose or other nutrients. The decrease in DOC was not due to stripping, evaporation, and/or sorption; it was due to biological oxidation. Biostabilization was rapid. Mixed microbial cultures exhibited a two-rate (diauxic) growth pattern (Figure 1). As signaled by the increase in pH during the first exponential growth phase, it is likely that the mixed culture utilizes the fatty acid fraction of the organic

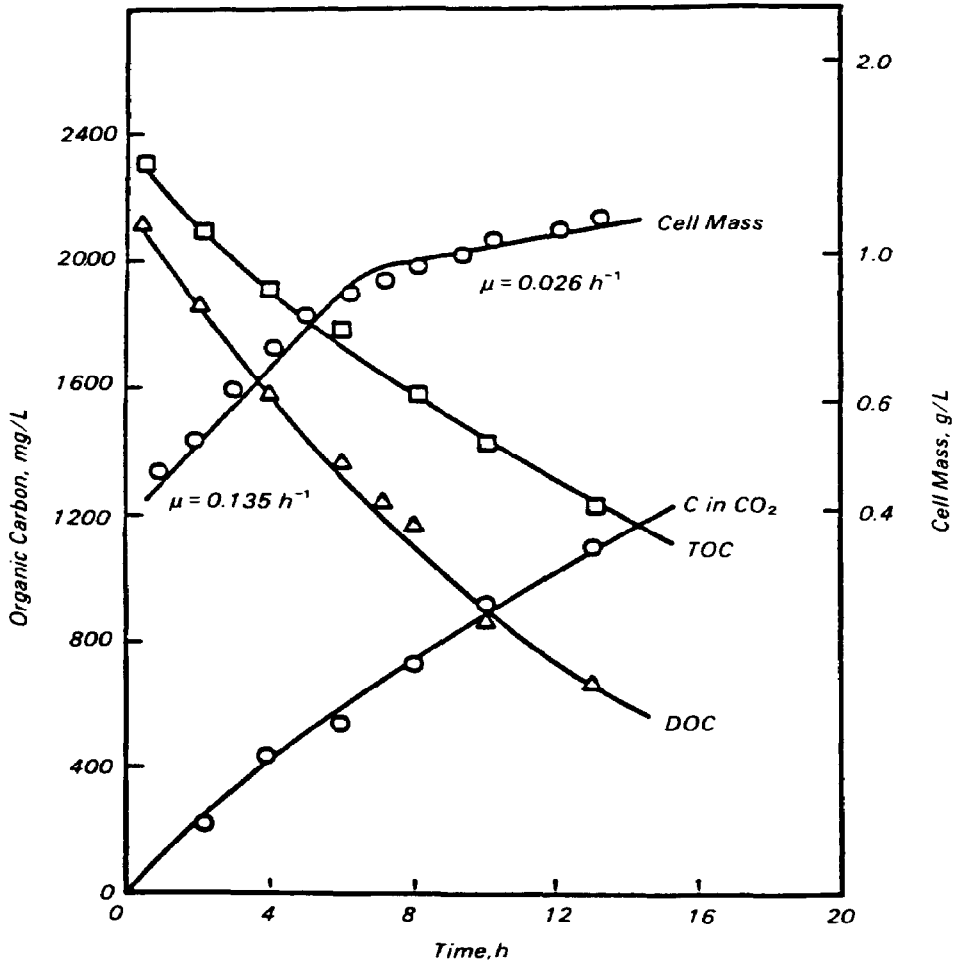


Figure 1. Fate of organic carbon and microbial responses observed during a study with 20% leachate (with pH control @ 7.5 ± 0.1).

solutes in this first phase. Further, it is probable that at least two groups of organisms participate in the biooxidation process. Fatty acid metabolizing organisms have a higher specific growth rate than the other organisms that contribute to the second, lower rate portion of the growth pattern. Good agreement in carbon balances provides clear evidence for biodegradation of the organic species present in the leachate.

Low sludge yield was observed in this study; this implies a reduced sludge problem associated with aerobic treatment. Oxygen uptake rates, as reflected in the volumetric flow of air-per-reactor volume, were quite nominal. If it is assumed that microbial maintenance requirements are negligible, as has been reported frequently for wastewater systems, it is possible to quantify the role of co-metabolism in the biological oxidation of anthropogenic compounds. The possibility of oxidative assimilation (nonproliferation) is ruled out because of the quantitative evolution of carbon dioxide; increase in cell mass and protein content were not measured. The ability of the acclimated population to utilize organic carbon and other nutrients solely

from the leachate further improves process prospects. It was possible to treat highly concentrated waste liquor, i.e., up to 10,000 mg/L of organic carbon. The absence of highly fluctuating DOCs indicates a stable and well-acclimated microbial population.

Anaerobic biological studies demonstrated a DOC reduction of 64% for a culture grown on leachate and a reduction of 69% for a culture selected for the degradation of acetate, propionate, and butyrate. Specific DOC utilization rates of 0.15 and 0.21 day⁻¹ were observed for the leachate and these volatile fatty acid digesting cultures, respectively. Cell growth was not observed, to any significant extent, during these batch experiments. Leachate effects on the cultures were studied through examination of individual volatile fatty acids in the course of the experiments (Figure 2). Large concentrations of acetate were accumulated before overall removal was observed. The butyrate profile demonstrated responses similar to that of acetate removal.

Propionate and isobutyrate were more difficult to remove, as both left an appreciable amount of unmetabolized

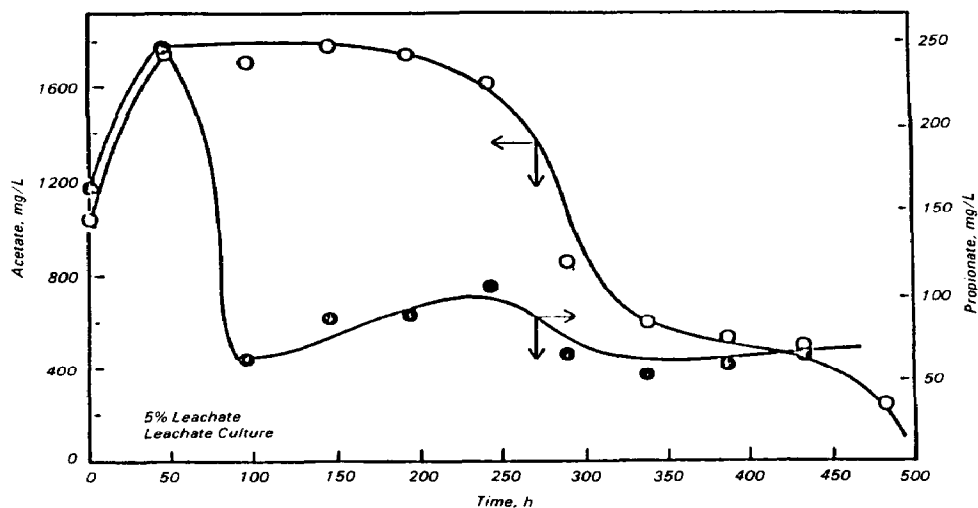


Figure 2. Acetate and propionate concentrations as functions of batch reaction time.

acid. However, their concentrations were small relative to acetate and butyrate. Acetate and butyrate are the major fatty acids contributing to methanogenesis. Also, the fraction of the nonvolatile fatty acid contaminants in the leachate that were converted to volatile fatty acids by the acid formers ended up primarily as acetate, with a small fraction converted to butyrate, propionate, and isobutyrate. Reactor failures were encountered in studies with 20 volume-% leachate. These failures were probably the result of overloading the system with volatile fatty acids. At leachate concentrations of 5% and 10%, no toxicity problems due to nonvolatile fatty acids were observed. Methane was produced at levels of 0.95 to 0.99 L/g (m^3/kg) DOC removed.

The data from this study clearly indicated that aerobic and anaerobic biological treatment can be used in conjunction to stabilize organic compounds found in high-strength hazardous waste residues.

Microbiology of Chlorinated Hydrocarbons

This phase examined mixed anaerobic population degradation of the haloorganic compounds dichloromethane (DCM), 1,1-dichloroethane (DCA), and TCA. Half-kill doses, determined from batch experiments, defined a relative degree of toxicity for each of the compounds. The microorganisms exhibited great tolerance for DCA; there was no apparent inhibition at concentrations up to 35 mg/L.

Acclimation studies with TCA demonstrated that continued periods of zero gas production do not necessarily reflect the death of the organisms. Reactors dosed with 2 and 4 mg/L recovered after 20 days of zero gas production. After this lag period, daily gas production was greater than or equal to control reactors. The overall acclimation period was 33 days, less than half the acclimation period of 10 wk cited in reports of previous work. However, acclimation periods tend to vary greatly for anaerobic seed cultures.

Studies with separate anaerobic populations indicated that the methanogens were most likely responsible for degradation of the chlorinated compounds considered.

Microbial Reactor Design

Soil-based sequential aerobic/anaerobic microbial degradation was investigated as a potential onsite or *in-situ* treatment process. Laboratory soil column experiments were carried out for initial evaluation of the proposed process using three different contaminant streams and several soil types.

Treatment of landfill leachates achieved reductions in DOC in excess of 90% (Figure 3). Influent leachate-derived organic carbon (LOC) concentration, organic carbon removal, effluent pH, and long-term system permeability are interrelated. Microbial acclimation periods increased in length with increased influent leachate concentration. Increasing influent LOC concentration resulted in greater overall removal efficiency for DOC. In addition, increased influent LOC concentration is associated with reduced incidence of plugging, allowing the system to operate more closely to target volumetric flux.

Treatment of TCA using the soil-based microbial system, operated under anaerobic conditions, resulted in quantitative removal of solvent. Influent concentrations of 20 mg/L corresponded to effluent concentrations of less than 20 μ g/L. Failure to observe any breakthrough phenomena, over long periods of operation, confirmed that sorption onto soil constituents was not controlling TCA removal. Gas evolution rates and gas analyses indicated that methanogenesis was the most probable rate-controlling step.

Microbial Process Demonstration

Positive results from laboratory soil column experiments were followed by the

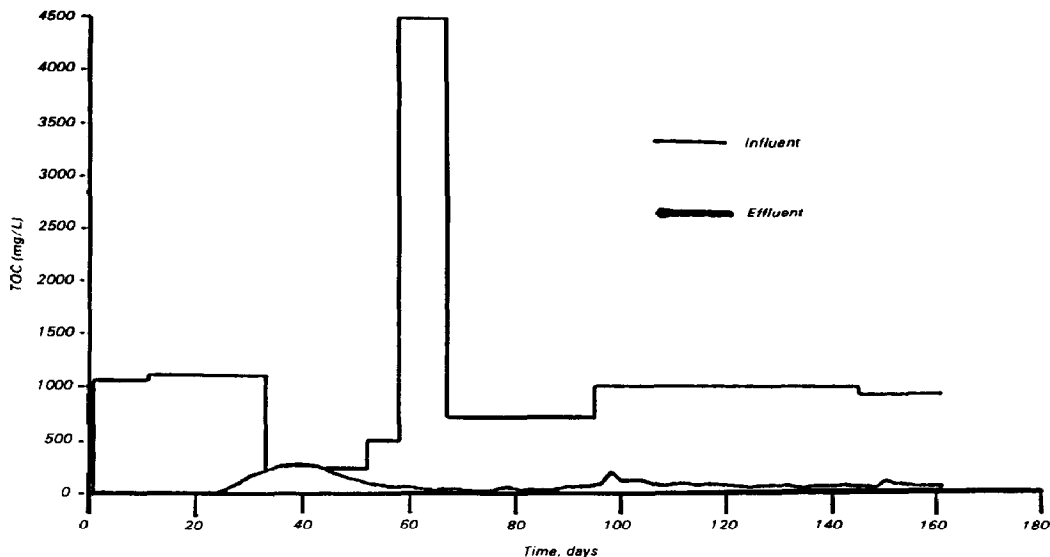


Figure 3. Typical influent and effluent responses for sequential aerobic/anaerobic soil-based microbial treatment.

design, construction, and operation of three field pilot plants to demonstrate the process feasibility for large-scale applications. One of the pilot plants was located at Rutgers and the other two at the actual sites of differing contamination problems.

The first pilot plant in the series consisted of six self-contained lysimeters (bioreactor columns packed with soil), 2 ft in diameter and 6 ft in depth. These units were implanted in the ground, at a location on campus, and operated in simulation of site conditions. Pretreated leachate from a CERCLA-NPL industrial landfill was treated. TOC mineralization to CO_2 and CH_4 was obtained with a single-pass efficiency of 90% to 97%. Operation was carried out for two consecutive spring-through-fall operating periods of approximately 160 days each. Laboratory results were readily transferable to field operation.

The second pilot plant was designed to demonstrate *in situ* sludge extraction coupled with soil-based microbial treatment of recovered extract; it was constructed and operated at the sludge disposal site for 140 days. The cleanup process consisted of two steps in

sequence (Figure 4). The first step was removal of contaminants from mixed primary and secondary industrial sludges through *in situ* extraction with aqueous sodium hydroxide. Extractant solution was injected into the sludges through well-points or applied to the surface through a perforated pipe distribution network. Extract was recovered by means of two wells screened near the bottom of the sludge deposits. The results of system operation indicated that as much as a 15-fold increase in removal rate, relative to natural processes driven by infiltrating rainfall, could be obtained through controlled alkaline extraction. An additional 4-fold increase in the rate of site renovation can be obtained through increased hydraulic flux through the sludges.

In this second pilot plant, extract recovered from the sludges was treated to remove TOC with a soil-based, sequential aerobic/anaerobic microbial reactor. Treatment occurred onsite, immediately adjacent to the extraction unit. A diverse, mixed microbial population was developed in the soil system. Neutralized extract was applied to the surface of the treatment bed and

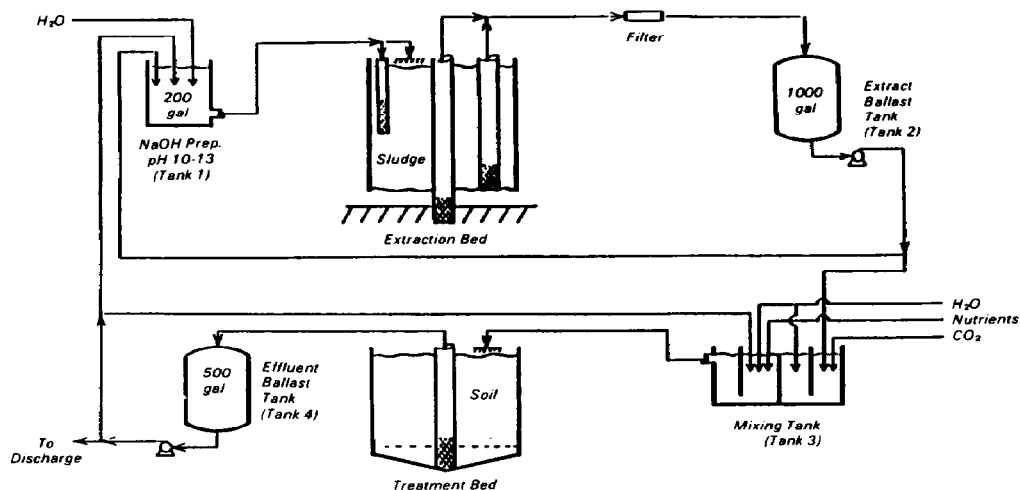


Figure 4. Pilot plant process flow diagram.

allowed to percolate through the soil column. Aerobic and anaerobic microbial populations metabolized organic contaminants to CO_2 and CH_4 . Treatment efficiencies in excess of 95% were observed.

A third pilot plant, designed to demonstrate the treatment of groundwater contaminated with TCA, was operated at the site of a solvent spill. This pilot plant consisted of two self-contained lysimeters, 3 ft in diameter and 6 ft in depth. The soil packing employed was excavated from the site. Influent to the two lysimeters was contaminated groundwater, recovered from a monitor well, with TCA concentrations of 5 to 20 mg/L. Reactors were operated under entirely anaerobic conditions. At steady state, effluent TCA concentrations were less than 20 $\mu\text{g/L}$.

Sorption and Extraction

Sorption and extraction are processes that influence the distribution of solutes between separate phases. The absolute performance of these processes is dictated by thermodynamic equilibria. Thus, the ultimate distribution of a solute between otherwise homogeneous phases (steady state in batch contact circumstances) is that at which the chemical potential of the solute is the

same in the several phases. As used in this study, sorption is the exchange of dissolved organic solutes between aqueous solutions and a variety of solid substances. The direction of exchange is dictated by thermodynamic considerations, and the rate is influenced by physical transport and the strength of binding forces. Extraction is the removal of constituents from a solid phase by contact with solvent. Distribution and rate are controlled by thermodynamic equilibria and, also, by physical barriers to exchange.

Granular Activated Carbon

The time required to approach thermodynamic equilibrium must be determined experimentally for each carbon (GAC) and organic solute system combination. In general, greater than 95% of equilibrium sorptive capacity is attained in several days. However, it may take much longer periods to reach final equilibrium because of slow diffusion in carbon particle pores and/or slow changes in surface binding states.

Pretreatment with lime to remove oily phases from otherwise aqueous leachate was necessary before the determination of carbon sorption isotherms. Interactions of GAC with leachate were independent

of the primary pretreatment process. Control of pH through recarbonation with CO_2 , air stripping, or sulfuric acid addition had little or no detectable effect on subsequent sorption of organic solutes onto GAC. The treatability of two leachate samples (EPA #01 and EPA #02) with GAC was identical.

The relationship between equilibrium organic sorbate loading and equilibrium solute concentrations, in multiple solute systems, is dependent on initial conditions. Type A isotherms were obtained for full-strength leachate and varying masses of GAC. Type B_n isotherms were constructed with a constant mass of GAC; the subscript "n" represents the ratio of carbon-mass-to-volume of full-strength leachate. Finally, Type C isotherms used data for a fixed mass of GAC and varying leachate dilutions. With this conceptual separation of driving forces for sorption, it was possible to construct a mechanistic description for the process within classes (types). Plots of equilibrium loading versus equilibrium concentrations of TOC for these three types of isotherms can be used for leachate sample characterization.

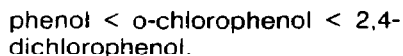
There is a weak pH effect on sorptive capacities of GAC for TOC in leachate. It appears desirable to carry out measurements and treatment at near-neutral pH rather than at higher pH levels.

Soil

Soil is an active sorbent because of organic matter (humic) and clay fractions. These fractions interact with organic solutes in groundwater and infiltrating surface water to exchange organic substances and dissolved inorganic species. Thus, the presence of organic contaminants in groundwater and soil water infers the distribution of these substances in stable or transient equilibria. As an example of the role of the organic carbon fraction, the mass of 2,4-dichlorophenol sorbed onto a loam containing 4.7% organic matter has been observed to be approximately 5 times greater than the mass sorbed onto a

sandy loam containing 0.84% organic matter.

The sorption of a series of phenolic compounds onto a loam increases in the order:



This order is preserved for the sorption of these solutes onto cupric and calcium salts of commercially available humic acid, which is a primary component of soil organic matter.

The mass of TCA sorbed onto a loam containing 4.7% organic matter was observed to be 2.5 times greater than the mass sorbed onto a sandy clay loam containing 1.4% organic matter. In the presence of a mixed solvent (10 volume % ethanol), the mass of TCA sorbed onto a loam decreased by 40%, as compared to the single solute in aqueous solution.

Solvent Extractions

The presence of components of a landfill leachate solute matrix altered the distribution of phenol and o-chlorophenol between a bulk organic phase and the aqueous wastewater phase. The alteration was more pronounced in experiments involving phenol than in experiments in which o-chlorophenol was the distributed solute. Since phenol favors the aqueous phase, it is reasonable to expect solute-salt interactions in the aqueous phase to produce a larger change in the distribution of phenol than in the distribution of o-chlorophenol, which favors the organic phase. The components of a leachate solute matrix that contribute most to the salting-out of phenol appear to be the larger inorganic anions, i.e., CO_3^{2-} and SO_4^{2-} . High concentrations of acetic, propionic, and butyric acids in leachate also contribute to observed changes in phenol as a result of solute-salt interactions in the aqueous or bulk organic phases.

Membrane Separations

Thin semi-permeable films become important in the separation of dissolved

species, especially from aqueous solution. Membranes have been used for the production of process water and/or drinking water from sea water and natural brines. In addition, membranes have been adopted for commercial separations and concentration of products and valuable process constituents such as catalysts and recyclable intermediates. Membrane techniques have a role to play in high-strength wastewater renovation.

Reverse Osmosis

Several hazardous wastewaters, e.g., industrial landfill leachates, lagoon wastes, pesticide wastewaters, and synthetic organic manufacturing effluent were successfully renovated with an RO system. Moderate and high-strength industrial landfill leachates, pretreated by physical and chemical methods and treated biologically, were separated and concentrated in semi-batch, steady-state, and unsteady modes of operation. Physical/chemical pretreatment with lime was found necessary to remove suspended and colloidal matter, heavy metals, and dispersed oil phases in the raw leachate; these constituents can cause membrane fouling and rapid flux loss.

All physically, chemically, and biologically treated leachates were separated to produce clear, turbidity-free permeates. Eight landfill leachate experiments were conducted over extensive periods of time. For example, high-strength, pretreated leachate EPA #07 with conductivity of 30,000 micromho/cm, TDS of 27,000 mg/L, and TOC of 6,700 mg/L was separated and concentrated in a semi-batch, unsteady experiment. At room temperature and moderate feed pressure (approximately 400 psig), inorganic solute rejection exceeded 95%. During feed concentration in the retentate (concentrate) recycle mode, operation was limited to feed TDS concentrations of less than 30,000 mg/L. Flux became unacceptably low and pressure had to be increased to overcome the high osmotic pressure of the feed. In addition, concentration polarization appeared to

occur at high recoveries accompanied by high-feed TDS concentrations. When feed was too concentrated, solutes may have exceeded solubility limits and caused additional deposition of membrane surfaces.

Moderate-strength leachates were renovated to a greater extent. In a study with a recovery of 75% at 170 hr of operation, initial and final rejections for inorganic species were in excess of 99%. Initial TOC rejection was low but increased, with time, to over 70%. This phenomenon of increasing TOC rejection is explained by the fact that the more permeable solutes were purged from the system early in the process, thus leaving the feed with organic species that were rejected continually at higher efficiencies as time/recovery advanced. No fouling was observed in any of the moderate-strength leachate studies.

Biologically-treated landfill leachate was renovated successfully. TDS and conductivity rejection were in excess of 98%; maximum TOC rejection was 94%. Bulk permeate TDS and TOC concentrations of 47 and 14 mg/L respectively, were obtained at recoveries of over 60%. No fouling was observed in this study; flux averaged 0.29 m³/m²d.

Lagoon sludge extracts, resembling industrial landfill leachate, were also treated with an RO process. In a steady-state experiment, conductivity and TDS rejections averaged 97% and 99%, respectively; TOC rejection was 79%. A slight increase in rejection and decrease in flux appeared evident, possibly because of the formation of a nonfouling gel layer.

Ultrafiltration

Results of UF experiments indicated that a high proportion of the organic matter in leachate samples had a molecular weight below about 500. This agrees well with results in the literature from similar experiments. For raw leachate and lime-treated leachate, approximately 80% and 85% of the organic solutes had a molecular weight below 500, respectively. These results suggest that leachate samples contain

primarily synthetic organic compounds and lesser amounts of biogenic matter, such as proteins and humic and fulvic substances. These observations were expected, since the leachate was generally of an industrial rather than a biochemical origin.

Since most organic solutes in leachates studies do not pass the 500 MW membrane, the utility of UF for efficient removal of organic contaminants is subject to question. At best, UF can be used as a pretreatment process to remove high molecular weight compounds that interfere with other treatment technologies, i.e., RO.

This UF study confirmed the pretreatment study results; lime treatment did not remove a significant mass of the organic solutes from industrial landfill leachate samples. The UF investigation suggested that lime treatment may remove organic species with molecular weights greater than 10,000; these represent a relatively small fraction of the total organic matter present in solution.

Although membrane UF may not be effective for removing organic matter of low molecular weight from leachate, it is a valuable tool for evaluating the nature of a leachate sample and the effectiveness of other pretreatment processes. UF is not an effective treatment technique, since it does not eliminate any of the low molecular weight organic matter that is destroyed efficiently by biological renovation.

Conclusions

Several important conclusions can be drawn based on the study results. These are summarized in the same order as the sections of this summary.

Pretreatment

- Treatment of aqueous wastes with significant concentrations of dispersed or suspended phases—high levels of turbidity—by membrane or biological techniques either was not possible or inefficient without pretreatment to produce a homogeneous aqueous phase.

- Lime addition to pH 12, followed by flocc separation and recarbonation to pH 7 (addition of CO₂), was an effective pretreatment process that resulted in greater than 98% reduction in turbidity.

Microbial Treatment

- Aerobic mixed microbial populations degraded a significant fraction of the dissolved organic solutes present in some leachates (80% to 90%), while being inherently limited in degrading dissolved organic solutes in other leachates (< 50 %).
- Aerobic mixed microbial populations may require a readily biodegradable co-substrate to mineralize anthropogenic compounds (co-metabolism) and may exhibit two distinctive growth regimes.
- Anaerobic mixed microbial populations degraded a significant fraction of the dissolved organic solutes present in some leachates (60% to 70%).
- Anaerobic mixed microbial populations degraded several chlorinated hydrocarbons present in aqueous solution from initial concentrations up to 20 mg/L to final concentrations below the detection limit of 20 µg/L. Half-kill doses and toxicity inhibition levels were determined.
- Methanogens were most likely the group of organisms responsible for degradation of the chlorinated compounds considered.
- Soil-based sequential aerobic/anaerobic microbial degradation mineralized between 90% and 99% of the dissolved organic solutes present in all leachates tested. Carbon dioxide and methane were principal end products.
- Soil-based anaerobic microbial degradation reduced TCA in contaminated groundwater from 20 mg/L to less than 20 µg/L. Gas

production rates and gas composition indicated that methanogenesis was the controlling process.

- Three pilot plants were designed, constructed, and operated in the field to demonstrate process feasibility for the following wastes:
 - (a) An industrial landfill leachate was treated using a soil-based sequential aerobic/anaerobic microbial process with single-pass organic destruction efficiencies between 90% and 97% .
 - (b) *In-situ* sludge extraction was coupled with soil-based microbial treatment of the re-covered extract to demonstrate controlled, rapid removal and mineralization of extractable organic species, with treatment efficiencies greater than 95%.
 - (c) TCA in groundwater was reduced from 5 to 20 mg/L to less than 20 µg/L, utilizing anaerobic soil-based microbial treatment.

Pilot plants (a) and (b) treated wastes from CERCLA-NPL sites. Pilot studies (b) and (c) were conducted on site.

Sorption and Extraction

- Activated carbon adsorption was inefficient when dispersed oily phases were present in the aqueous waste.
- Relationships between equilibrium, organic loading and equilibrium concentrations were dependent on initial conditions.
- The mass fraction of organic matter strongly influenced the sorptive capacity of a soil.
- A landfill leachate solute matrix can significantly alter aqueous/organic phase solute partitioning.

Membrane Separations

- RO was effective for removing inorganic species after biological treatment.
- UF was an effective tool for characterizing leachates, but was of limited value for treatment because a majority of the solutes present had a molecular weight less than 500.

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 The complete report, entitled "Treatment of Hazardous Landfill Leachates and Contaminated Groundwater," (Order No. PB 89-124 648/AS; Cost: \$28.95, subject to change) will be available only from:
 National Technical Information Service
 5285 Port Royal Road
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