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# Project Summary

# Critical Review and Summary of Leachate and Gas Production from Landfills

Frederick G. Pohland and Stephen R. Harper

**A Cooperative Agreement between the Municipal Environmental Research Laboratory and Georgia Institute of Technology was established in 1983 to provide an evaluation of the state-of-the-art in municipal waste, landfill leachate and gas management. Accordingly, summaries of full-scale and experimental-scale data on leachate and gas characteristics, control methods, and the performance of a number of biological and physical-chemical treatment alternatives have been developed and are presented together with recommendations for process implementation and future research.**

***This Project Summary was developed by EPA's Hazardous Waste Engineering Research 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

In the United States, sanitary landfills are the most frequently employed method for disposal of solid waste. Unfortunately, sanitary landfills remain poorly understood and are often loosely managed. During the last decade, the problem of leachate and gas in landfills received major attention, particularly in terms of environmental consequences associated with their migration during conversion of waste constituents. These concerns led to a variety of developments for control, including the concepts of leachate containment and total landfill isolation. Various techniques have been proposed and implemented for the treatment and disposal of landfill gases and leachates.

The purpose of this project was to provide a review and summary of the nature of leachate and gas production at landfills, and to couple this with a concomitant inventory of available techniques for containment, control and treatment. The review begins with a brief historical perspective of hazards associated with the migration of leachate and gas from landfill disposal sites. Factors affecting the quantity and quality of landfill leachate and gas are then addressed, followed by processes used or advocated for leachate and gas treatment. Hence, investigations into activated sludge, aerated lagoons, trickling filters, biodisks, anaerobic contact processes and *in situ* leachate recycle technologies as well as coagulation, precipitation, chemical oxidation, disinfection, adsorption, ion exchange, and reverse osmosis processes in either separate or combined configurations are detailed. Finally, methods for the ultimate disposal of leachate and gas are addressed, including discharge to municipal wastewater treatment plants, land application, and energy recovery.

## General Conclusions

The development of rational and economically sound solutions to landfill leachate and gas migration hazards encompasses the analysis of several major factors. A given landfill in its natural setting will affect and be affected by numerous hydrologic and geologic circumstances that must be properly recognized and managed to minimize human and environmental risks. In particular, leachate and gases formed as a consequence of external moisture inputs and waste degradation may migrate into the surrounding environment, contaminate drinking water supplies, and create other environmental hazards.

Logically, effective management of gas and leachates at susceptible landfill sites begins with containment; i.e., installation of "impermeable" barriers augmented by sufficient drainage, venting, and collection systems to handle the inevitable production of leachate and gas. Following their generation and capture, leachate and gas must be treated and disposed of in an environmentally and economically sound manner.

As shown in Figure 1, a number of options are available for leachate and gas management prior to ultimate disposal. Before discharge onto land or into a publicly owned treatment works (POTW), landfill leachate and gas require treatment by biological and/or physical-chemical methods, some of which are successfully proven, while others have limited applicability. Moreover, it is widely recognized that the quantity and quality of landfill leachate and gas are influenced by numerous variables, resulting in a diversity of relative treatment efficiencies. Some generalizations on the advantages and disadvantages of these processes are outlined in the remainder of this section of the project summary.

## Leachate Treatment and Process Performance

When considering external treatment of raw leachate for removal of biodegradable contaminant fractions, biological treatment systems are significantly superior to physical-chemical techniques, as indicated in the performance summary in Table 1. If given sufficient residence time ($\Theta_c$), biological processes typically achieved up to 99% organics ($BOD_5$ and COD) removal and yielded effluents having COD concentrations less than 500 mg/1. Generally, the aerobic treatment processes were capable of 90% $NH_3-N$ conversion and yielded effluents containing less than 10 mg/l $NH_3-N$ for $\Theta_c$ >10 days. Also, for $\Theta_c$ of 6 to 10 days, the limiting range for aerobic carbonaceous material conversion, 60% to 80% nitrification was generally achieved.

Like the aerobic biological processes, anaerobic biological processes have been successfully applied for treatment of raw leachates. Typically, COD and $BOD_5$ removals of 90% were achieved at residence times longer than 10 days and gas production from anaerobic processes ranged from 0.4 to 0.6 $m^3$/kg COD or 0.8 to 0.9 $m^3$/kg $BOD_5$ destroyed.

Aerobic biological processes were fairly efficiently applied to removal of heavy metals. Removal efficiencies were best with zinc, iron, cadmium and manganese; followed by chromium, lead and nickel. Zinc, chromium, and iron were removed at efficiencies greater than 90% during anaerobic treatment; copper, lead, cadmium, and nickel removals were on the order of 50% to 90%. Removals of alkaline earth metals were relatively unaffected by either aerobic or anaerobic processes, although the literature reports that the activated sludge process has removed 64% to 99% calcium.

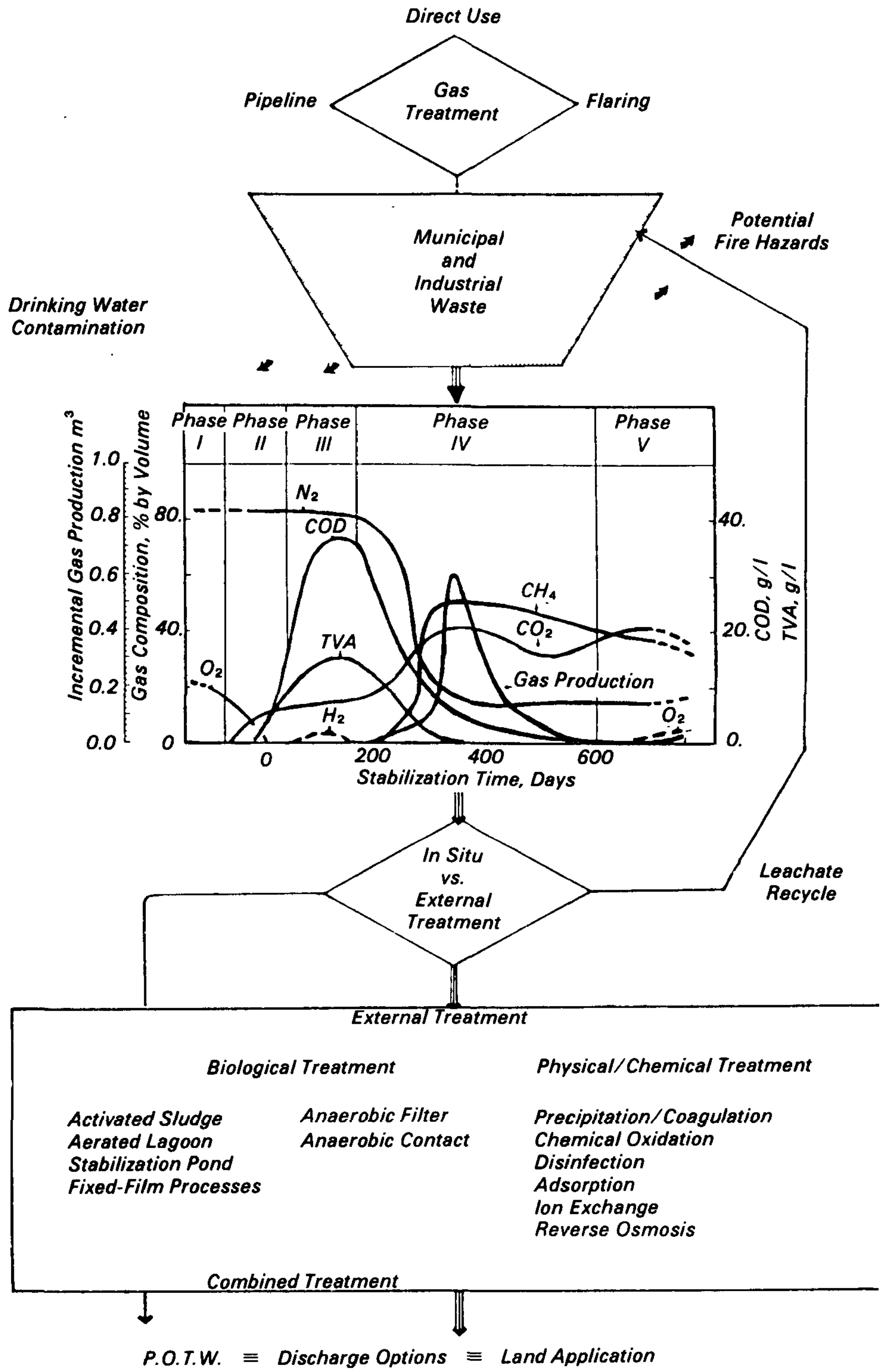


**Figure 1.** *Treatment options available for leachate and gas management and ultimat disposal.*

*Table 1. Summary of Leachate Treatment Process Capabilities*

| | $BOD_5$ | | COD | | TKN | | Fe | | Zn | | Ni | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rem., % | Effl., mg/l | Rem., % | Effl., mg/l | Rem., % | Effl., mg/l | Rem., % | Effl., mg/l | Rem., % | Effl., mg/l | Rem., % | Effl., mg/l | Comments |
| **Aerobic Biological Processes** | | | | | | | | | | | | | |
| Activated Sludge | 95 | 100 | 95 | 500 | 70-95 | 10-100 | 96-99 | 10-40 | 96-99 | 3-10 | 60 | 0.25 | $\theta_c$ = 6-10 days |
| Combined Leachate and Sewage | 94-99 | 3-15 | 92-98 | 25-60 | – | – | – | – | – | – | – | – | ratio <5% |
| Aerated Lagoon | 99 | 5-60 | 92-98 | 300-800 | 40-70* | 40-80 | 99 | 0.2 | – | – | – | – | $\theta_c$ >10 days |
| Stabilization Pond | 93-99 | 10-100 | 99 | 100-400 | 70-99 | 4-100 | 80-99 | 1-100 | – | – | – | – | $\tau$ >40 days |
| Aerobic Fixed Film* | | | | | | | | | | | | | |
| **Anaerobic Biological Processes** | | | | | | | | | | | | | |
| Attached Growth | 85-98 | 100-900 | 75-95 | 200-1000 | – | – | 80-99 | 5-25 | 80-99 | 0.5-10 | 10-80 | 0.1-1 | $\theta_c$ >10 days |
| Suspended Growth | 85-98 | 100-900 | 75-95 | 200-1000 | – | – | 80-99 | 5-25 | 80-99 | 0.5-10 | 10-80 | 0.1-1 | $\theta_c$ >5 days |
| Leachate Recycle | NA | <100 | NA | <5 | NA | 20-1000 | NA | 5-50 | NA | 0.2-1 | NA | – | $\theta_c$ >500 days |
| **Physical/Chemical Processes** | | | | | | | | | | | | | |
| Coagulation | – | – | 12 | 100-10,000 | – | – | 95-99 | 2-17 | 75-98 | <1 | – | – | Lime, alum, ferric chloride |
| Oxidation | – | – | 10-50 | | | | 99 | <1 | 90 | <1 | – | – | Ozone, chloride permanganate |
| Reverse Osmosis | – | – | 60-90** | 1000-8000 | – | – | – | – | – | – | – | – | Raw Leachate |
| | | | 86-94 | <10 | | | | | | | | | Pretreated Leachate |
| Ion Exchange | – | – | 40-70 | 100-300 | – | – | 40-80 | 1-10 | 20-96 | <1 | 14-96 | <1 | Commercial IX Resins and GG |
| Adsorption | – | – | 75-99 | <10 | – | – | 65-95 | 2-15 | – | – | – | – | GAC and PAC |

*Rem. = Removal; Effl. = Effluent.*
**Insufficient data to make an adequate judgment;*
***TOC Basis.*

Generally, with the exception of activated carbon, the physical-chemical processes were unsuccessful in removal of organic materials from raw leachates. However, reverse osmosis, activated carbon (GAC and PAC) and ion exchange (IX) were all successfully applied to treated effluents from biological treatment processes. Reverse osmosis treatment removed a high percentage of organics from both raw and treated leachates, although fouling problems limited its applicability to raw leachates. Ion exchange treatment was generally ineffective for organics removal, although cation exchange resins such as glauconitic greensand (GC) successfully removed copper, lead and nickel that were poorly removed in biological processes. Also, iron and zinc were fairly well removed, as were chromium, manganese, calcium and magnesium.

Activated carbon adsorption was shown to be capable of removing the majority of residual organics from chemical and biological leachate treatment process effluents, yielding $BOD_5$ concentrations after adsorption of less than 50 mg/l. Raw leachates, also treated using activated carbon, achieved >95% TOC removal (<100 mg/l effluent) with a maximum asdsorptive capacity of 200 mg TOC/g AC.

*In situ* treatment of leachate using leachate containment and recycling back through the landfill waste mass was successful. Pilot- and full-scale demonstration of effluents from leachate recycle studies were typically 30 to 350 mg/l $BOD_5$, 70 to 500 mg/l COD, 4 to 40 mg/l iron and <1 mg/l zinc. Also, the implementation of leachate recycling generally reduced the time required for biological stabilization of the readily biologically degradable leachate constituents by as much as an order of magnitude. Whereas wastes in landfills without leachate recirculation may require 15 to 20 years to stabilize, leachate recycle may shorten this period to 2 to 3 years. Moreover, if removal and ultimate disposal of accumulated leachate are followed by appropriate capping and maintenance of closed landfill sections, the potential for long-term adverse environmental impacts will be greatly diminished by concomitant removal of refractory substances remaining in the stabilized leachate, while also depriving the system of that liquid (leachate) transport medium. Even though the ultimate reactivity or fate of refractory compounds within landfills have not been well established, leachate recycle appears to offer a management option for reducing the degree of uncertainty and providing a better basis for predicting ultimate behavior.

## Gas Treatment Process Performance

Effective recovery of energy (methane) from landfills requires appropriate provisions for gas collection and treatment, perferably prior to initiation of the landfill operations. Collection and treatment systems must be sized according to expected gas rates and yields. The literature indicates that the 0.005 $m^3$ to 0.10 $m^3$ of total gas are produced per kilogram of dry refuse placed. Most of the total gas is produced over a relatively short period during the life of a landfill; most of the methane is produced within a few years after the onset of rapid stabilization and methanogenesis. Accordingly, typical gas production rates reported in the literature range from 0.001 to 0.008 $m^3$/kg of dry refuse/year. These rates may be increased with recycle-augmented stabilization due to the shortened period (months versus years) for accelerated conversion of the readily available biodegradable materials present in the refuse leachate. The associated gas composition ranges from 45% to 60% methane; the balance is primarily carbon dioxide with smaller amounts of hydrogen, oxygen, nitrogen and traces of other gases.

The choice of treatment technologies for purifying recovered landfill gas depends on the intended use of the product. For high BTU pipeline quality gas, treatment traditionally included the removal of water, carbon dioxide, hydrogen sulfide, hydrocarbons and, on occasion, nitrogen. For on-site applications, lesser degrees of treatment have been commonly required to remove water and hydrogen sulfide; however carbon dioxide, hydrocarbons and nitrogen are not necessarily removed.

Water removal may be best effected by either adsorption or absorption; absorption with ethylene glycol at <20°F (<6.7°C) is the method of choice. Non-methane hydrocarbons are removed using carbon adsorption. Carbon dioxide is removed by organic solvents, alkaline salt solutions, or alkanolamines. Hydrogen sulfide is removed along with $CO_2$ by the above methods, or it may be selectively removed by particular absorbents or adsorbents. Because many of the solvent processes exhibit a higher affinity for $H_2S$ than for $CO_2$, these two gases may be removed concurrently. Dry oxidation processes (such as iron sponges) are more specific for hydrogen sulfide, although the non-regenerative nature of the support materials (such as wood shavings) often poses a requirement for additional recharging procedures. Nitrogen is removed by liquefying the methane fraction of landfill gas, although this is energy intensive, underscoring the need to avoid introducing air during extraction from the landfill.

## General Recommendations

The generation and treatment of landfill leachate and gas are influenced by a number of factors, many of which are poorly understood and ineffectively controlled or managed. Collectively, these issues have been emphasized by the results of studies reviewed in this report. Associated uncertainties tend to stymie management efforts and, as a result, the design, construction and operation of external leachate treatment facilities have not been standardized. Similarly, efforts directed toward energy (methane) recovery have been limited because of the difficulties in predicting variations in gas quality and production, as well as securing justification for such an initiative within the user community.

To help alleviate such problems during design and operation of leachate and gas management systems, generation of leachate and gas must be controlled so as to transfer the process from the realm of uncertainty to that of predictability. This can be accomplished only if control over leachate constituents is exercised either through the pre-selection of waste source ingredients or by management of their rate of generation and transfer to the transport medium (leachate or gas). The latter approach appears to be a more logical choice in the case of municipal landfills; the former, perhaps coupled with the latter, would seem more attractive for industrial landfills.

Based upon an understanding of the processes effecting leachate characteristics, management of generation and transfer rates can be implemented by control of the moisture regime within the landfill. Without moisture, the transport medium will not exist and the conversions and interactions determining leachate (and gas) quality will be suppressed. Once under control, the availability of moisture can be used to advantage to accelerate processes producing leachable constituents, to carry the constituents from the waste mass, to dilute out inhibitory ingredients and/or refractory compounds, to add seed, nutrients or buffer capacity to augment biological activity, and to transport residuals for ultimate treatment or disposal.

Implicit in this management concept are requirements for containment and ultimate disposal. Current technology provides a sufficiency of techniques for containment with natural or fabricated liners which have become generally accepted. Ultimate disposal relates to the sensitivity of the eventual environmental receptor, whether it be the land or the water. However, under prevailing regulatory constraints and state-of-the-art technology, both require some degree of leachate pretreatment before ultimate disposal is acceptable. It is the premise here that such pretreatment can be best provided in engineered systems that have the resiliency to cope with changing leachate characteristics.

## *In situ* Treatment of Leachates

For on-site applications, it is recommended that leachate recycle be recognized as affording the flexibility needed to successfully manage landfill leachates, both with respect to leachate quality and quantity and energy recovery. Associated design of leachate and gas collection and distribution systems should be standardized and coupled with management plans allowing sequenced operation of the landfill and reuse of appurtenances to minimize overall costs and maximize the benefits of such treatment. Current evidence suggesting lower costs of leachate recycle in contained sites as compared to either separate aerobic or anaerobic treatment systems should be confirmed. In addition, since with leachate recycle the landfill itself provides the treatment system, operational contingencies should be established in relation to the accelerated production of leachate constituents and their eventual conversion to gas.

Whether leachate values are attractive for recovery and/or reuse also relates to the type of treatment provided. At many conventional municipal landfills, gross uncertainties persist throughout operation and after closure of the site. Accordingly, gas and leachate production events are generally unpredicatable and neither gas nor leachate may be efficiently recovered for controlled discharge. With leachate recycle and its inherent ability to accelerate waste and leachate conversion with concomitant methane production, gas collection and possible utilization becomes more viable and such an option should be investigated further, particularly on full-scale. Moreover, the degree of stabilization of the waste mass as compared to conventional landfill practice needs to be established with regard to residual leachate character and decisions on ultimate leachate disposal including foreclosure and postclosure requirements.

## External Treatment of Leachates and Gas

In the case of external treatment of leachates, the most logical first step appears to be biological treatment. Stabilization ponds or aerated lagoons can be most cost effective if land area is readily available; if not, anaerobic treatment or aerobic activated sludge processes may be used. The choice between anaerobic and aerobic processes for leachate treatment is a difficult one, although the retention times needed in either case are similar. Therefore, the energy surplus associated with methane production and aerator elimination may favor anaerobic processes. Both processes require further site specific testing on pilot- and full-scale to determine these issues. In particular, these systems will require attention to the flexibility in design and operation necessary to meet the challenges imposed by the stochastic nature of leachates (and gas) in both quality and quantity.

Following external biological treatment (or *in situ* treatment, as above), the effluents will still contain significant organic and inorganic residual concentrations. Therefore, polishing treatment prior to disposal on land or into a POTW such as by activated carbon adsorption, ion exchange or reverse osmosis needs to be included in the overall study approach. Precipitation and coagulation processes should also be considered where justified. In all cases, gas management or recovery need to be an integral part of any investigative initiative.

## Directions for Future Research

Based upon the observations gained from this review, the present state-of-the-art in landfill leachate and gas management appears to be comprised of the elements represented in Figure 2. From this figure, it is suggested that 90 to 95% of the organics and metals leached from landfill waste may be removed by biological processes such as leachate recycle or external aerobic and anaerobic treatment systems. However, the capabilities of these processes are not fully established; further study is needed in each area to develop meaningful economic and realistic process control comparisons of these alternatives. Evaluations of leachate treatment and the gas production possible from the use of leachate recycle on full-scale are particularly needed, as well as parallel evaluations of both aerobic and anaerobic fixed-film processes on pilot- and full-scale, respectively. The sequence approach to leachate recycle on full-scale needs development to establish the economic incentives associated with minimizing leachate distribution and gas collection appurtenances and maximizing gas/recovery utilization. In all biological treatment cases, the stochastic nature of leachate and gas production in both quantity and quality needs to be merged with design and operational procedures.

Activated carbon, ion exchange or reverse osmosis polishing of effluents from biological treatment processes need further confirmation on full-scale. Included in these analyses should be a characterization of organics and inorganics escaping treatment, and the potential for improving final polishing by chemical pretreatment or posttreatment. Coupled with this initiative should be more detailed analyses of the character and fate of the priority pollutants appearing throughout the various phases of landfill stabilization and/or *in situ* or separate treatment.

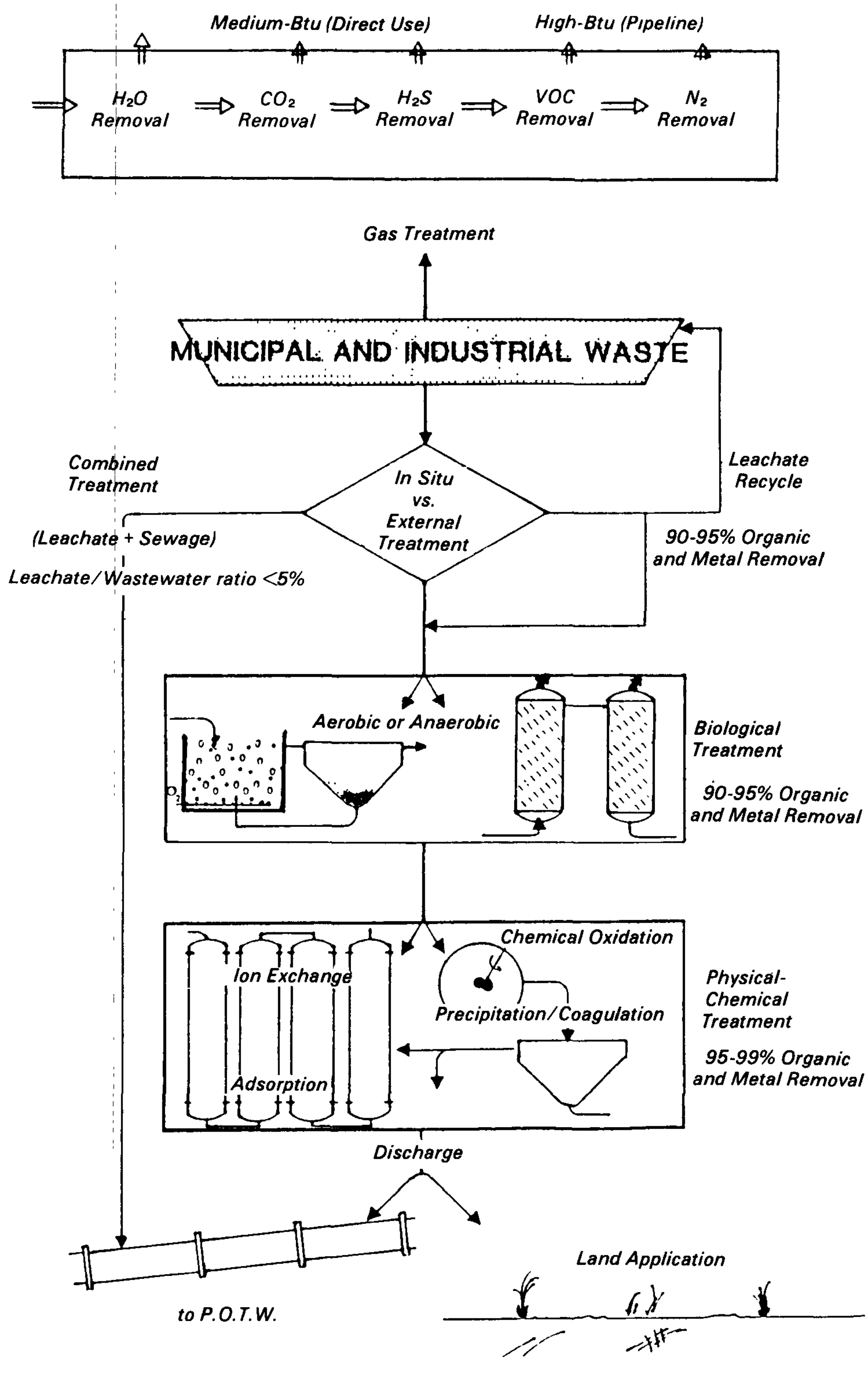


**Figure 2.** *Solutions to the management of leachate and gas from landfill disposal of solid wastes.*

Finally, the present state-of-the-art of leachate and gas management from landfills fails to provide a unified approach to leachate and gas treatment and possible resource recovery. Particularly lacking is the recognition of factors influencing leachate and gas formation and an integration of these factors for optimization of design and operational strategies in order to improve overall acceptance of this waste management technology. Therefore, complementary research and/or demonstration studies should be directed toward such a goal with the eventual development of standardized management and control procedures for all types of landfills.

*Frederick G. Pohland and Stephen R. Harper are with Georgia Institute of Technology, Atlanta, GA 30332.*
***Steve James** is the EPA Project Officer (see below).*
*The complete report, entitled "Critical Review and Summary of Leachate and Gas Production from Landfills," (Order No. PB 86-240 181/AS; Cost: $16.95, subject to change) will be available only from:*
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