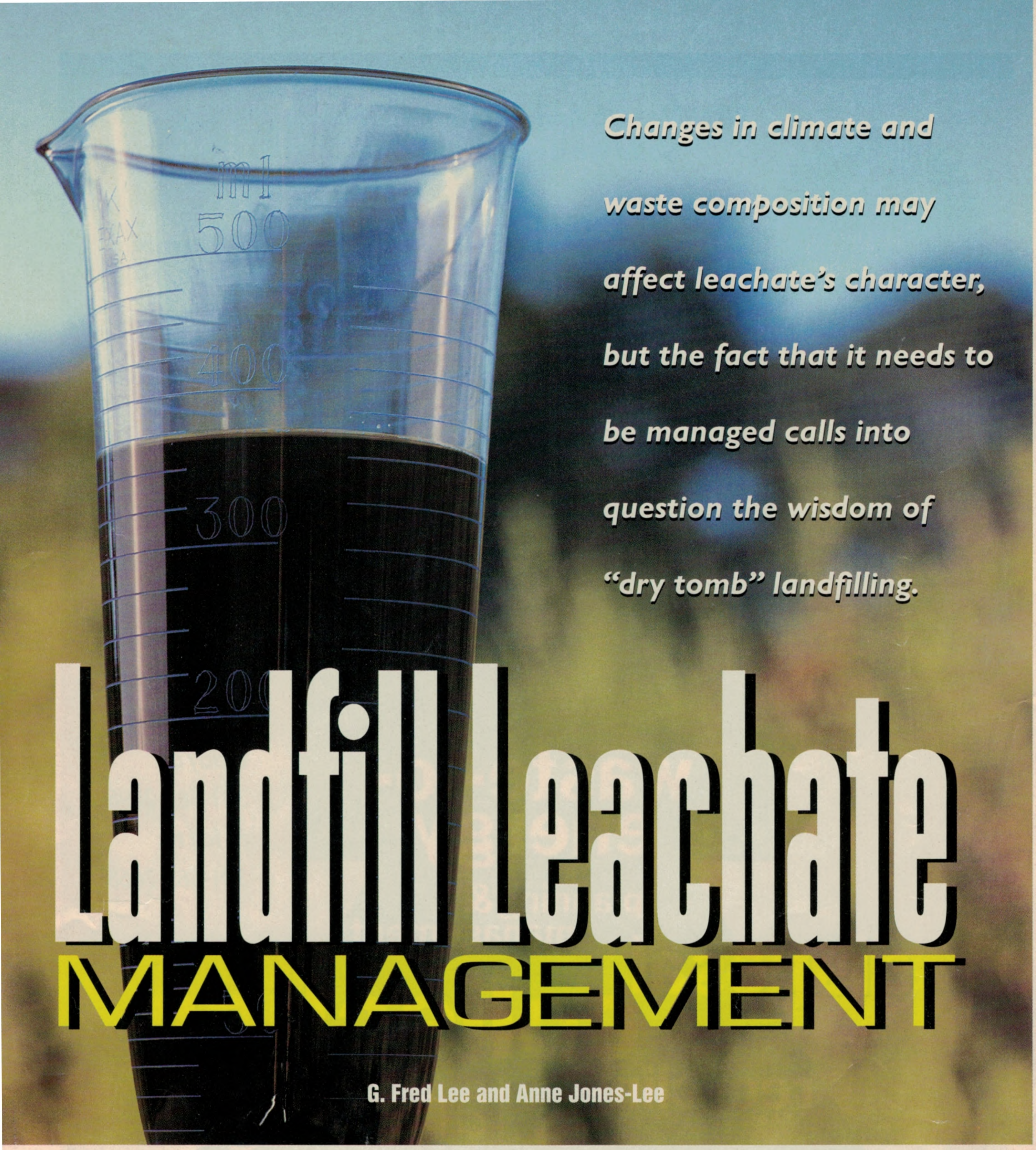

Photo: Erika Gentry, Brooks Institute of Photography

*Changes in climate and waste composition may affect leachate's character, but the fact that it needs to be managed calls into question the wisdom of "dry tomb" landfilling.*

# Landfill Leachate MANAGEMENT

G. Fred Lee and Anne Jones-Lee

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In a classical, unlined sanitary landfill that contains appreciable moisture, bacterial action leads to gas formation and leachate generation. While both are dependent on moisture, they are largely independent processes. Landfill gas formation in a classical, sanitary landfill in a humid climate can be completed within a 30-year period, but leachate generation has been found to continue for thousands of years. The dry tomb environment created at the time of landfill closure provides a situation where the wastes remain inactive until moisture enters the wastes. Failure to properly maintain the cover of the dry tomb landfill will, upon entry of significant moisture to the landfill, result in landfill gas and leachate generation.

## Pollution Potential of Leachate

MSW leachate typically contains high concentrations of conventional, nonconventional, and hazardous chemicals such as BOD, TOC, Fe, Mn, $H_2S$, TDS, $NH_3$, etc., as well as the so-called "hazardous" chemicals including heavy metals, VOCs, chlorinated and other solvents, and other priority pollutants. While there are over 60,000 chemicals in commerce in the United States today, roughly 200 of those potentially present in MSW are regulated. Indeed, more than 95% of the organics in MSW leachate are uncharacterized and unregulated.

The current regulatory approach for assessing the pollution potential of MSW and hazardous waste leachate focuses on the priority pollutants and ignores the wide variety of chemicals in such leachate that can render a groundwater unusable for domestic purposes. The state of California Water Resources Control Board's Chapter 15 governing the landfilling of municipal and hazardous waste takes a more enlightened approach by requiring that all groundwater pollution impairment by leachate be prevented for as long as the wastes in the landfill will be a threat.

## Characteristics of Leachate

Overall, the characteristics of MSW leachate are changing with a more neutral pH value and less of some of the bulk chemical characteristics such as TOC. A major change took place several years ago when the indiscriminate disposal of large amounts of hazardous wastes in municipal landfills was terminated by the implementation of RCRA. The days when 55-gal. drums of chlorinated solvents were disposed of in a municipal landfill are over. This does not mean, however, that today's municipal landfills do not contain a wide variety of chemicals arising from the disposal of household hazardous wastes, small generator exemptions, and illegal disposal of industrial hazardous wastes in the MSW wastestream. The difference in cost of disposal of wastes in an MSW landfill versus a hazardous waste landfill—typically a factor of five to 10—provides significant economic incentive to dispose of so-called hazardous wastes in an MSW landfill.

**More than 95% of the organics in MSW leachate are uncharacterized and unregulated**

RCRA focuses on the large hazardous waste generators and wastestreams. It does not try to regulate the small wastestreams that still may be highly hazardous. For example, RCRA will regulate the disposal of spent automobile batteries in municipal landfills because of their lead content; however, large amounts of lead enter municipal landfills through street sweepings and urban soils that contain leaded gasoline residues. There are many urban soils in city centers and highways that contain over 1,000 mg/kg total lead. In some states, such as California, this concentration of lead is classified as a hazardous waste; however, there are no restrictions under RCRA concerning the placement of street sweepings or urban soils that contain large amounts of lead in MSW landfills because of the high lead content, even though street sweepings are one of the most significant sources of lead.

Waste reduction and recycling programs are causing significant changes in MSW leachate. Diversion of essentially inert materials such as bottles and aluminum cans tends to make the MSW wastestream more concentrated with leached components. Diversion of newspapers and yardwastes removes a large component of the organic fraction of MSW that can lead to landfill gas and organics in landfill leachate. In time MSW landfills will produce significantly less gas, and the leachates will contain less TOC. This, in turn, should result in a less acidic leachate with a reduced ability to mobilize heavy metals and some other constituents through complexation and organic colloid production.

## Leachate Generation

Leachate generation is dependent upon moisture entering the landfill from either the atmosphere through the cover or from groundwater. Subtitle C and D landfill covers are not designed to keep the wastes dry. They can allow small amounts of moisture to enter the wastes at the time of construction. Over time the properties of the low-permeability layer(s) of the cover deteriorate, allowing increasing amounts of moisture to enter the landfill. This moisture can, in turn, generate leachate.

The misconception that leachate only can be generated under conditions where the field capacity (moisture-holding ability) of the wastes is exceeded ignores the unsaturated generation and transport of leachate through the so-called "dry" waste to the bottom of the landfill. Depending upon the characteristics of the liner, it is possible that the field capacity of the waste just above the drainage layer in the leachate collection system will be exceeded at that point as a result of the accumulation of unsaturated leachate transport.

*Landfill Leachate in Arid Climates.* Studies conducted by the Hazardous Materials Lab show that MSW leachate in California, and presumably other arid states, has significantly different characteristics than that often found in the more humid parts of the US. Data from several operating landfills in California show that leachate from these landfills tends to be more neutral in pH and has a significantly lower TOC than leachates reported for landfills located east of the Mississippi River. The climate in central and southern California is arid with less than 15 in. of precipitation per year. Further, and most importantly, there is a few-month rainy period each winter/spring followed by a long dry period during which there is no rainfall.

Since both landfill gas and leachate production are dependent upon moisture in the wastes, it is apparent that the landfills in central and southern California and some other arid areas that do not receive summer precipitation experience an annual cycle of short-term leachate and gas production during the winter and spring and the early summer followed by a period of limited leachate and gas production during mid- and late summer and the fall. During this summer/fall period the landfill tends to be considerably less active. It is this cyclic pattern that is apparently responsible for the significantly different characteristics of MSW leachate in central and southern California and some other areas than are typically found for midwestern and eastern landfills.

The state of California Water Resources Control Board recently released the results of its latest solid waste assessment test (SWAT), finding that of the 528 landfills evaluated, 72% are polluting groundwaters by landfill leachate. As expected, clay-lined landfills that were allowed in California from 1984 to 1993 caused groundwater pollution. During this period the regional water quality control boards in California allowed the construction of MSW landfills that met only the minimum design requirements set forth in Chapter 15 of 1 ft. of compacted clay with a permeability at the time of construction of no greater than $10^{-6}$ cm/sec. Such a liner would be expected, based on Darcy Law calculations, to be penetrated by leachate at the design permeabilities within one year. The SWAT results confirm this expectation. They also found that there is no correlation between landfill pollution of groundwater and such factors as depth to groundwater, annual average precipitation, waste acceptance rate, and rock type.

## Organic Solvent Permeation

Organic solvents that are common leachate components have a unique property (permeation) that must be considered in managing leachate. Waste residues such as the chlorinated solvents, benzene, TCE, and its degradation products, such as vinyl chloride, etc., can pass through an intact (i.e. no holes), flexible membrane liner in a short period of time. This is a chemical process that does not cause the liner to deteriorate, but involves the diffusion of the organics into the plastic sheeting and then through the plastic sheeting into the media on the other side of the plastic sheeting that typically is the compacted clay layer. It is important to note that permeation is particularly significant since it results in the transport of highly hazardous, persistent mobile constituents through the liner system under conditions where the liner is perfectly formed and intact. It occurs not only from concentrated solvent solutions, but it also occurs with dilute aqueous solutions of the solvents.

## Alternative Landfilling Approaches for Managing Leachate

Both the design and operation of dry tomb landfills can be readily modified to protect groundwater from pollution by landfill leachate for as long as the wastes in the landfill will be a threat by incorporation of double composite-lined systems with a reliable leak-detection system between the two composite liners. This is the approach used in Michigan's Rule 641 for MSW landfills as well as by USEPA in Subtitle C landfills, except that USEPA has failed to develop adequate liner action leakage rates that will be protective of the groundwaters in the vicinity of the landfill when the lower composite liner is no longer an effective barrier to leachate. In order to guarantee adequate safety whenever the leakage through the upper composite liner becomes sufficiently great to impair groundwater use for domestic or other purposes, it becomes the landfill owner/operator's responsibility to stop the leakage through the upper composite liner or to exhume the wastes. Since this liner cannot be inspected and repaired without removal of the wastes, stopping the leakage through it requires that an impermeable cover be installed on the landfill with a primary component a leak-detection system operated and maintained in perpetuity, that is, for as long as the wastes in the landfill represent a threat. The Robertson system, the Gundle-GSE leak-detection system, the I-Corp leak-detection system, as well as others that are being developed, all potentially can be used for this purpose. While these systems cannot function effectively in the landfill-liner system, they can be made to work in the landfill cover, which is accessible for repair. Such an approach requires that a dedicated trust fund of sufficient magnitude to ensure that adequate funds are present to operate and maintain the leak-detectable cover, leachate-collection system and the leak-detection system between the two composite liners be developed from disposal fees during the landfill's active life. While other financial instruments currently are allowed in RCRA postclosure funding, such financial instruments are likely to be unreliable.

Rather than trying to develop and maintain a dry tomb landfill, or ultimately failing to do so, there are alternative approaches for managing MSW that can better control leachate generation and production and manage its impacts. In much the same way as industrial hazardous wastes require some treatment before disposal, municipal wastes could be pretreated to remove those components that represent long-term threats through leachate generation. An alternative solution involves the addition of moisture to the wastes after disposal. In this regard increasing attention is being given to MSW landfill leachate recycle (sometimes called bioreactor) as a means of leachate disposal and landfill "stabilization." For those landfills that do not have inexpensive leachate disposal at a nearby publically owned treatment works (POTW), leachate recycle can save the landfill operator considerable money in leachate management. Further, the reintroduction of leachate to the landfill is recognized as a means of increasing the rate of landfill "stabilization" where this stabilization refers to the production of landfill gas ($CH_4$ and $CO_2$). However, there has been and continues to be considerable controversy on the merits of MSW leachate recycle. The principal opposition to landfill leachate recycle is that it increases the hydraulic loading to the landfill, and therefore could increase the rate of groundwater pollution by leachate.

While MSW leachate recycle is often supported based on a decreased time for the MSW in a landfill to be "stabilized," i.e. cease landfill gas production, the reduction in the time for landfill gas production that has been found in laboratory studies and in some field studies, such as those conducted in Sonoma County, CA in the 1970s by EMCON, will likely have limited applicability to describing the landfill gas generation in today's landfills. Much of today's MSW is placed in landfills inside of plastic bags that will serve for a period of time as a significant barrier to the recycled leachate interacting with MSW. Since landfill gas production rates are highly dependent on the moisture content of MSW, those parts of the MSW stream that are not exposed to the recycled leachate will produce landfill gas at a very slow rate compared to those that fully interact with the recycled leachate. In order for leachate recycle to significantly shorten the time that landfill gas production will take place in today's landfills, and therefore decrease the time for landfill "stabilization," it will be necessary to shred the wastes.

If the purpose of leachate recycle is to decrease the period of landfill gas production, then leachate recycle only should be practiced in double composite-lined landfills that contain shredded wastes, where the leachate-recycle process will be terminated when it is found that the upper composite liner has failed to prevent leachate migration through it that could lead to groundwater pollution.

Leachate recycle should be part of a wet cell fermentation and leaching approach where leachate recycle is followed by a 10- to 15-year period of washing of the fermented MSW residues with relatively clean water on a single-pass basis in order to leach these residues to remove from them those components that at some time in the future can pollute groundwater in the vicinity of the landfill. In order to practice in-situ leaching in a properly designed, constructed, and operated wet cell fermentation and leaching landfill, it will be necessary to change Subtitle D regulations to allow the introduction of water into the landfill to accomplish this leaching.

## Leachate Treatment

With the advent of leachate collection systems as a standard part of landfill design and operations, the issue of adequate treatment of leachate that is removed from a landfill has become important. Typically it has been found that leachate produced in a landfill is taken to a local POTW where it is treated. It has been found, however, that POTWs often experience problems in adequately treating leachate, both from the perspective of treatment process upset as well as failure to remove some of the components of leachate that represent hazards to receiving water quality. A general rule is that typical MSW leachate cannot be added to a POTW in more than a few percent by volume without disrupting the biological treatment processes.

In order to adequately treat MSW leachate, a variety of physical, chemical, and biological processes involving a combination of aerobic and anaerobic, activated-carbon biological treatment coupled with coagulation, flocculation, sedimentation, and filtration possibly followed by activated carbon columns that may be needed to properly treat MSW leachate. For some situations it may be necessary to add reverse osmosis to this treatment train to reduce the total salt content of the leachate below adverse levels.

In conclusion, RCRA Subtitle D and Subtitle C landfills provide an opportunity for management of leachates that would prevent groundwater pollution for a few years, possibly several decades, after construction of the landfill. However, since the wastes will be a threat to groundwater quality for as long as a dry tomb-type landfill exists, eventually these landfills will threaten groundwater resources in the vicinity.

There are a variety of alternative approaches that can readily be adopted that would provide for true groundwater quality protection without significantly changing the cost of landfilling of hazardous waste residues and MSW. A modified dry tomb approach involving double composite-lined landfills where the lower composite liner is a leak-detection system for the upper liner, which includes a leak-detectable cover for the landfill that is maintained and operated in perpetuity, could enable dry tomb landfills to be used for waste storage for very long periods of time. However, substantial funds are needed, preferably derived from disposal fees and maintained in a dedicated trust to ensure that the funds needed to operate and maintain the dry tomb landfill system, especially the leak-detectable cover, will be available in perpetuity as needed.

A more desirable alternative approach is either pretreatment of the wastes to remove fermentable and leachable components before burial, or in-situ treatment of shredded wastes where leachate recycle is followed by clean water washing—leaching of the wastes to remove, under controlled conditions, the leachable components—during the time that the double composite-lined landfill containment system would be expected to be effective in managing leachate. **MSW**

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**Landfill Leachate Management:**
**Overview of Issues[1]**

G. Fred Lee, PhD, PE, DEE and Anne Jones-Lee, PhD

Report of
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One of the adverse impacts of the landfilling of municipal and industrial solid wastes is the production of leachate (garbage juice) which can cause significant impairment of the use of groundwaters for domestic water supplies. Landfill leachate can also significantly impair the quality of surface waters. The primary thrust of the US EPA RCRA Subtitle C (hazardous waste) regulations and Subtitle D (municipal solid waste, MSW) regulations is the management of leachate. Both sets of regulations established, as national policy, the "dry tomb" landfilling approach in which a liner system is constructed as the base of the landfill which has as its purpose the collection of leachate that is generated within the landfill. After the landfill is filled - closed, i.e. at the end of its active life, the landfill is covered with a low permeability cover which is designed to minimize moisture entry into the landfill that generates leachate.

## "Dry Tomb" Landfilling Approach

The "dry tomb" landfilling approach attempts to isolate the waste components in the landfill from moisture that can generate leachate by wrapping the waste in a plastic sheeting (HDPE flexible membrane liner) and compacted clay layer in the form of a composite liner(s) and cover. The liner system is designed to collect the leachate that is generated in the landfill so that it can be removed from the landfill and treated before disposal, typically to surface waters.

Both types of landfills require groundwater monitoring systems for the detection of leachate that has passed through the liner system based upon vertical monitoring wells spaced hundreds to a thousand or more feet apart at the point of compliance for groundwater monitoring. Superficially, it might appear to those not knowledgeable on the ability of landfills to generate leachate, the threat that leachate represents to public health, groundwater resources and the environment, the ability of the landfill liner systems being used today to collect leachate and the ability of the groundwater monitoring systems used to detect groundwater pollution by landfill leachate before widespread pollution occurs that today's Subtitle C and D landfills represent technically valid, cost-effective approaches for managing leachate that will protect public health,

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[1] Published in condensed form in *MSW Management* 6:18-23 July/August (1996)
[https://www.gfredlee.com/Groundwater/leachatemgmt.pdf]

For additional information and more recent publications and reports on these and related issues, visit the authors' website at https://www.gfredlee.com groundwater resources and the environment from the adverse impacts of leachate for as long as the wastes in the landfill will be a threat. Unfortunately, this is not the case.

**Deficiencies in Today's Landfilling Regulations**

Environmental groups were largely responsible for developing the current approaches for regulating leachate management in landfills. They influenced the federal Congress in the early 1980's as part of rewriting RCRA to dictate to the US EPA how to design leachate management systems (landfill liners, covers, groundwater monitoring, etc.). The environmental groups and other advisors to Congress made a significant error in developing the "dry tomb" landfilling approach where they assumed that hazardous waste landfills and municipal solid waste landfills will only represent a threat for leachate generation and groundwater pollution for a period of less than 30 years after landfill closure. The fact is that municipal solid wastes in a Subtitle D MSW "dry tomb" landfill will be a threat to groundwater quality and the environment, effectively forever, as the result of generating leachate that can cause groundwater pollution. The same situation applies to Subtitle C landfills that contain treated hazardous waste residues.

Environmental groups and Congress failed to properly distinguish between landfill gas formation in a classical unlined sanitary landfill which contains appreciable moisture that promotes bacterial action that leads to gas formation and leachate generation. While both are dependent on moisture, they are largely independent processes. While landfill gas formation in a humid climate classical sanitary landfill can be essentially completed within a 30-year period, leachate generation that can pollute groundwaters in such a landfill has been found to continue for thousands of years. In a "dry tomb" type landfill the period over which the leachate generation can occur is controlled by the effectiveness of the landfill cover in preventing moisture from entering the landfill. The "dry tomb" environment created at the time of landfill closure provides a situation where the wastes remain inactive until moisture enters the wastes. Failure to properly maintain the cover of the "dry tomb" landfill will, upon entry of significant moisture to the landfill, result in landfill gas and leachate generation.

A critical review of the characteristics of today's landfill leachate management systems and groundwater monitoring systems shows that, at best, with high quality construction, today's Subtitle C and D landfills only postpone when groundwater pollution occurs for those landfills sited where there are high quality groundwaters hydraulically connected to the base of the landfill. The "dry tomb" landfilling approach advocated by environmental groups and adopted by Congress is a fundamentally flawed approach for protecting groundwaters from pollution by landfill leachate. It enables today's populations to dispose of their solid waste at less than real cost, thereby passing on the cost, health hazards and loss of groundwater resources to future generations. The "dry tomb" landfilling approach is not allowed in Ontario, Canada and some parts of western Europe because of its inevitable failure to prevent leachate pollution of groundwaters.

Lee and Jones-Lee (1996a) have recently reviewed the fundamental problems with "dry tomb" landfills. There can be no doubt that, ultimately, the US will abandon this approach in favor of an approach for managing solid wastes in landfills that will more appropriately protect groundwater resources from eventual pollution from landfill leachate than today's Subtitle C and D landfills. The minimum design requirements that were adopted in the early 1980's for Subtitle C hazardous waste landfills and the minimum design requirements for Subtitle D MSW landfills which are based on Subtitle C approaches are badly out-of-date. These requirements need to be changed as part of rewriting RCRA in order to properly reflect the current understanding of the ability of plastic sheeting and compacted clay layers to manage leachate for as long as the wastes in the landfill will be a threat and to reliably monitor leachate pollution of groundwaters before widespread groundwater pollution occurs.

**Pollution Potential of MSW Leachate**

Municipal solid waste leachate typically contains high concentrations of a variety of conventional, non-conventional and hazardous chemicals that represent significant threats to groundwater quality, public health and the environment. Jones-Lee and Lee (1993) have summarized the characteristics of solid waste leachate. In addition to high concentrations of conventional pollutants such as BOD, TOC, Fe, Mn, $H_2S$, TDS, $NH_3$, etc. and the so-called "hazardous" chemicals including heavy metals, VOC's, chlorinated and other solvents and other priority pollutants, MSW leachate contains a large number of unregulated, non-conventional pollutants. At this time, only about a hundred to two hundred chemicals of the many thousands that are present in MSW are regulated. There are over 60,000 chemicals in commerce in the US today; many of these can find their way into the municipal solid wastestream as an unregulated chemical. As discussed by Jones-Lee and Lee (1993), over 95% of the organics in MSW leachate are uncharacterized and unregulated. Every few years new hazardous chemicals are found in MSW leachate that were not known to be present previously. There could readily a highly hazardous chemical in MSW leachate that would represent the next PCB or dioxin that is not now recognized as a hazardous chemical.

Jones-Lee and Lee (1993) point out that the current regulatory approach used in RCRA for assessing the pollution potential of MSW and hazardous waste leachate focuses on the Priority Pollutants and ignores the wide variety of chemicals in such leachate that can render a groundwater unusable for domestic purposes. For example, MSW leachate has high concentrations of salts and hardness which, while not hazardous to consumers' health, cause increased corrosion and scale in pipe and plumbing systems, hot water heaters, dish washers, coffee makers, etc., shortening their useful life.

The state of California Water Resources Control Board's Chapter 15 governing the landfilling of municipal and hazardous waste takes a more enlightened approach to protecting groundwaters from landfill leachate than RCRA by requiring that all pollution - impairment of use of groundwaters by leachate be prevented for as long as the wastes in the landfill will be a threat. It is now well established that the wastes in a "dry tomb" type landfill (both hazardous and "non-hazardous") will be a threat, effectively, forever. This is the approach that RCRA and all state regulations should adopt in order to protect this and future generations from all adverse impacts of MSW and hazardous waste landfill leachate.

**Changing Characteristics of MSW Leachate**

The chemical characteristics of MSW leachate have changed and are continuing to change. A major change took place several years ago when the indiscriminate disposal of large amounts of hazardous wastes in municipal landfills was terminated by the implementation of RCRA. The days when 55 gallon drums of chlorinated solvents were disposed of in a municipal landfill are over. This does not mean, however, that today's municipal landfills do not contain a wide variety of chemicals arising from the disposal of household hazardous wastes, small generator exemptions and illegal disposal of industrial hazardous wastes in the municipal solid wastestream. The difference in cost of disposal of wastes in a MSW landfill versus a hazardous waste landfill, typically a factor of five to ten, provides significant economic incentive to dispose of so-called hazardous wastes in a MSW landfill.

Control of Hazardous Waste and Hazardous Chemicals. Typically, landfill applicants will claim in permitting hearings that their landfill will not allow the landfilling of hazardous wastes in the landfill. While it may be their intent to try to prevent such disposal, the typical waste screening that is used by landfill operators to detect hazardous waste does not prevent disposal of hazardous chemicals in the landfill. It can however, if properly carried out, prevent large-scale disposal of hazardous waste.

It is important to understand that the definition of hazardous waste used by the US EPA and RCRA was not based on the finding that the so-called "non-hazardous" wastes are not hazardous to health and the environment. The RCRA hazardous waste definition is a political definition that was designed to minimize the amount of industrial hazardous waste that had to be managed as hazardous waste. When RCRA was adopted, and today, it focuses on the large hazardous waste generators and wastestreams. It does not try to regulate the small wastestreams which still may be highly hazardous. For example, RCRA will regulate the disposal of spent automobile batteries in municipal landfills because of their lead content, however, large amounts of lead enter municipal landfills through street sweepings and urban soils that contain leaded gasoline residues. There are many urban soils in city centers and highways that contain over 1000 mg/kg total lead. In some states, such as California, this concentration of lead is classified as a hazardous waste, however there are no restrictions under RCRA concerning the placement of street sweepings or urban soils that contain large amounts of lead in a municipal solid waste landfill because of the high lead content, even though street sweepings are one of the most significant sources of lead for a municipal landfill that lead to lead concentrations in MSW leachate that are significant threats to groundwater quality.

Waste Reduction and Diversion. Waste reduction and recycling - diversion is causing significant changes in municipal solid waste leachate. Many states have waste reduction goals which require from 25 to 50% of the MSW wastestream to be diverted from landfilling. Some of the materials that are being diverted such as bottles and aluminum cans, which are essentially inert in a landfill, will tend to make the MSW wastestream more concentrated with leached components. The diversion of newspapers and especially yard wastes will remove a large component of the organic fraction of MSW that can lead to landfill gas and organics in landfill leachate. In time, MSW landfills will produce significantly less gas, and the leachates will contain less TOC. This, in turn, should result in a less acidic leachate which has the potential of reducing the ability of leachate to mobilize heavy metals and some other constituents through complexation and organic colloid production. In addition to reducing the total amount of organic matter in the MSW wastestream, which will reduce the TOC in MSW leachate, other benefits in leachate characteristics may accrue from the diversion of yard wastes such as the diversion of home-use herbicides.

For example, Gintautas *et al.* (1992) reported finding phenoxyalkanoic acid herbicides in municipal landfill leachates. These chemicals are part of the 60,000 unregulated chemicals that are used in the US today, many of which could be present in the MSW wastestream and MSW landfill leachates. These herbicides were derived from their use on home lawns. They are a threat to public health, yet as with many other chemicals of this type, they are not now regulated. It is situations such as this that lead to the conclusion that it should never be assumed that because a groundwater that has received small amounts of MSW or hazardous waste leachate but does not contain any regulated chemical above drinking water MCL's can be considered safe for consumption. All groundwaters that contain landfill leachate in any amount must be considered highly hazardous due to the unregulated chemicals in them.

It is important to understand that this difference in leachate characteristics is not yet under the effects of the diversion of the components such as yard wastes from the MSW wastestream. That diversion will cause even greater changes in the characteristics of MSW leachate in California.

Overall, the characteristics of MSW leachate are changing. These changes are, in general, in the direction of causing it to contain less of some of the bulk chemical characteristics, such as TOC, and to have a more neutral pH. However, MSW leachate will still continue to contain conventional, hazardous and non- conventional pollutants at sufficient concentrations so that small amounts of leachate can render large amounts of groundwater unusable for domestic water supply purposes.

**Leachate Generation**

In today's RCRA Subtitle C and D landfills, where the disposal of liquid waste is prohibited, leachate generation is dependent upon moisture entering the landfill from either the atmosphere through the cover or from groundwater. Subtitle C and D landfill covers are not designed to keep the wastes dry. They can allow small amounts of moisture to enter the wastes at the time of construction. Over time, the properties of the low permeability layer(s) of the cover deteriorate, allowing increasing amounts of moisture to enter the landfill. This moisture can, in turn, generate leachate.

<u>Unsaturated Transport of Leachate</u>. There is a misconception that leachate can only be generated under conditions where the field capacity (moisture holding ability) of the wastes is exceeded. The authors have observed that some landfill applicants and their consultants will state in landfill permitting hearings that the wastes in a landfill in the region where they propose to develop or expand an existing landfill are "dry," i.e. the waste field capacity is not exceeded. It is then

asserted that no leachate can be generated under these conditions. Such assertions are technically invalid. Unsaturated transport of leachate, which occurs in soils and waste when the field capacity of the waste is not exceeded, allows leachate to be generated and transported through the so-called "dry" waste to the bottom of the landfill. Depending upon the characteristics of the liner, it is possible that the field capacity of the waste just above the drainage layer in the leachate collection system will be exceeded at that point due to the accumulation of unsaturated leachate transport. Unsaturated transport is an important transport mechanism of hazardous and non-hazardous chemicals in waste and geological strata that must be considered in leachate generation and transport.

Landfill Leachate in Arid Climates. Recently, the authors, through their work with the California Department of Toxic Substances Control Waste Classification Focus Group, have become aware of work by Hooper of Cal EPA DTSC Hazardous Materials Lab which shows that MSW leachate in California, and presumably other arid state, has significantly different characteristics than those often found for MSW leachate in the more humid parts of the US. As part of a study on the leaching potential of MSW leachates in connection with evaluating the leaching tendencies of various leaching agents used in hazardous waste classification in California (especially acetic acid vs. citric acid), Hooper (1996) has obtained data on MSW leachate characteristics from several operating landfills in California. He is finding that the MSW leachate from these landfills tends to be more neutral in pH and has a significantly lower TOC than leachates reported for landfills located east of the Mississippi River. The climate in central and southern California is arid with less than 15 inches of precipitation per year. Further, and most importantly, there is a few-month rainy period each winter/spring followed by a long dry period during which there is no rainfall.

Since both landfill gas and leachate production are dependent upon moisture in the wastes, it is apparent that the landfills in central and southern California and some other arid areas that do not receive summer precipitation experience an annual cycle of short-term leachate and gas production during the winter/spring and early summer followed by a period of limited leachate and gas production during mid/late summer and fall. During this summer/fall period, the landfill tends to be considerably less active. It is this cyclic pattern that is apparently responsible for the significantly different characteristics of MSW leachate in central and southern California and some other areas than is typically found for midwest and eastern landfills.

It is important not to conclude from this that landfills in California and other arid areas do not generate leachate that causes groundwater pollution. While landfills in these areas generate less leachate than those in more humid areas and the pattern of leachate generation is cyclic, sufficient leachate is still generated even in desert landfills receiving an average annual precipitation of two inches or so to cause groundwater pollution.

The state of California Water Resources Control Board has recently released the results of its latest Solid Waste Assessment Test (SWAT) which reports on the pollution of groundwaters by California's landfills (Mulder and Haven, 1995). It has been found that of the 528 landfills evaluated, 72% of these landfills are polluting groundwaters by landfill leachate. Many of these landfills are located in areas where there is an average of less than 12 inches of rain per year.

The SWAT results found that clay-lined landfills which were allowed in California from 1984 to 1993, as expected, caused groundwater pollution. During this period, the regional water quality control boards in California allowed the construction of MSW landfills which met only the minimum design requirements set forth in Chapter 15 of one foot of compacted clay with a permeability at the time of construction of no greater than $10^{-6}$ cm/sec. Such a liner would be expected based on Darcy Law calculations to be penetrated by leachate at the design permeabilities within one year. The SWAT results confirm this expectation. They also found that there is no correlation between landfill pollution of groundwater and such factors as depth to groundwater, annual average precipitation, waste acceptance rate and rock type.

Mulder and Haven (1995) state that the SWAT data show that landfills tend to pollute groundwaters even if they have not accepted wastes for more than 30 years. Again, this is to be expected based on the findings of Belevi and Baccini (1989). They predicted that classical sanitary landfills in humid climates can be expected to produce leachate that can pollute groundwaters with lead above drinking water standards for over 2,000 years. Freeze and Cherry (1979) have reported that Roman Empire landfills developed approximately 2,000 years ago are still producing leachate.

The finding of the SWAT program raises serious questions about the appropriateness of some of the approaches that are being used in states and proposed for hazard ranking of landfills, such as Hagemeister *et al.* (1996), based on climatic and geological factors. The SWAT program demonstrates that unlined or clay-lined landfills leak regardless of factors such as climate and site-specific geology.

Landfill applicants and their consultants have been found to claim that since pollution of groundwaters by landfill leachate has not been found in Subtitle C and D landfills, this means that the liner systems in these landfills will prevent leachate from passing through them. However, as discussed by Lee and Jones-Lee (1996b) the leakage of leachate through plastic sheeting-lined landfills would not be expected to be detected at groundwater monitoring wells since at many landfills, the distance between the bottom of the landfill and the monitoring wells is sufficient so that the leakage that has occurred through the liner has not yet reached the point of compliance. Further, as discussed below, the groundwater monitoring systems that are used to detect this leakage are highly unreliable in detecting leachate-polluted groundwaters until groundwater pollution has occurred beyond the point of compliance.

<u>Siting Landfills in High Watertable Areas</u>. Some landfill applicants attempt to site landfills in areas where the watertable and/or piezometric surface is at or above the bottom of the landfill. Some regulatory agencies will allow the construction of such a landfill provided that the landfill applicant constructs a groundwater drainage system. It is sometimes asserted that this groundwater drainage system underlying the landfill can provide additional protection from leachate leakage through the liner since any leakage would become part of the groundwaters and be collected in the groundwater drain.

Such approaches can prove to be highly unreliable in preventing groundwater pollution by leachate. The typical MSW leachate has a significant salt content which makes its density the equivalent of about one third to one half sea water. This gives the leachate that leaks through the liner a significant downward gradient that must be properly considered in evaluating its flowpath in any groundwater underdrain system for a landfill sited with a high watertable.

Another problem with such landfills is that it assumes that the position of the watertable - piezometric surface that exists now will continue to exist for as long as the wastes in the landfill will be a threat. A variety of factors such as pumping of groundwaters under adjacent properties that can take place at sometime in the future can significantly impact the position of the watertable - piezometric surface. Further, during the next 50 years or so there will be appreciable climate change, which in some areas will raise the watertable and in other areas will lower it. The wastes in today's "dry tomb" landfills will still be a threat then. Engineered systems that attempt to manage high groundwater to prevent it from generating leachate in the landfill or use it to collect leachate that passes through the liner in a groundwater drain based on current conditions may not function reliably under the future conditions that will exist at landfills with high watertables.

**Organic Solvent Permeation**

The organic solvents which are common components of municipal and hazardous waste landfill leachate have a unique property (permeation) that must be considered in managing leachate. Common organic solvents that are present in municipal solid wastes and in treated hazardous waste residues such as the chlorinated solvents, benzene, TCE and its degradation products such as vinyl chloride, etc., can pass through an intact, i.e. with no holes, flexible membrane liner in a short period of time. This is a chemical process that does not cause the liner to deteriorate, but involves the diffusion of the organics into the plastic sheeting and then through the plastic sheeting into the media on the other side of the plastic sheeting which typically is the compacted clay layer. Permeation of dilute solutions of organic solvents through HDPE liners was discussed by Haxo and Lahey (1988). This process has been investigated in detail by Sakti *et al.* (1991). Recently, Buss *et al.* (1995) have published further information on it. Even though this process has been well-known in the literature for many years, regulatory agencies at the federal and state levels are ignoring it as a cause of groundwater pollution by landfills.

It is important to note that this mechanism of leachate component transport through the liner is particularly significant since it results in the transport of highly hazardous persistent mobile constituents through the liner system under conditions where the liner is perfectly formed and intact. It occurs not only from concentrated solvent solutions, but it also occurs with dilute aqueous solutions of the solvents. The various solvents that are of concern can be purchased by the public at the local hardware store and therefore are not exotic chemicals that would not be expected at a landfill, but are common chemicals that are expected in today's municipal landfills. Many of these solvents are known or expected carcinogens which are projected to cause cancer in people in very low concentrations in domestic water supplies. The US EPA (1988), as part of promulgating Subtitle D regulations, noted that one of the best ways to detect liner leakage of leachate is through measurement of organic solvents.

**Alternative Landfilling Approaches for Managing Leachate Production and Impacts**

Lee and Jones-Lee (1995a,b) have discussed how Subtitle C and D "dry tomb" type landfills can be readily modified in design and especially operation so they will, in fact, protect groundwaters from pollution by landfill leachate for as long as the wastes in the landfill will be a threat.

<u>Modified "Dry Tomb Landfills</u>. Basically, it involves the construction of all hazardous waste landfills and so-called "non-hazardous" waste (MSW) landfills using double composite-lined systems with a reliable leak detection system between the two composite liners. This is the approach that is used in Michigan's Rule 641 for municipal solid waste landfills. Such landfills consist of a double composite lined system where the lower composite liner is part of a leak detection system for the upper composite liner. It is also the approach that is used by the US EPA in Subtitle C landfills except that the US EPA has failed to develop adequate Liner Action Leakage Rates which will be protective of the groundwaters in the vicinity of the landfill when the lower composite liner is no longer an effective barrier and leachate passes through it.

The approach that should be followed is that whenever the leachate leakage through the upper composite liner is sufficiently great so that the groundwaters under the landfill could be polluted, i.e. impaired use for domestic or other purposes, by the leakage through the liner, then the landfill owner/operator must stop the leakage through the upper composite liner or exhume the wastes.

Since this liner cannot be inspected and repaired without removal of the wastes, stopping the leakage through it will require that an impermeable cover be installed on the landfill which has a primary component a leak detection system that is operated and maintained in perpetuity, i.e. as long as the wastes in the landfill represent a threat. The Robertson system, the Gundle - GSE leak detection system, the I-Corp leak detection system as well as others that are being developed can all potentially be used for this purpose. While these systems cannot function effectively in the landfill liner system, they can be made to work in the landfill cover, which is accessible for repair.

Today's RCRA Subtitle C and D landfill covers involve the use of the equivalent of a composite liner in which thin plastic sheeting and a compacted clay layer is constructed on top of the waste layer. This low permeability layer is designed to minimize but not prevent moisture from entering the landfill and generating leachate. Daniel and Koerner (1991) discuss the variety of factors that influence the stability of a landfill cover such as the differential settling of the wastes which can be highly disruptive of the cover integrity. Typically, landfill owners/operators will assert at a landfill permitting hearing that if any problems develop in the integrity of the landfill cover, that these will be repaired. However, the low permeability layer of the landfill cover (the plastic sheeting and compacted clay) are buried below several feet of topsoil and a drainage layer. Cracks can develop in the low permeability layer which cannot be perceived upon visual inspection of the landfill cover. It is for this reason that Lee and Jones-Lee (1995b) advocate that leak detectable covers be used in Subtitle C and D landfills.

If the landfill owner/operator cannot or will not stop the leakage of leachate through the upper composite liner, then the owner/operator must remove (exhume) the wastes in the landfill, properly treat them, and manage the residues from such treatment in such as way as to not lead to further groundwater pollution. Failure to adopt this approach will mean that the wastes in a landfill will pollute the groundwaters of the area.

As discussed by Lee and Jones-Lee (1995b), such an approach requires that a dedicated trust fund be developed from disposal fees during the landfill's active life. This trust fund should be of sufficient magnitude to ensure that sufficient funds are present to operate and maintain the leak detectable cover, leachate collection system and the leak detection system between the two composite liners. While other financial instruments are currently allowed in RCRA post-closure funding, such financial instruments are likely to be unreliable. Hickman (1992, 1995) has discussed the importance of using a dedicated trust as a reliable financial instrument to address long-term contingencies associated with "dry tomb" type landfills.

<u>Wet Cell Approach</u>. Rather than trying to develop and maintain a "dry tomb" landfill, ultimately failing to do so, there are alternative approaches for managing municipal solid wastes that can better control leachate generation and production and manage its impacts. The landfilling of industrial hazardous wastes in Subtitle C landfills requires some treatment of the wastes before disposal. This treatment, however, does not produce a landfill treated residue that is not a significant threat to the quality groundwater resources. A few of the potential thousands of chemicals present in industrial hazardous waste that are regulated only have to be treated so that they do not release constituents in the TCLP test at concentrations above 100 times drinking water standards. The 100 value was arbitrarily selected by the US EPA without a proper technical base.

Further, there is no regulation governing the landfilling of the many unmeasured, unregulated hazardous and deleterious chemicals present in hazardous waste that represent significant threats to groundwater quality. The leachates generated in today's hazardous waste landfills still represent highly significant threats to public health, groundwater resources and the environment.

<u>Solid Waste Pretreatment</u>. There is increasing recognition that, rather than placing untreated municipal solid wastes in a landfill, the wastes should be pretreated to remove those components that represent long-term threats through leachate generation. Some countries, such as Germany, have adopted requirements that establish a limit on the amount of organics (<3%) that can be present in a MSW landfill. This approach, however, does not limit the amount of inorganics present in the wastes that can lead to groundwater pollution. It would be possible, although likely very expensive compared to what the public has been paying in the past for MSW disposal, to treat municipal solid waste to remove those components before landfilling that represent long-term threats in leachate to groundwater resources and the environment.

*In Situ* Treatment. An alternative approach for treating municipal solid wastes involves the treatment of the wastes after landfilling by addition of moisture to the wastes. Increasing attention is being given to MSW landfill leachate recycle (sometimes called bioreactor) as a means of leachate disposal and landfill "stabilization." For those landfills that do not have inexpensive leachate disposal at a nearby POTW, leachate recycle can save the landfill operator considerable money in leachate management. Further, the addition of leachate back into the landfill is recognized as a means of increasing the rate of landfill "stabilization" where this stabilization refers to the production of landfill gas ($CH_4$ and $CO_2$). However, there has been and continues to be considerable controversy on the merits of MSW leachate recycle.

Leachate recycle as being implemented today is largely based on the pioneering work of Pohland (1975). There have been a number of recent papers devoted to the merits of MSW leachate recycle. For example, Townsend *et al.* (1996) and Reinhart (1995) have discussed some of the benefits of leachate recycle. These articles, however, do not discuss some of the significant problems that can result from leachate recycle. Further, they do not discuss the fact that leachate recycle today is likely to produce significantly different results in terms of the rate of landfill "stabilization" than what was found by Pohland in his laboratory studies of a number of years ago.

In the mid-1980's, the authors (Lee *et al.*, 1985, 1986) conducted a comprehensive review of MSW landfill leachate recycle. While it was encouraged by some, several states prohibited its practice. The principal opposition to landfill leachate recycle is that it increases the hydraulic loading to the landfill and therefore could increase the rate of groundwater pollution by leachate.

While MSW leachate recycle is often supported based on a decreased time for the MSW in a landfill to be "stabilized," i.e., cease landfill gas production, the reduction in the time for landfill gas production that has been found in laboratory studies and in some field studies, such as those conducted in Sonoma County, California in the 1970's by EMCON (1975, 1976), will likely have limited applicability to describing the landfill gas generation in today's landfills. Much of today's MSW is placed in landfills inside of plastic bags. The plastic bags will serve for a period of time as a significant barrier to the recycled leachate interacting with MSW. Since landfill gas production rates are highly dependent on the moisture content of MSW, those parts of the MSW stream that are not exposed to the recycled leachate will produce landfill gas at a very slow rate compared to those that fully interact with the recycled leachate. In order for leachate recycle to significantly shorten the time that landfill gas production will take place in today's landfills and therefore decrease the time for landfill "stabilization," it will be necessary to shred the wastes.

The primary reason for not allowing MSW landfill leachate recycle (increased potential for groundwater pollution) can be addressed in a double composite-lined landfill. While the US EPA and some states allow leachate recycle in a single composite-lined landfill, such practices are dangerous as a result of the inability of groundwater monitoring programs involving vertical wells spaced hundreds to one thousand or so feet apart to detect composite liner leakage before widespread groundwater pollution occurs. Initial leakage from a FML-lined landfill, such as a Subtitle D landfill, will leak through holes, rips or tears in the FML. As discussed by Cherry

(1990) and Lee and Jones-Lee (1994), such leakage will produce finger plumes of leachate that can readily pass undetected between the vertical monitoring wells which have zones of capture of only about one foot on each side of the well.

Lee and Jones-Lee (1994) discuss that a double composite-lined landfill system provides the opportunity to use the lower composite liner as a leak detection system for the upper composite liner, thereby becoming able to more reliably detect if the increased hydraulic loading on the landfill as a result of leachate recycle is promoting the possibility of groundwater pollution. If during the practice of landfill leachate recycle leachate is found in the leak detection system between the two liners in sufficient amounts to pollute the groundwaters underlying the landfill if the second composite liner were not present, it is obvious that the leachate recycle must be terminated. Further, if the leak through the upper composite liner cannot be stopped, then it will become necessary to exhume the wastes since the upper composite liner system has failed, and it is only a matter of time until similar failure occurs in the lower composite liner.

An important aspect of leachate recycle that is not generally understood is that it does not ultimately result in a leachate that has limited potential for groundwater pollution. While leachate recycle tends to reduce the strength of many of the constituents in MSW leachate, compared to non-recycled leachate, the leachate produced after recycle has been terminated (when gas production ceases) still has the ability to pollute large amounts of groundwaters, rendering them unusable for domestic water supply purposes with hazardous or otherwise deleterious chemicals that can cause a homeowner or a water utility to have to abandon the groundwater well as a source of water supply.

In summary, the authors advise against the disposal of leachate in today's landfills because of the increased potential for groundwater pollution in an unlined classical sanitary landfill as well as a Subtitle D single composite-lined landfill. If the purpose of leachate recycle is to decrease the period of landfill gas production, then leachate recycle should only be practiced in double composite-lined landfills that contain shredded wastes where the leachate recycle process will be terminated when it is found that the upper composite liner has failed to prevent leachate migration through it that could lead to groundwater pollution.

Leachate recycle should be part of a wet cell fermentation and leaching approach (See Lee and Jones, 1990 and Lee and Jones-Lee, 1993) where leachate recycle is followed by a 10- to 15-year period of washing of the fermented MSW residues with relatively clean water on a single pass basis in order to leach these residues to remove from them those components that at some time in the future can pollute groundwaters in the vicinity of the landfill. In order to practice *in situ* leaching in a properly designed, constructed and operated wet cell fermentation and leaching landfill, it will be necessary to change Subtitle D regulations to allow the introduction of water into the landfill to accomplish this leaching.

**Leachate Treatment**

With the advent of leachate collection systems as a standard part of landfill design and operations, the issue of adequate treatment of leachate that is removed from a landfill has become important. Typically, it has been found that leachate produced in a landfill is taken to a local POTW where it is treated. It has been found, however, that POTW's often experience problems in adequately treating leachate, both from the perspective of treatment process upset as well as failure to remove some of the components of leachate that represent hazards to receiving water water quality. A general rule is that typical MSW leachate cannot be added to a POTW in more than a few percent by volume without disrupting the biological treatment processes.

Increasing scrutiny is being given to the role of MSW and hazardous waste landfill leachate as causes of NPDES permit discharge limit violations for POTW's. Of particular concern are some of the heavy metals and whole effluent toxicity. While in the past MSW leachate was added to POTW inflows without much regard for the potential impact it would have on the ability of the POTW to meet its discharge limits, with the implementation of the National Toxics Rule, POTW's are under increasing scrutiny by regulatory agencies to ensure that the effluent is not toxic to a variety of forms of aquatic life and that the concentrations of the regulated chemicals do not exceed the discharge limits. In conventional POTW treatment, an appreciable part of the so-called treatment of the MSW leachate constituents is by dilution. The exotic and hazardous constituents in MSW leachate when added in small amounts to a high volume of conventional domestic wastewaters can result in the hazardous chemicals being diluted below detection or adverse limits.

Lee *et al.* (1985) conducted a review of MSW leachate treatment technology and concluded that in order to adequately treat MSW leachate, a variety of physical, chemical and biological processes may be needed that are not normally achieved in a conventional POTW treatment works. Lee *et al.* (1985) concluded that a combination of aerobic and anaerobic powdered activated carbon biological treatment coupled with coagulation, flocculation, sedimentation and filtration possibly followed by activated carbon columns may be needed in some cases to properly treat MSW leachate. For some situations, it may be necessary to add reverse osmosis to this treatment train to reduce the total salt content of the leachate below adverse levels. Copa *et al.* (1995) have described a commercial process marketed by Zimpro Environmental Inc. which combines many of the processes that Lee *et al.* suggested may be necessary for leachate treatment. It is likely that processes such as those described by Lee *et al.* (1985) and Copa *et al.* (1995) will receive increasing use in leachate management because of the difficulty of treating MSW leachate at the POTW's while complying with increasingly stringent regulatory requirements. Of particular concern will be the compliance with whole effluent toxicity limits.

**Conclusions**

MSW landfill leachates and hazardous waste treated residue landfill leachates have been and continue to be a major management problem for landfill owners/operators. The US EPA RCRA Subtitle D municipal solid waste and Subtitle C hazardous waste landfills provide an opportunity for management of leachates that would prevent groundwater pollution for a few years, possibly several decades, after construction of the landfill. However, since the wastes in both a hazardous waste and a municipal solid waste landfill will be a threat to groundwater quality for as long as a "dry tomb" type landfill exists, eventually with the failure of the liner system to preclude leachate collection and thereby prevent leachate from passing through the liners, the RCRA Subtitle C and D landfills will ultimately lead to groundwater pollution for those landfills sited where there are groundwaters to be polluted by landfill leachate in the vicinity of the landfill. The landfilling approach now currently being practiced under US EPA RCRA Subtitle C and D landfills is a fundamentally flawed technology that will not prevent groundwater pollution. At best it only postpones when pollution occurs.

There are a variety of alternative approaches that can readily be adopted that would provide for true groundwater quality protection without significantly changing the cost of landfilling of hazardous waste residues and municipal solid waste. A modified "dry tomb" approach involving double composite-lined landfills where the lower composite liner is a leak detection system for the upper liner, which includes a leak detectable cover for the landfill that is maintained and operated in perpetuity, could enable "dry tomb" landfills to be used for waste storage for very long periods of time. However, substantial funds are needed, preferably derived from disposal fees and maintained in a dedicated trust to ensure that the funds needed to operate and maintain the "dry tomb" landfill system, especially the leak detectable cover, will be available in perpetuity as needed.

A more desirable alternative approach is either pretreatment of the wastes to remove fermentable and leachable components before burial or *in situ* treatment of shredded wastes where leachate recycle followed by clean water washing - leaching of the wastes is practiced to remove, under controlled conditions, the leachable components of the wastes during the time that the double composite-lined landfill containment system would be expected to be effective in managing leachate.

From an overall perspective, the US EPA RCRA Subtitle C and D landfills as now being developed are a flawed technological approach for leachate management. RCRA should be immediately changed to address the problems of these types of landfills in order to protect this and future generations' groundwater resources from pollution by landfill leachate.

**Further Information**

Further information on these topic areas, including copies of the authors' papers and reports on them, is available from the authors' website, https://www.gfredlee.com.

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