Assessing the Potential of Minimum Subtitle D Lined Landfills to Pollute: Alternative Landfilling Approaches[1]

G. Fred Lee, PhD, PE, BCEE, F.ASCE and Anne Jones-Lee, PhD

G. Fred Lee & Associates
27298 E. El Macero Drive, El Macero, CA 95618
https://www.gfredlee.com

June 1998

Abstract

The US EPA Subtitle D regulations specify as a minimum, MSW landfills be lined with a single composite liner which is part of a leachate collection and removal system. Upon reaching the landfill capacity, a low-permeability cover is installed. A groundwater monitoring system is used to detect liner failure during the 30-year mandated post-closure care period. The waste in a minimum Subtitle D "dry tomb" landfill will be a threat to pollute groundwaters by leachate, effectively forever. The landfill liner and cover have a finite period of time when they can be expected to function effectively to keep moisture out of the landfill that generates leachate and to collect leachate formed within the landfill. The groundwater monitoring systems typically used with monitoring wells having zones of capture of about one foot on each side, spaced hundreds of feet apart, have low probabilities of detecting landfill liner failure that leads to groundwater pollution before off-site pollution occurs. The 30 years of mandated post-closure care is an infinitesimally small part of the time that the waste in a minimum Subtitle D "dry tomb" landfill will be a threat to generate leachate that can pollute groundwater. Fundamentally, the minimum Subtitle D MSW landfill is a technologically flawed approach that, at best, only postpones when groundwater pollution occurs for those landfills sited at geologically unsuitable sites, i.e. those without natural groundwater quality protection. The US EPA Subtitle D regulations also fail to address the justifiable NIMBY associated with active life releases (odors, dust, blowing paper, etc.) from the landfill to the surrounding area. This paper discusses the deficiencies in minimum Subtitle D landfilling of MSW and provides guidance on alternative landfilling approaches that can protect public health, groundwater resources, environment and the interests of those within the sphere of influence of the landfill.

Introduction

In 1991, the US EPA promulgated final Subtitle D regulations governing the landfilling of municipal solid wastes (MSW) (US EPA, 1991). These regulations specified that the landfilling of MSW must be conducted with a minimum liner system composed of a single composite liner consisting of two feet of compacted clay with a permeability of no greater than 10^{-7}cm/sec overlain by a flexible membrane liner which, if constructed of high-density polyethylene

---

[1]Lee, G. F. and Jones-Lee, A., “Assessing the Potential of Minimum Subtitle D Lined Landfills to Pollute: Alternative Landfilling Approaches,” Proc. of Air and Waste Management Association 91st Annual Meeting [98-WA71.04(A46)], San Diego, CA, 40pp, June (1998).

(HDPE), shall have a minimum thickness of 60 mil. Overlying the liner system is a leachate collection and removal system in which the HDPE layer serves as the foundation for the removal of leachate from the landfill. The flexible membrane liner (FML) is sloped so that leachate that is generated in the landfill during the active life when the landfill is open to the atmosphere and accepting wastes as well as during the post-closure period, will be transported on the surface of the FML to a sump where it can be pumped from the landfill. The collected, pumped leachate is then treated and typically discharged to surface waters, either directly after treatment or through discharge to a municipal wastewater treatment plant, where it is treated/diluted to acceptable wastewater discharge standards.

There are few restrictions on the siting of minimum Subtitle D MSW landfills outside of locating them too close to an active earthquake fault, near an airport runway, in a flood plain or wetlands or a geologically unstable area. Minimum Subtitle D landfills can be located essentially at any location where the landfill owner can acquire property and gain the necessary zoning permits. There are no national requirements on the siting of minimum Subtitle D landfills with respect to protecting underlying groundwater resources from pollution by landfill leachate. Subtitle D requires that there be at least a five-foot separation between the high groundwater table and the base of the wastes. Frequently this separation is not enforced by regulatory agencies. There are numerous examples of where Subtitle D landfills are sited where the groundwater table is within a few feet of the base of a landfill and can, at times, be higher than the base of the wastes. Under these conditions, a subdrain system is installed in an attempt to try to keep the groundwaters out of the landfill and thereby serving as an additional source of moisture which can generate leachate within a landfill.

Once the landfill is filled to its capacity, a cover is placed over the top of the landfill with a permeability of no greater than the landfill liner. Minimum Subtitle D landfills are required to have a groundwater monitoring system that will have a high probability of detecting leachate-polluted groundwaters at the point of compliance for groundwater monitoring. The point of compliance is a vertical plane located down groundwater gradient from the landfill at a distance of no more than 150 meters from the waste management unit. The point of compliance must be on the landfill owner's property. The owners of the landfill are required to provide post-closure funding of sufficient magnitude to be able to close the landfill in accord with minimum Subtitle D requirements and to construct, operate and maintain the landfill cover and the groundwater monitoring system for a period of at least 30 years after landfill closure.

In principle, the minimum Subtitle D landfill should prevent off-site groundwater pollution by landfill leachate based on the single composite liner and the associated leachate collection removal system, cover and groundwater monitoring systems. Basically, Subtitle D regulations attempt to create a "dry tomb" of municipal solid wastes where the wastes will be isolated through plastic sheeting (FML) and compacted clay from moisture that would generate leachate. Any leachate that is generated in the landfill would, in principle, be collected in the leachate collection and removal system. If this system fails to collect all the leachate and some of it passes through the liner system, then the groundwater monitoring system would detect the leachate-polluted groundwaters at the point of compliance for groundwater monitoring, thereby enabling the landfill owner to determine the extent of the leachate release through the liner system and initiate remediation of the groundwaters to control off-site leachate migration.

The US EPA claims in the preamble to the Subtitle D regulations that minimum Subtitle D landfills can be sited at any location, even a poor location, and protect groundwaters from pollution by landfill leachate. However, there is increasing recognition of what was obvious to some at the time that the US EPA promulgated Subtitle D regulations in 1991, that at best minimum Subtitle D MSW landfills sited at geologically unsuitable sites where there is no natural protection of the groundwater resources hydraulically connected to the base of the landfill, will only postpone when groundwater pollution occurs by landfill leachate. Contrary to the US EPA's preamble statement, a minimum Subtitle D landfill will not protect vulnerable groundwaters from pollution by landfill leachate for as long as the wastes in the landfill will be a threat.

REVIEW OF SUBTITLE D LANDFILL CONTAINMENT AND MONITORING SYSTEMS

In order to assess the potential of an existing or proposed landfill to pollute the environment (water, soil and air) in the vicinity of the landfill, it is necessary to understand the characteristics of the landfill with respect to its siting, design, closure and post-closure care. A review of these issues as they relate to the development of minimum Subtitle D landfills is presented herein. This section presents an overview review of the expected performance of each of the key components of a minimum Subtitle D landfill containment and monitoring system. The authors have developed comprehensive literature reviews on each of the topic areas discussed. Some references to their work as well as the work of others are provided herein. Additional references to the literature are provided in the papers and reports listed in the reference section of this paper.

Throughout this discussion, the term "minimum Subtitle D landfill" is used. This refers to the design, operation and closure of a landfill that meets the US EPA's regulatory minimum set forth in the 1991 regulations (US EPA, 1991). The sphere of influence of a Subtitle D landfill can extend not only to the immediate sphere of several miles for those directly impacted, but as discussed by Lee and Jones-Lee (1997a), considerable distances from the landfill through affecting agricultural or other economic interests near the landfill through actual or perceived tainting of the crop through airborne and waterborne releases from the landfill that cause the farming and/or other interests to experience a decreased value of their crop. This, in turn, can adversely impact economic interests who depend on the agricultural or other activities for sales or employment located many miles from the landfill.

The discussions presented herein apply to essentially all Subtitle D landfills being permitted today. Some landfill applicants and their consultants claim in landfill permitting hearings that their proposed landfill or landfill expansion design, operation, closure and/or post-closure care represent more than the minimum required under Subtitle D regulations. It is the authors' experience that this so-called "more than the minimum," while possibly affecting when groundwater pollution occurs, does not change the fact that ultimately Subtitle D landfills sited at geologically unsuitable sites for which there is no long-term natural protection of the groundwater resources connected to the base of a landfill through a vadose zone will pollute these groundwater resources at some time in the future, rendering them unusable for domestic and many other purposes.

Liner System

A critical review of the information available at the time that the US EPA promulgated Subtitle D regulations in 1991 shows that the "dry tomb" landfilling approach in which a single composite liner is used in an attempt to collect leachate that can be generated in a minimum Subtitle D MSW landfill for as long as the waste in the landfill represents a threat, shows that this landfilling system is fundamentally technologically flawed. Of particular concern is the ability of flexible membrane liners, such as those constructed from HDPE, to function as an effective barrier to moisture/leachate transfer through them. Lee and Jones-Lee (1992, 1994a, 1995a) discuss that the "dry tomb" type landfill can be expected to increase the period of time that the wastes in the landfill will be a threat. The key to determining this length of time is the availability of moisture which allows fermentation and leaching of the wastes to take place. By severely restricting moisture entering the landfill, the time for completion of fermentation and leaching of the wastes can effectively become infinite.

Belevi and Baccini (1989) reported that classical sanitary municipal solid waste landfills in which there is no attempt to restrict moisture entering into the wastes except through the conventional sanitary landfill cover, can be expected to produce leachate that is a threat to groundwater quality for a thousand or more years. Freeze and Cherry (1979) reported that Roman Empire landfills are still producing leachate, some 2,000 years after their construction. These are landfills in wet climates where there is an opportunity for moisture to interact with the wastes. While the minimum Subtitle D "dry tomb" landfill will not, as currently being developed, create a true "dry tomb" which will keep the wastes dry in perpetuity, the "dry tomb" landfilling approach will cause the wastes to be a threat to groundwater quality, effectively forever. For planning purposes, it should be assumed that the wastes in a minimum Subtitle D landfill will be a threat to generate leachate that can pollute groundwater forever.

By the late 1980s it was beginning to be understood that HDPE liners of the type that are used in municipal solid waste landfills have finite periods of time when they can be expected to function effectively for leachate collection and thereby serve as a barrier to leachate migration through the liner system. It is now well-known that HDPE and other liner materials will not prevent leachate generated in the landfill from entering the underlying groundwater system associated with a landfill sited where there are groundwaters hydraulically connected to the base of the landfill through a vadose zone. As discussed by Lee and Jones (1992, 1993) and Lee (1994) there are a variety of known mechanisms for HDPE degradation, such as free radical attack, as well as unknown mechanisms by which HDPE liners and other flexible membrane liners can be expected to degrade while the wastes in the landfill are still a threat.

The US EPA Solid Waste Disposal Criteria (August 30, 1988a) state,

> *"First, even the best liner and leachate collection system will ultimately fail due to natural deterioration, and recent improvements in MSWLF (municipal solid waste landfill) containment technologies suggest that releases may be delayed by many decades at some landfills."*

The US EPA Criteria for Municipal Solid Waste Landfills (July 1988b) state,

> *"Once the unit is closed, the bottom layer of the landfill will deteriorate over time and, consequently, will not prevent leachate transport out of the unit."*

The US EPA at the time of initial promulgation of the Subtitle D regulations faced a threat of a court order arising from litigation initiated by environmental groups for failure to comply with RCRA requirements for promulgating regulations for the landfilling of municipal solid waste as required by the reauthorized RCRA. This situation led to the Agency adopting Subtitle D regulations that were known or should have been known at that time would only postpone when groundwater pollution occurs.

Upon release of the 1991 regulations, the authors contacted the US EPA Office of Solid Waste and found that the administrators of the program, Clay (1991) indicated that the Agency still believed that ultimately the landfill liner systems would fail. However, this failure would be detected by the groundwater monitoring systems that are required. As discussed below, however, while the Agency prescribed a groundwater monitoring system performance that if achieved would be protective, in fact, the groundwater monitoring systems actually used today are fundamentally flawed in achieving this level of protection.

Peggs (1998) has recently reviewed some of the issues that need to be considered in using flexible membrane liners and other geosynthetic materials in municipal solid waste and hazardous waste landfills. As he discusses, there are a number of significant technological problems associated with geomembranes that can cause these materials to fail to function as designed for as long as the wastes in an MSW landfill will be a threat.

Recently, Dellinger, current Director of the US EPA Office of Solid Waste, has indicated that the Agency still maintains the position that minimum Subtitle D landfills can be sited at sites without natural protection and still be protective of groundwater resources (Dellinger, 1998). This protection, however, is based on a risk assessment that was performed by the Agency in the early 1990s which assumed that the period of concern was 300 years and that only a limited number of people would reside within the sphere of influence of the landfill. Based on Dellinger's recent comments, this protection is based on the assumption that only a slow rate of leakage of leachate through the liner system will occur. It does not consider the fact that ultimately the liner systems that are used could readily allow for widespread failure that could influence groundwater quality at considerable distances beyond the US EPA's adopted conditions for its risk assessment. Another error made by the US EPA in its risk assessment is the assumption that the only costs associated with liner failure and leachate pollution of groundwaters would be the cost of replacing the domestic water supply for those who use groundwaters within the sphere of influence of the landfill. The US EPA failed to address the situation which will occur in some areas of there not being alternative sources of water supply for domestic and agricultural uses that are readily available as an alternative supply for the leachate-polluted groundwaters. Overall, in the early 1990s and today, the US EPA is still conducting an inappropriate assessment of the ability of a minimum Subtitle D landfill sited at geologically unsuitable sites where there is no natural protection of groundwater from pollution by landfill leachate to protect the health, groundwater resources, welfare and interests of those within the sphere of influence of the landfill. The Agency in 1990 and today is still attempting to practice cheaper-than-real-cost garbage disposal at the expense of those within the sphere of influence of the landfill.

In summary, the wastes in a minimum Subtitle D, "dry tomb" type landfill will be a threat to pollute groundwaters, effectively forever. While it is not possible to reliably predict how long the FML-based liner system will function as an effective barrier to leachate passage through it and thereby collect leachate generated in the landfill, it is clear that the FML component of the liner system will become an ineffective barrier to prevent leachate from passing into the underlying groundwater system for as long as the wastes in a landfill will be a threat. The net result is that the landfill liner system which cannot be inspected and repaired cannot be relied on as an effective barrier to prevent leachate generated in the landfill from passing into a groundwater system of the landfill region.

At the time of construction, the compacted clay layer of a single composite liner could under one foot of head, restrict the passage of leachate through the 2 ft thick liner for about 25 years assuming that a permeability of 10^{-7} cm/sec is achieved in this layer. However, there are several mechanisms that can cause compacted clay layers to allow leachate to pass through them at a much higher rate than predicted based on design characteristics (Lee and Jones, 1992). One of the most important issues that is not now being addressed is the desiccation cracking of this clay layer due to the unsaturated transport of the moisture that is added to the clay at the time of construction in order to achieve an optimum or near optimum moisture density relationship. This moisture will move by unsaturated transport out of the clay into the underlying strata. This, in turn, can cause desiccation cracking of the clay. These cracks can serve as pathways for rapid transport of leachate that passes through holes that occur or develop in the overlaying FML. The re-wetting of these cracks does not lead to attainment of the original design permeability.

Another problem that is occurring today in landfill liner design is associated with the substitution of geosynthetic clay layers for 2 ft thick compacted clay layers. The geosynthetic clay layers consist of a thin layer of bentonite clay sandwiched in a porous geosynthetic material (not a FML). While the advective transport of water through geosynthetic clay layers can be measured as 10^{-8} or 10^{-9} cm/sec, such measurements are not reliable indicators of the rate of transport of leachate through the clay layer. Gray (1988) reported that diffusion becomes the dominant transport mechanism through clay layers when the permeabilities are less than about 10^{-7} cm/sec.

Another problem with geosynthetic clay layers, is that their thinness can lead to cracking unless a well-prepared base underlies the layer. Further, bentonite-type clays used in geosynthetic clay liners are subject to cation exchange in which the sodium in the clay is substituted by calcium and magnesium. Such substitution leads to a shrinking of the clay lattice and cracking (Lee and Jones, 1992).

Landfill proponents and their consultants frequently assert at landfill permitting hearings that there are no documented cases of groundwater pollution by today's Subtitle D landfills as part of an effort to try to gain approval for a minimum Subtitle D landfill. However, as discussed by Lee and Jones-Lee (1996a) such claims are without technical merit from several perspectives. First and foremost is the fact that the failure of a minimum Subtitle D composite liner would not be expected to have occurred in the approximately four years that Subtitle D landfilling has been required nationally. The possible exception would occur under extremely poor quality design and construction or inappropriate initial waste placement within the landfill that ruptures the liner. There are some areas, such as New York and New Jersey, where landfills similar in design with respect to requiring a minimum single composite liner have been used since the mid-1980s. Early experience with single composite liners in these states caused the state regulatory agencies to adopt double composite liners for MSW landfills.

The second reason why the ultimate failure of minimum Subtitle D landfills has not been detected is that as discussed herein, the groundwater monitoring systems being developed by landfill proponents and allowed today by regulatory agencies are inadequate to detect leachate polluted groundwaters when they first reach the point of compliance for groundwater monitoring. A critical review of the reliability of the groundwater monitoring systems used shows that they would not be expected to detect leachate polluted groundwater associated with the initial failure of the FML in a minimum Subtitle D landfill. This issue is discussed further below.

It is inappropriate for anyone to claim that because there are no documented cases of groundwater pollution by minimum Subtitle D landfills in the four years that Subtitle D landfilling has been required, that minimum Subtitle D landfilling will protect groundwaters from pollution by landfill leachate for as long as the wastes in the landfill will be a threat. Obviously this will not be the case.

Leachate Collection System

The functioning of the leachate collection and removal system is dependent on the integrity of the flexible membrane liner. While these systems are designed to maintain a low head on the liner, throughout most of the base of the landfill except near the sump where as much as one foot of head (depth of leachate) can occur, leachate collection and removal systems are well-known to clog due to biological and chemical fouling (Lee and Jones, 1992). This clogging leads to a build-up of leachate behind the clogged areas which when it intersects a hole in the FML increases the rate of leakage through the hole.

Landfill Cover

The landfill cover system for a Subtitle D landfill typically consisting of a plastic sheeting layer (FML) located below a drainage layer and topsoil of two or more feet thick can, at the time of construction, represent an effective barrier which can prevent moisture from entering the closed landfill and generating leachate within the landfill. However, the low permeability layer (compacted clay or flexible membrane liner) is well-known to be subjected to severe stresses which can readily lead to failure of this layer to prevent moisture from entering the landfill (Lee and Jones, 1992; Lee and Jones-Lee, 1995a;1997b; Daniel & Koerner, 1991). While often the HELP model is used to predict infiltration of moisture into a landfill as part of the design and permitting of the landfill, the HELP model only applies to situations that exist at the time that the landfill cover is constructed and cannot be used as a reliable basis for estimating the rate of moisture entering the landfill for as long as the wastes in the landfill will be a threat.

While it is often stated by landfill applicants and regulatory agencies that a landfill cover can be repaired should problems develop in it, this repair pertains to the visual defects associated with major deformities in the topsoil surface. Defects in the low permeability layer which is a key layer for preventing moisture from entering the landfill that generates leachate can readily occur without being detected by visual inspection of the surface of the landfill. Further, even if defects of the low permeability layer could be detected from the surface, the post-closure funding requirements of Subtitle D do not provide the necessary assured funding to maintain the cover to restrict moisture from entering the landfill for as long as the wastes are a threat, i.e. forever. The net result is that a minimum Subtitle D landfill cover as currently required is largely a facade with respect to preventing leachate from being generated in a landfill that can lead to groundwater pollution when this leachate passes through the failed landfill liner system.

Groundwater Monitoring

The groundwater monitoring system prescribed by the US EPA and Subtitle D regulations is supposed to be a fail-safe system where if, or more properly when, the moisture that passes through the cover generates leachate that passes through the failed liner system into the underlying groundwaters is detected at the point of compliance for groundwater monitoring. The US EPA (1991) in Subtitle D groundwater monitoring system requirements stated:

> *"The design must ensure that the concentration values listed in Table 1 of this section not be exceeded in the uppermost aquifer at the relevant point of compliance..."*

and specify that

> *"(a) A ground-water monitoring system must be installed that consists of a sufficient number of wells, installed at appropriate locations and depths, to yield ground-water samples from the uppermost aquifer (as defined in '258.2) that: (2) Represent the quality of ground water passing the relevant point of compliance..."*
>
> *"(c) The sampling procedures and frequency must be protective of human health and the environment."*

While as written, a groundwater monitoring system that complies with this requirement would be protective, i.e. have a high probability of detecting leachate-polluted groundwaters when they first reach the point of compliance for groundwater monitoring, examination of the typical approach used for complying with this monitoring requirement shows that regulatory agencies allow vertical monitoring wells to be spaced hundreds to 1,000 or more feet apart along the point of compliance for groundwater monitoring. The way these monitoring wells are operated in which three bore hole volumes are extracted prior to actual sampling means, that in many aquifer systems the groundwater monitoring wells sample about one foot on each side of the well. Therefore, unless the initial leakage through the landfill liner system produces large plumes of leachate-polluted groundwater, polluted groundwater could readily pass by the point of compliance and not be detected by the wells.

Cherry (1990) in his classic 1990 paper on the unreliability of groundwater monitoring near landfills pointed out that the initial leakage through a plastic sheeting-lined landfill, such as a minimum Subtitle D landfill, will be significantly different in character than unlined landfills. While classical sanitary landfills effectively leak from all locations underlying the landfill and produce large plumes of leachate-polluted groundwater, plastic sheeting-lined landfills produce finger-like plumes of leachate of a few feet to a few tens of feet in width for many types of aquifer systems. Parsons and Davies (1992) discuss the approach that should be used in developing monitoring well spacing for groundwater monitoring of plastic sheeting-lined landfills. They point out that the zones of capture of the monitoring wells should have a high probability of intersecting the initial plumes of leachate-polluted groundwaters before they pass the point of compliance for groundwater monitoring. While for the classical unlined sanitary landfill, monitoring wells spaced hundreds or 1,000 feet or so apart down groundwater gradient of the landfill can be effective in detecting groundwater pollution by landfill leachate before off-site groundwater pollution occurs for many but not all hydrogeologic systems, for plastic sheeting-lined landfills, i.e. minimum Subtitle D landfills, the monitoring well spacing must be developed based on the premise that the initial leakage from the landfill produces finger-like plumes of limited lateral dimensions. The net result is that the groundwater monitoring system that is typically used for minimum Subtitle D landfills is fundamentally flawed in complying with US EPA requirements of detecting leachate-polluted groundwaters before widespread off-site pollution occurs.

The unreliability of groundwater monitoring systems discussed above applies to systems where there is a fairly well-defined, predictable hydrogeology governing the transport of leachate-polluted groundwaters. Subtitle D regulations, however, allow landfills to be constructed at locations where the geological strata under the landfill are fractured rock in which the leachate-polluted groundwater will move along the fractures. This creates a much more complicated groundwater monitoring problem. Haitjema (1991) states,

> *"An extreme example of Equation (I) (aquifer heterogeneity) is flow through fractured rock. The design of monitoring well systems in such an environment is a nightmare and usually not more than a blind gamble."*
>
> *"Monitoring wells in the regional aquifer are unreliable detectors of local leaks in a landfill."*

Additional information on deficiencies in groundwater monitoring systems typically used at Subtitle D landfills is provided by Lee and Jones-Lee (1994b, 1997c).

Permeation

While well-understood as a potential mechanism for groundwater pollution associated with HDPE-lined landfills, permeation of organic solvents through HDPE landfill liners is largely ignored by landfill owners, operators and regulatory agencies in the development of MSW landfills under Subtitle D. Haxo and Lahey (1988) were the first to point out that organic solvents, such as trichloroethylene, benzene, toluene, etc., that are available from the local hardware or paint store which can be disposed of in a MSW landfill in a small container can readily pass through an intact (without holes) high-density polyethylene liner in a short period of time. Permeation involves the interaction of organic solvents with the liner organic matrix where the organic solvents dissolve into the organic matrix and pass through the liner. Sakti *et al.* (1991) and Park *et al.* (1996a,b) found that a variety of dilute concentrations (100 mg/L) of aqueous solvents which could be present at some locations in a landfill associated with the disposal of a small container containing one of these solvents could pass through the HDPE liner in a few days time. They found that a variety of dilute aqueous solvents could pass through 100-mil (2.54 mm) HDPE in 13 days. Subtitle D regulations allow the use of HDPE liners for landfills that are only 60 mil thick. Half a gallon of trichloroethylene which can be purchased at many locations for home use when disposed of in a municipal landfill has the potential to pollute over one million gallons of groundwater above drinking water standards (Lee and Jones, 1992). Some of this solvent would not be collected in leachate collection systems, but would pass through the FML on the way to the leachate collection system sump. This passage through the liner would not be through holes in the liner, but through the intact liner. Buss *et al.* (1995) consider permeation of organic solvents to be an important mechanism for groundwater pollution by MSW landfill leachate. The water quality significance of permeation of solvents through flexible membrane liners needs to be considered in the siting and development of MSW landfills that are hydraulically connected to high-value groundwaters that could be used for domestic water supply purposes at some time in the future.

Landfill Gas Releases

Lee and Jones-Lee (1994c) have reviewed the potential impacts of gaseous and other releases from landfills on public health and the environment. As they discuss, there are numerous documented cases of the methane in landfill gas through subsurface soil migration leading to explosive conditions in buildings and other structures at considerable distances from the landfill. Landfill gas migration is also a well-known cause of damage to vegetation through blocking of oxygen transport to plant roots. This can lead to large areas of no plant growth on landfill covers. Of particular importance is harm to turf grass as part of golf courses constructed on old landfills. Further, there is increasing recognition that landfill gases contain a variety of hazardous components that are a threat to cause cancer in man and animals (Hodgson *et al.*, 1992). Hazardous airborne chemical release studies have shown that VOC releases from landfills have been predicted to increase the cancer risk to people living near and downwind from the landfill by a factor of 10 compared to those living nearby but outside the sphere of influence of landfill gas releases. An area that is not often considered is the impact of VOC releases from landfills is the impact on wildlife populations who graze on or near landfills. These animals are exposed to higher concentrations of potential carcinogens associated with their grazing than are of typical concern associated with landfill gas impact evaluations where appreciable dilution of the gas occurs.

Prosser and Janechek (1995) have presented a review of the potential for subsurface migration of landfill gas-associated VOCs to cause groundwater pollution. They point out that VOC migration from landfills is a far more common cause of groundwater pollution than generally suspected. This pollution can occur up hydraulic groundwater gradient for a landfill leading to contamination of upgradient reference wells.

One of the typical methods of "control" of landfill gas emissions is the flaring of the landfill gas in a gas combustor. Eden (1993) has found that typical landfill gas combustors provide the necessary conditions to convert landfill gas components to dioxins. While not typically conducted today, landfill gas combustion through flares or other processes should be evaluated with respect to the production of dioxins that represent a threat to public health, surface water resources and the environment.

Post-Closure Funding

Current minimum Subtitle D MSW landfilling requirements mandate that post-closure care funding is provided during the active life of the landfill to close the landfill in accord with minimum Subtitle D requirements and to maintain the cover with respect to its obvious physical characteristics as viewed from a walk-over of the landfill surface as well as to operate the groundwater monitoring system. A review of the typical post-closure funding requirements established by regulatory agencies shows that the funding levels required are minimal and, at best, can be characterized as enough to kick dirt into the obvious holes in the landfill cover (Lee and Jones-Lee, 1995a). This funding is significantly deficient compared to that needed to ensure that the closed landfill will not be significantly detrimental to the health, groundwater resources, welfare, economic and other interests of those within the sphere of influence of the landfill (Lee and Jones-Lee, 1992, 1994a). The 30-year mandated funding period which is addressed through the development of funding during the active life is an infinitesimally small part of the total period of time for which funding will be needed to properly close and maintain a municipal solid waste landfill at most locations where they are now being permitted (Lee and Jones-Lee 1992, 1993a, 1994a, 1995a).

Summary of the Deficiencies of Subtitle D Landfills

From an overall perspective, not only will minimum Subtitle D MSW landfills sited at geologically unsuitable sites, i.e. those where there are usable quantities of groundwater hydraulically connected either directly or through a vadose zone to the base of the landfill, pollute the groundwaters in the vicinity of the landfill during the time that the landfill wastes will be a threat. This pollution will most likely first be detected in off-site, adjacent/nearby property owners' production wells used for domestic and other purposes. The "dry tomb" landfilling approach, coupled with the landfill containment system design and the inadequate post-closure care funding that is provided as part of permitting minimum Subtitle D landfills leads to a fundamentally flawed approach for managing municipal solid wastes where those who generate the wastes, i.e. today's public and commercial establishments, are able to have their wastes disappear from their premises at far less than the true long-term costs associated with proper waste management.

Landfill applicants and their consultants frequently assert that the landfill containment and monitoring systems provide a high degree of redundancy in protecting groundwaters from pollution by landfill leachate. A critical unbiased examination of this claim shows as discussed herein and in the literature, that each of the so-called redundant components of the landfill containment system and its groundwater monitoring system are fundamentally flawed with respect to performing as required by Subtitle D to protect groundwaters from pollution by landfill leachate, for as long as the waste in the landfill will be a threat. There is no reliable redundancy associated with today's minimum Subtitle D landfills.

In 1993, the League of Women Voters' book entitled, "The Garbage Primer: A Handbook for Citizens" included a chapter devoted to landfills. In its discussion of "state-of-the-art" landfills entitled, "How Safe Is State-of-Art?" it was stated with reference to the lined, "dry tomb" type MSW landfills prescribed by US EPA's Subtitle D,

> *"The term 'state-of-the-art' evokes unequivocal faith in current science and technology. However, even the best liners will eventually degrade, tear, or crack. Landfills are designed to accept waste for 10-40 years, and the new EPA regulations require owners to maintain and monitor their landfills for at least 30 years after closure. The questions remain. What happens after 30 years? Who will need protection then? Who will pay for cleaning up ground and surface water sources when leaks occur?*
>
> *State-of-the-art landfills may not be a cure, but they are a tremendous improvement over their predecessors."*

The concerns expressed about reliance on so-called "state-of-the-art" landfills for protection of groundwater resources are justified. However, the concluding statement quoted, regarding the comparative safety of classical unlined sanitary landfills and Subtitle D landfills, deserves further examination. Lee and Jones-Lee (1993b) have reviewed the question of whether Subtitle D landfills represent a significant improvement over classical sanitary landfills. As they discuss, is it really better for today's society to practice MSW landfilling which only postpones groundwater pollution where the impacts and costs are passed on to future generations, rather than being experienced by those who generate the wastes? If each subdivision of a metropolitan area had its own landfill for managing its own wastes and was dependent on local groundwater as a water supply source, the active life and long-term problems associated with MSW landfilling would be more appropriately addressed than is being done today. As long as the majority of the public who generate the wastes can pass the impacts from inadequate waste management on to others who are in the unfortunate position of having acquired property or otherwise use lands near an existing or proposed landfill, the problems with landfilling of municipal solid waste will continue.

The statement in the preamble to the US EPA Subtitle D regulations (US EPA, 1991) about Subtitle D landfills being protective of groundwater resources from pollution by landfill leachate, even at poor sites, is based on an inappropriate assessment of what was known at the time, much less today, about the ability of minimum Subtitle D landfill liner systems, leachate collection and removal systems, cover, groundwater monitoring systems and post-closure care funding to develop, operate, close and maintain a landfill. A review of the basis for this statement provided by the US EPA shows that the Agency assumed a low density of population that would consume groundwaters that could be polluted by a landfill leachate. They also assumed that the landfill would only represent a threat for a limited amount of time compared to the infinite period of time that the wastes in a "dry tomb" Subtitle D landfill will be a threat as well as there being a readily available alternative source of groundwater that can be used as a water supply when leachate pollutes an adjacent property production well located near the landfill.

This "protective at any location" statement is also based on considering the only adverse impact of MSW leachate pollution of groundwaters being the risk of individuals consuming the water acquiring cancer. It does not consider the adverse impacts on agricultural water supplies and many other impacts of municipal solid waste leachate as it may impact a homeowner or agricultural interest's use of a groundwater water supply. Jones-Lee and Lee (1993) and Lee and Jones-Lee (1996b) have discussed the pollutional characteristics of MSW landfill leachate, pointing out that Subtitle D focuses on so-called known hazardous Priority Pollutants and largely ignores the groundwater use impairment that can occur from conventional pollutants, as well as the unregulated, hazardous constituents present in MSW leachate. As they discuss, only about 100 chemicals out of the over 75,000 chemicals in use today are regulated with drinking water standards (MCLs). Typically, 95% or more of the organics in MSW leachate-polluted groundwaters are uncharacterized. Based on the total organic carbon content of MSW leachate there could readily be a variety of hazardous and deleterious constituents in MSW leachate-polluted groundwaters which are not now being analyzed for/regulated.

The chemicals of potential concern are not necessarily exotic chemicals that are not commonly used. Gintautas *et al.* (1992) reported finding phenoxyalkanoic acid herbicides in municipal landfill leachate that were migrating through groundwater systems. These herbicides were derived from homeowners' use on lawns. Since they are not on the Priority Pollutant list, they are not analyzed for in the typical groundwater pollution investigation associated with MSW landfills. The current US EPA RCRA approach of focusing groundwater pollution on a few Priority Pollutants is significantly deficient in protecting public health and groundwater resources from impaired use by MSW leachate.

The importance of the conventional pollutants in MSW leachate which are not now adequately regulated by Subtitle D was discussed by the US EPA (1988b) in the Agency's discussion of the potential impacts of municipal solid waste leachate on groundwater quality. The US EPA acknowledged what is well-known - that once a groundwater is polluted by municipal landfill leachate, the well has to be abandoned because of the large number of hazardous or otherwise deleterious constituents present in the leachate. These include taste- and odor-producing compounds that would cause the water to be unsuitable for domestic purposes without extensive, expensive treatment.

Ultimately, today's minimum Subtitle D landfills at most locations where they are being developed will become tomorrow's "Superfund" sites where millions of dollars will have to be spent in an attempt to clean up the polluted groundwaters, and large amounts of money will have to be devoted to trying to stop further groundwater pollution by the residual wastes present in the landfill when the groundwater pollution is discovered. Further, more importantly, groundwater resource loss will occur which will never be recovered since once a groundwater is polluted by municipal landfill leachate, the aquifer can never be cleaned up to a satisfactory degree so that it can be considered safe for human consumption and many other potential uses (Lee and Jones-Lee, 1996b; Rowe, 1991).

Other Problems with Minimum Subtitle D Landfills

The problems with minimum Subtitle D landfills are not restricted to groundwater pollution. While the US EPA in its Subtitle D regulations asserted that the adoption of these regulations should minimize the NIMBY (not-in-my-backyard) approach that landfill developers encounter by those living or owning properties near a proposed or existing landfill, those who developed this statement obviously did not understand the basic justified nature of NIMBY. The authors have yet to find anyone who feels that a modern "high technology" Subtitle D landfill would be a good neighbor and thereby not be adverse to their interests. Municipal solid waste landfills, including today's minimum Subtitle D landfills, are, in general, poor neighbors to people who own or use properties within several miles of the landfill for a variety of reasons. These include:

Problem --- **Impact**

- Groundwater and surface water quality B public health, economics, aesthetics
- Migration of methane and VOCs - public health, explosions, toxicity to plants and animals
- Illegal roadside dumping and litter near landfill - aesthetics, public health, economics
- Truck traffic - highway safety and public health
- Noise - nuisance, public health
- Odors - nuisance, public health
- Dust - nuisance, public health
- Wind-blown litter - aesthetics, public health
- Vectors, insects, rodents, birds - nuisance, public health
- Condemnation of adjacent properties for many future uses
- Impaired view
- Decreased property values.

Lee and Jones-Lee (1993c, 1994c,d; 1997a,d) have discussed justified NIMBY associated with the typical approach for developing MSW landfills followed today. Hirschfeld, *et al.* (1992) have reported that municipal solid waste landfills can affect property values for several miles from the landfill waste disposal area. This impact is typically related to landfill releases (odors, gases, dust, fugitive waste, birds, vectors, etc.) during the active life of the landfill. These issues, however, were not addressed at all or adequately addressed by the US EPA in its Subtitle D regulations. There is no justification for the US EPA to claim that justified NIMBY would be lessened through adoption of the minimum Subtitle D landfilling approach set forth in 1991.

Impact on Waste Recycling and Reduction

Another consequence of the artificially low tipping fees that are being charged today for minimum Subtitle D landfilling is that it is strongly detrimental to the 3Rs - waste reduction, recycling and reuse. The 3Rs typically cost on the order of $100 to $120/ton. When the tipping fees for disposal of municipal solid wastes are from $20 to $40/ton, the economics are such that there is little incentive to practice the 3Rs. The so-called economic advantage of landfilling of recyclable materials is based on a flawed analysis of economics that does not consider the long-term, Superfund-like costs that will ultimately have to be borne by future generations as the result of this generation failing to properly manage its MSW.

The recycling, reuse and reduction of MSW components should be an important part of MSW management. While Tierney (1996) claimed that the practice of the 3Rs was inappropriate because of the high cost compared to conventional Subtitle D landfilling and because of the "safety" of today's landfills, Lee and Sheehan (1996) and Lee and Jones-Lee (1997e) discussed the flawed analysis conducted by Tierney in developing this conclusion. As they discuss, the practice of the 3 R's is an important component in reducing the amount of groundwater pollution that will occur from Subtitle D landfills through reducing the number of such landfills that will be needed. Reducing the number of landfills will lead to less new areas where Subtitle D landfills will pollute groundwaters. It is possible to achieve 50% reduction/diversion of the municipal solid waste stream from MSW landfills without significantly changing current waste generation approaches. Several states such as California, have mandated that this level of waste reduction/diversion shall be achieved by the year 2000. Achieving this level of waste diversion will significantly extend the existing state's landfill's operating life and reduce the number of new landfills that will be needed to manage MSW.

As discussed by Lee and Jones-Lee (1997e) and herein, in order to promote the practice of 3Rs, it is important that the true costs, including the ultimate "Superfund"-like costs of today's minimum Subtitle D landfills be incorporated into the disposal fees (tipping fees) used. When this is done, the practice of the 3Rs will be much more competitive with MSW landfilling. Additional justification for the practice of the 3Rs is the conservation of natural resources by reducing the amount of raw material "mining" needed to provide the feedstock for the goods that can be recycled/reused.

Environmental Ethics in the Permitting of Landfills

It is appropriate to ask why there is not more discussion of the deficiencies of Subtitle D landfills to protect groundwaters from impaired use for as long as the wastes represent a threat than is occurring today by those familiar with these deficiencies. This is an issue that Lee and Jones-Lee (1995b) addressed in a review of the environmental ethics issues associated with the permitting of landfills. Many individuals working with landfill companies, public agencies and consultants to landfill developers understand many of the deficiencies in today's Subtitle D landfills. There are few, however, who will speak out on them. The basic problem is that if a consultant openly discusses these issues, they will find that they will not get another job for a landfill developer. Others, however, such as editors or columnists for some solid waste trade magazines and other public magazines, are speaking out on these issues. For example, Michaels (1998) who writes "Solid Waste Forum" for *Public Works* magazine has repeatedly discussed in this monthly column the significant deficiencies that exist in the approaches that are being used today in the development of Subtitle D landfills. Further, in a recent editorial for *MSW Management*, Trotti (1996) has discussed the longer-term problems with today's Subtitle D landfills. There is growing recognition that the US EPA and the state regulatory agencies must stop the facade that exists today that minimum Subtitle D landfills sited at most locations where they are being permitted will be protective of groundwater resources for as long as the wastes in the landfill will be a threat.

Lee and Jones (1992) have documented a number of situations where landfill applicant consultants that represent national consulting firms have repeatedly deliberately distorted the professional literature on the findings of others with respect to the ability of landfill liner systems to protect groundwaters from pollution by landfill leachate. The problem centers around quoting one paragraph from a particular report or paper which seems to indicate that the landfill liner system will be protective, but failing to quote the next sentence or paragraph which qualifies what defines or is meant by protective. This approach violates professional engineers codes of ethics for public safety.

Lee and Jones-Lee (1995b) have discussed an approach for addressing the significant environmental ethics problem that exists today where those proposing the landfill or consultants working on behalf of landfill applicants take an adversarial approach and only present the positive aspects of the landfill without discussing the negative aspects, such as the long-term failure of the liner system, the unreliability of the groundwater monitoring system, etc. Such an approach for professional engineers is in violation of several professional engineering codes of ethics which require full disclosure of public health and safety issues as part of engineering practice.

Lee and Jones-Lee (1997f) have developed a set of questions that landfill proponents and their consultants, as well as regulatory agency boards and their staff should answer in a peer review arena associated with the permitting of a proposed new or expanded Subtitle D landfill. This peer review should be a full public peer review of the adequacy of the proposed design, operation, closure and post-closure care of a proposed new or expanded landfill is reviewed before the regulatory board and the public. This peer review would enable presentation of differing opinions and supporting documentation on the ability of the liner system, cover, groundwater monitoring system or the adequacy of post-closure care to protect public health and the environment during the active life of the landfill and for as long as wastes in the landfill represent a threat.

The current regulatory board review of proposed landfills permits individuals to make statements about issues which are obviously not technically valid and in accord with what is well known in the literature today. Under the recommended full, public peer review process, each proponent of a particular position would present their position along with any supporting evidence and be questioned by those who have differing findings. Adoption of this approach could lead to regulatory boards and the public receiving the whole truth - full disclosure on the deficiencies in Subtitle D landfilling. Once these problems are openly discussed and understood by the public, it will be possible to develop truly protective landfills that address justifiable NIMBY during the active life and the long-term threats that MSW in a "dry tomb" landfill represents to groundwater resources in the vicinity of the landfill.

Many landfills require that an environmental impact assessment (statement/report) be developed as part of the initial phase of permitting of the landfill. The environmental assessments developed by landfill applicants and their consultants typically present a superficial discussion of potential environmental impacts of a proposed landfill or landfill expansion and thereby fail to reliably inform the county boards of supervisors and others responsible for evaluating the potential environmental impact of the potential problems of a proposed landfill. The environmental assessment should provide full disclosure of active life and long-term problems associated with the proposed landfill. Environmental assessments, even when developed by consultants selected by other than the landfill proponent, are examples of the environmental ethics problems discussed herein. Environmental assessment firms know that if they provide the whole truth in discussing potential impacts of proposed landfills that they will not gain another contract to do work for another client on landfill matters. The worst-case scenario failure approach described herein should be the key component of the environmental impact assessment. Those who prepare environmental impact assessments on landfills, should be required to provide full disclosure discussions of potential problems of a proposed landfill. This full disclosure presentation should be subject to full public peer review of the type described herein.

ALTERNATIVE LANDFILLING APPROACHES

The authors through their publications on today's municipal solid waste landfilling approach problems have suggested alternative approaches for municipal solid waste management using landfilling that will protect public health, groundwater resources and the interests of those within the sphere of influence of the landfill for as long as the wastes in the landfill represent a threat. It is the authors' finding that municipal solid waste landfills can be developed which will be protective of the health, welfare and interests of those within the sphere of influence of the landfill for as long as the wastes represent a threat for a cost of about 10 to 20 cents per day per person who deposits wastes in a landfill during the active life of the landfill (Lee and Jones-Lee, 1993c; 1997a). An overview of the basic approach that should be followed in developing a protective landfill is presented below. Additional information on each of the components of this approach are provided in the references sited herein.

Assessing/Controlling the Potential of a Subtitle D Landfill to Pollute

There are a number of factors that determine whether a proposed MSW landfill will pollute the environment in the vicinity of the landfill. They include landfill siting, design, operation, closure and post-closure care. These issues are summarized in the following section.

Landfill Siting

The key to assessing/controlling whether a potential Subtitle D landfill could pollute groundwaters and the environment is a review of the site characteristics. Of particular importance is the adequacy of the bufferlands owned by the landfill owner between the areas where wastes will be deposited and the adjacent property line. Associated with the development of a landfill should be a critical review of landfill siting issues with reference to managing the emissions and the other adverse impacts of the landfill during its active life and post-closure care period. Of particular concern for active life emissions is adequate bufferland owned by the landfill owner to dissipate all of the emissions, such as odor, blowing trash, dust, etc., on the landfill owner's property so they do not trespass onto adjacent properties. It is the author's experience that at least one mile and preferably two miles of landfill owner property should exist between the edge of where wastes will be deposited and the adjacent property line.

The landfill property should no longer be just the area where the wastes will be deposited in which wastes are deposited within close proximity to public roads, adjacent properties, etc. The landfill property should be the waste deposition area plus adequate bufferlands. The magnitude of the bufferlands will depend on the characteristics of the region. There are some hilly situations in which landfilling in a canyon associated with temperature inversions carry malodorous releases from the landfill for several miles down the canyon. That type of situation should be considered in landfill development. Municipal solid waste landfills should no longer be allowed to cause malodorous conditions on adjacent properties. This leads to justifiable NIMBY since there are few people who find landfill odors pleasant and acceptable.

Not only is there a significant aesthetic problem associated with landfill odors, but also such odors can be detrimental to public health. Shusterman (1992) and Lee and Jones-Lee (1994c) have reported on the public health impacts of landfill odors where people become ill associated with repeated exposures to malodorous MSW gaseous releases. Either the landfill owner constructs systems that will collect and treat the odorous compounds released from the landfill or acquire sufficient property so that the airborne malodorous compounds are adequately diluted below detectable levels at the adjacent property line. An adjacent property owner should be able to be present at his/her property line and not detect malodorous conditions. Detection of such conditions represents trespass of waste-derived constituents from the landfill that leads to adverse impacts on adjacent property owners and justified NIMBY.

Sites with inadequate bufferlands to dissipate the airborne releases, including odors and other landfill gas components, dust, blowing trash and the effects of birds, rodents and other vermin, can readily pollute adjacent properties with landfill-derived constituents. The development of the landfill should include acquisition of sufficient bufferlands to dissipate all airborne releases from the landfill that are not adequately controlled through the landfill operations during its active life and post-closure care period, including treatment of the landfill gases and other airborne releases to control the releases at the landfill site.

With respect to protecting groundwater resources in the vicinity of the landfill, the key is hydraulic connection. The issue that should be reliably evaluated is whether there is a transport path between the base of the landfill in which leachate that leaks through the landfill liner system can reach groundwaters at some time in the future that are or could be used for domestic or other purposes. While it is sometimes said that deep groundwater tables protect the groundwaters from pollution by landfill leachate, such statements are inappropriate in that the depth to groundwater below the base of the landfill only increases the time of transport; it does not prevent it.

The key to groundwater quality protection from pollution from minimum Subtitle D landfill leachate is the siting of the landfill relative to the proximity and hydraulic connection to groundwaters that are or could be used at any time in the future as a source of domestic, agriculture or other water supplies where leachate pollution of the waters would render them impaired or unusable. There are some geologic situations where there are no usable groundwaters hydraulically connected to the base of the landfill. Areas where there is no usable groundwater due to a lack of groundwater or where the groundwater is naturally of poor quality due to the presence of salts are areas that potentially could be suitable for a minimum Subtitle D landfill.

One of the most important issues for a minimum Subtitle D landfill sited at most locations is whether there is a low permeability layer of sufficient thickness and permeability to prevent the transport of MSW leachate-derived constituents through the layer(s) to any underlying groundwater system. Low permeability clay layers with permeabilities of less than 10^{-7}cm/sec which are hundreds of feet thick can be effective barriers for long periods of time to prevent groundwater pollution by landfill leachate.

Some landfill applicant consultants claim that a low permeability layer that is 10 to 30 feet thick will be protective of groundwater resources from pollution by landfill leachate. However, a permeability of 10^{-7} cm/sec with 1 ft head translates to an advective transport rate of about 1 in per year. A 20 ft thick layer with a permeability of 10^{-7} cm/sec can delay groundwater pollution; it will not necessarily prevent it. The people who in the future inhabit a region near a landfill will want and have the same right to unpolluted groundwaters 200 to 500 years from now as today's population. Subtitle D does not provide that landfill developers have the right to pollute future generations' groundwaters including those that would want to use groundwaters hundreds of years from now.

Another common mistake made by landfill developers and their consultants, is to claim that geological strata with advective permeabilities of 10^{-8} cm/sec or less are even more protective than those with permeabilities of 10^{-7} cm/sec. Such claims however, are an error in that they ignore diffusional transport. Daniel (1990) and Gray (1988) have reported that diffusional transport of chemical constituents in compacted clay layers becomes a dominating transport mechanism when the advective permeability is less than about 10^{-7} cm/sec. It is therefore inappropriate to assert that because a measured advective permeability is 10^{-9} cm/sec that the rate of transport of potential pollutants through the clay layer will be about 0.01 in/year. It will still be about 1 in/year.

It is important, however, that any attempt to utilize such clay layers as protection for groundwater quality from pollution by landfill leachate must be accompanied by intensive field studies that demonstrate that the low permeability layer is, in fact, an effective barrier for as long as the wastes in the landfill will be a threat. Frequently, investigation of low permeability layers shows that they contain cracks, sandy lenses and/or areas of higher permeability which can lead to a much greater rate of passage of leachate through the aquifer system than predicted based on the mean permeability of the strata. In calculating rates of transport, the highest permeabilities found should be used, rather than the mean or some other measure of a strata permeability since it is this permeability that could ultimately impact an adjacent property owner's groundwater based water supply quality. The burden should be on the landfill developer to prove that the geological strata are, in fact, an effective barrier. It should not be on the public or the regulatory agencies to disprove that the strata will not be effective in preventing leachate from passing through it for as long as the wastes represent a threat.

Another common problem in assessing the ability of a clay layer to prevent leachate polluted groundwaters from passing through it relates to the use of inappropriate techniques for assessing permeability. Laboratory based permeability tests are unreliable for this purpose (Lee and Jones, 1992). All permeability measurements should be based on properly conducted field measurements of sufficient number and appropriately spaced to reliably characterize the permeability of the geological strata of concern. If there is inadequate data available, then the landfill developer must conduct the field studies to reliably characterize the geological strata underlying the existing or proposed new or expanded landfill.

Frequently, landfill proponents and their consultants will assert that the constituents in leachate will be removed through sorption onto the clays and other components of the strata and therefore would not cause groundwater pollution. Such assertions, however, ignore the fact that municipal landfill leachate contains a variety of constituents which are not sorbed and are transported with the water as rapidly as the water that can lead to groundwater pollution. The characteristics of leachate and its potential to cause groundwater pollution have been discussed by Jones-Lee and Lee (1993).

A potentially effective approach to demonstrate whether there is a hydraulic connection between surface waters and groundwaters underlying a so-called impermeable layer is the use of isotope dating or characterization of the groundwater system. If the groundwater is of relatively young age compared to the predicted rate of transport of surface water through the layer, then it is obvious that there is a high rate of transmission through this layer which can lead to groundwater pollution by near surface-associated constituents. It is also possible through stable isotope characterization to determine if the groundwaters are of the same characteristics as the near surface waters. This can be useful in determining whether there is a direct connection between surface water infiltration in the vicinity of the landfill and the groundwaters of the area.

Landfill developers and their consultants for landfills located in the more arid parts of the country will frequently claim that the dry climate sometimes said to exist when the annual precipitation is less than about 20 in/year, prevents leachate generation. They inappropriately invoke net annual infiltration versus evapotranspiration - transpiration as "proof" that no leachate will be generated in the landfill. If such approaches were valid, there would be no groundwaters in most arid regions. This approach ignores the well established fact that groundwater recharge occurs in short pulses of saturated or near saturated flow through the vadose zone. This transport of water has been demonstrated to carry pollutants through the vadose zone to the groundwater table. Further, the average annual moisture content of the vadose zone as is sometimes used by landfill applicants and their consultants, is not a reliable basis for predicting rates of transport of constituents within the vadose zone. A far more reliable approach is to assume that the transport occurs as saturated transport associated with precipitation events.

The US EPA (1991) made a significant error in the development of the Subtitle D regulations where it asserted that dry climates (precipitation of less than 25 in/year) do not generate leachate. If the Agency had properly reviewed the literature on groundwater pollution by landfills in arid areas, they would have found that the state of California solid waste assessment test (SWAT) results, Parsons and Mulder (1991) discuss the fact that approximately 80% of California's landfills have been found to be polluting groundwaters with most of these located in areas of precipitation of less than 25 in/year. In fact there are many landfills in California desert regions with less than 10 in of precipitation per year that have been documented to be polluting groundwaters. While arid area landfills produce less leachate than landfills located in wetter climates, they produce leachate that pollutes groundwaters. Also, the production of leachate in landfills located in arid areas has been found to by cyclic where during the precipitation season leachate generation occurs. However, during the dry season, typically in California, the late spring, summer and early fall, no leachate generation occurs. This situation complicates the monitoring of groundwaters for detection of leachate pollution since there will be pulses of leachate generated in landfills present in the groundwater which can necessitate a more frequent monitoring than annual, biannual or quarterly monitoring that is frequently allowed by regulatory agencies. Such monitoring could miss the leachate pulses as they pass the point of compliance for groundwater monitoring.

Landfill applicants and their consultants also often unreliably report on leachate generation in landfills where they claim that since the waste in a landfill contains less than the moisture holding content of the waste, i.e. the point where moisture freely drains from the waste, no leachate generation is occurring. Such claims ignore the fact that moisture/leachate can move through the landfill through unsaturated transport where even though the waste appeared dry there is still migration of leachate components through the waste to the bottom of the landfill.

A high groundwater table represents a potential source of moisture for a landfill that can lead to leachate formation. Subtitle D regulations require a minimum of 5 ft separation between the base of the wastes and the high of a groundwater table. Landfill developers and some regulatory agencies are attempting to circumvent this regulation by installing subdrain systems below the landfill which are designed to convey the groundwater in any leachate to a location where it can be managed. While in principal such systems can be effective, in practice they are likely to experience severe operational problems. The fact that the waste in the landfill will be a threat forever means that the drainage systems must function reliably forever to keep moisture from entering the landfill that leads to increased leachate formation. Long-term changes in the groundwater table can lead to conditions that are significantly different than those that were initially used to develop the subdrain system that could cause the system to fail to operate as designed.

Landfills located in areas with high groundwater tables are sometimes developed with a reverse gradient or hydraulic trap approach in which the groundwaters allowed to infiltrate into the waste through a clay liner system and the leachate produced is pumped from the landfill. In principal, if an inward gradient either due to a natural or artificially developed high groundwater table surrounding the landfill of sufficient magnitude to overcome the diffusional transport of waste components through the liner to the surrounding groundwaters, then the groundwater of the area should be protected from pollution by landfill leachate. Angell (1992) and Burke and Haubert (1992) and Lee and Jones-Lee (1993e) have described the development of reverse gradient landfills. There are several aspects of reverse gradient landfills that need to be considered. These include the fact that the reverse gradient system will have to be maintained throughout the potential contaminating life span of the wastes in the landfill. This life span can be a thousand or more years dependent on the rate of moisture addition to the landfill through the cover and through the sides and bottom of the landfill. Further, the permeability of the clay layer that is used to control the rate of addition of groundwater to the landfill must be such that sufficient inward flow of groundwater occurs to overcome the diffusional transport of waste components to the surrounding groundwaters. As discussed by Lee and Jones-Lee (1993e) inward gradient landfills if properly developed and maintained for as long as the wastes represent a threat have potential merit as a means of enhancing waste treatment through fermentation and leaching of the wastes while preventing groundwater pollution.

Liner System

In those situations where there is any question about the potential for pollution of groundwaters by landfill leachate for as long as the wastes represent a threat, municipal solid wastes landfills should be constructed with a double composite liner with a leak detection system between the two liners (Lee and Jones-Lee, 1995c;1997g). There are eight states or parts of states that require this type of construction for MSW landfills. The legislatures of a number of US states have adopted regulations which prohibit its state regulatory agency from adopting more protective regulations for landfilling of MSW than the minimum specified under the US EPA under Subtitle D. While for most states, the lower composite liner in a double composite lined landfill is a secondary containment liner, in Michigan the lower composite liner is a leak detection system for the upper composite liner. As discussed by Lee and Jones-Lee (1994b) this is the recommended approach that can, under most situations, provide high degrees of protection for vulnerable groundwaters. The key to this approach is the ability to take action when the upper composite liner leaks leachate into the leak detection system between the two liners. Under these conditions, there must be funds available to stop leachate generation, i.e. moisture entry into the landfill, or it is only a matter of time until leachate has penetrated through both composite liners into the underlying groundwater system.

The double composite liner system approach with a leak detection system, not only provides significant additional protection of groundwaters from pollution by landfill leachate through the use of a more appropriate liner system, but also solves the liner leakage monitoring problem that exists with the minimum Subtitle D landfill. Leakage of leachate through the upper composite liner is a clear indication of liner failure that must be addressed.

Typically, the post-closure care funding provided for MSW landfills under RCRA Subtitle D is not sufficient to ensure that action will be taken when needed to stop leachate from passage through the upper composite liner into the leak detection system between the two liners. This action could require exhumation (mining) of the wastes. As discussed by Lee and Jones-Lee (1994b; 1995c; 1997g) sufficient funds must be set aside in a dedicated trust derived from tipping fees to ensure that funds will, in fact, be available to take action at any time in the future when leachate passes through the upper composite liner into the leak detection system between the two liners.

The magnitude of the post-closure care funding needed for true post-closure care for as long as the wastes are a threat should be sufficient for waste exhumation. Today, however, it would indeed be rare that waste exhumation would be necessary to stop leachate generation for those landfills sited above a groundwater table since it is possible to construct a leak detectable cover on the landfill that can, in fact, stop moisture from entering the landfill that produces leachate (Lee and Jones-Lee, 1994b;1995a).

Landfill Cover

The typical Subtitle D landfill cover with the low permeability layer buried below a drainage layer and top-soil layer is not a reliable basis for keeping moisture out of a landfill for as long as the wastes represent a threat (Lee and Jones-Lee, 1995a). A far more reliable, readily implementable approach is the installation of a leak detectable cover using a vacuum system (Robertson, 1990) or an electronic system (Nosko and Andrezal, 1993) (Peggs, undated) (GSE, undated). It is possible to readily detect failure of the flexible membrane liner (FML) through the development of holes of sufficient magnitude to transmit moisture into the landfill that could generate leachate. Since the landfill cover is accessible by removal of the topsoil and drainage layer and since the area of the leak is known through the leak detection system, it is possible to develop a "dry tomb" type landfill that will, in fact, protect groundwaters from pollution by landfill leachate, provided that failure of the cover is, in fact, detected, either through a combination of leakage through the upper composite liner into the leak detection system between the two liners in a double composite-lined system and/or the development of holes in the low permeability layer (FML) of the landfill cover. The key to the successful operation of a leak detectable cover is the development of a dedicated trust fund of sufficient magnitude from disposal fees that can operate and maintain the leak detectable cover in perpetuity.

Groundwater Monitoring

While the typical groundwater monitoring approach used with vertical monitoring wells spaced hundreds to a thousand or so feet apart is largely cosmetic and a waste of money, it is likely that it will continue to be used as the primary monitoring system for those landfills that do not have the double composite-lined system or as a back-up to that system. In those situations where the primary groundwater monitoring is based on vertical monitoring wells at the point of compliance, i.e. standard Subtitle D, a significantly different approach should be required in determining monitoring well spacing. Rather than the typical seat-of-the-pants, arbitrary well spacing that basically evolved from the monitoring of unlined landfills where there was leakage across the entire bottom of the landfill, groundwater monitoring well spacing should be based on a properly conducted evaluation of the well spacing necessary to achieve at least a 95% probability of detecting a leak through a FML that initially occurs from a potentially significant hole such as a six-inch rip, tear or point of deterioration in the FML. Such a leak at a particular location in the FML will produce a plume of a certain dimension at the point of compliance for groundwater monitoring dependent on the hydrogeologic characteristics of the aquifer system.

The landfill owner, through its consultants, should be required to determine the monitoring well spacing necessary to detect a plume of the minimum lateral dimensions that could be generated from a landfill with a 95% reliability. As discussed herein, the work of Dr. John Cherry (1991) at the University of Waterloo at the experimental site showed that a two-foot wide line source of leachate would spread in a sand aquifer system to about 10 feet within 150 meters from the source. This means that groundwater monitoring wells would have to be spaced at about 10 foot intervals at the point of compliance in order to have a high degree of reliability of detecting leachate leakage through a FML in that type of aquifer system that arises from a two-foot wide hole in the FML liner.

Each aquifer system will have different lateral spread characteristics. The aquifer system underlying the proposed landfill area should be sufficiently well characterized so that reliable estimates of the lateral spread of leachate plumes arising from various-sized holes, rips, tears or points of deterioration that develop in the FML can be estimated. Adoption of this approach would drastically change the well spacing that is now allowed to a spacing of 10 ft or so. It would also promote the double composite lined landfill system for containment of waste and groundwater monitoring.

A common problem with groundwater monitoring at the points of compliance near landfills is that regulatory agencies allow wells screened through the full depth of the aquifer to be used for monitoring. Such an approach should not be allowed since it means that leachate polluted groundwaters could intercept the well as a narrow band, but not be detected because of the dilution by the non-polluted groundwaters sampled within the well. Cherry (1991) and Lee and Jones (1992) have indicated that typically municipal landfill leachate contains sufficient salts so that it is denser than most groundwaters. This causes the leachate plume to sink within the aquifer. Such behavior must be considered in developing the screened intervals for monitoring wells. Typically the groundwater monitoring at the point of compliance should be based on a nested set of at least three wells screened at different intervals in order to be sure that bands of leachate that reach the point of compliance are reliably detected.

Post-Closure Care Period

The 30-year post-closure care period that was originally set forth by Congress in RCRA represents a significant error made by Congress, the US EPA and those who advised Congress on the period of time that municipal solid waste landfills would represent a threat to groundwater quality. Basically, it appears that those who promulgated the 30-year period considered only the typical period of time that classical sanitary landfills produced substantial quantities of landfill gas. They did not understand/ignored the fact that landfill gas production is just one of the processes of concern. The leaching of the waste components to produce leachate that pollutes groundwaters is the other. As discussed in the literature and herein, leachate production in the classical wet climate sanitary landfill can occur for thousands of years. In a "dry tomb" landfill, the potential to produce leachate will always exist. It is therefore imperative that as part of developing a Subtitle D landfill, that the post-closure care period be defined as is done in the state of California under Chapter 15 regulations, for as long as the wastes are a threat. It should be understood that this period of time would be, effectively, forever.

Post-Closure Care Funding

The approach for establishing post-closure care funding for MSW landfills should be significantly changed so that sufficient funds are obtained during the active life of the landfill from tipping fees to ensure that funds will be available forever to address plausible, worst-case failure scenarios that could occur for a particular landfill. These failure scenarios should include normal operation, maintenance and post-closure care activities and include waste exhumation processing and appropriate management of the mined waste residues. The mining of municipal solid waste has been found to be economically feasible (Lee and Jones, 1990a,1991; CalRecovery, Inc. 1993; Savage *et al.*, 1994). The costs of landfill mining in many situations will be $10 to $20 a ton. Mining municipal solid waste can result in about a 75% recovery of landfill space. Landfill mining is also an effective method of stopping pollution from existing landfills and gaining additional space for construction of a landfill that will be protective of public health and the environment.

Hickman (1992, 1995) and Lee and Jones-Lee (1993a,1995a,) have discussed the importance of establishing a reliable financial instrument to ensure that funds are developed during the active life of the landfill for post-closure care will, in fact, be available for as long as needed, i.e. as long as the wastes are a threat during the post-closure care period. While the US EPA and states allow a variety of financial instruments to "ensure" post-closure care funding, Hickman (1992, 1995) concluded that the only reliable financial instrument for this type of funding is a dedicated trust. A dedicated trust is a financial instrument that can be developed which provides a high degree of certainty that the funds deposited in the trust account can only be used for the intended purpose, i.e. landfill post-closure care monitoring, maintenance and remediation.

Lee and Jones-Lee (1993a, 1994a, 1995a) have discussed the long-term economics of landfills, pointing out that while a landfill can be profitable during its active life, the long-term costs associated with *ad infinitum* monitoring, maintenance and eventual "Superfund"-like remediation create a long-term liability that ultimately will have to be met. There have been a number of discussions, such as in Barrons (Cochran, 1992) of the significant liability that private landfill companies are developing today with the use of minimum Subtitle D landfills. From a long-term perspective, the private garbage companies, if they meet their current obligations under Subtitle D, will face massive costs associated with the clean-up - remediation of the Subtitle D landfills as they fail to prevent groundwater pollution.

An area of particular concern is the situation today where the major solid waste management companies such as Waste Management and BFI are selling off their less profitable solid waste collection and landfill operations to other firms that hope to gain a greater market share of the US solid waste management business. This type of situation could readily lead to further cost cutting in terms of environmental protection by the companies with the new solid waste business assets. Also, a number of the firms that are acquiring the less profitable solid waste businesses are considered to be of questionable ability to remain profitable over extended periods of time. This situation can readily lead to bankruptcies where there will be inadequate funds available to properly close and maintain for as long as the waste residues in the landfills will be a threat and to clean up the pollution that will occur at many of these landfills. The current post-closure care funding is not adequate to address this issue. The US Congress General Accounting Office (GAO 1990) has concluded that the funding of post-closure care liabilities remains uncertain for hazardous waste landfills. This situation also applies to municipal solid waste landfills. By far, one of the most significant deficiencies in today's Subtitle D landfilling approach is the failure of the US EPA and the states to require an adequate secure post-closure care funding to meet the long-term liabilities associated with today's minimum Subtitle D landfills.

There seems to be a mistaken belief, based on information presented by landfill companies in permitting hearings that their obligation for providing true long-term post-closure care funding will stop at the end of 30 years after closure of the landfill. A review of RCRA regulations, however, shows that the US EPA regional administrator can extend the post-closure care obligation to the period necessary to protect public health, groundwater resources and the environment. The basic problem with this approach, however, is that there are no funds set aside from the active life of the landfill while it is generating revenue, to fund the *ad infinitum* post-closure care requirements that will exist typically 50 years from now, i.e. after the typical 20-year active life and 30-year post-closure care. There is little support for the concept that today's garbage companies will be able to provide post-30-year post-closure care funding that will, in fact, be required at virtually every minimum Subtitle D landfill.

It is recommended that as part permitting a landfill that the landfill applicants present a credible worst-case post-closure failure scenario that discusses possible failures that could occur in the landfill containment system and groundwater monitoring systems for as long as the waste in the landfill will be a threat, that would allow leachate polluted groundwaters to pass the point of compliance for the groundwater monitoring. For each failure scenario, the landfill proponent should be required to discuss how the failure would be detected, when it would be expected to be detected relative to when it occurred, and most importantly, the magnitude of the funding necessary to control the failure and remediate any environmental contamination that has occurred. The landfill applicant should also be required to present a credible discussion of the source of the funds that will be needed to address all plausible worst-case failure scenarios that could occur in the future while the waste in the landfill will be a threat. For planning purposes, this period of time should be infinite.

This worst-case failure scenario should be publicly peer-reviewed in which independent experts would be able to critically review the reliability of the worst-case failure scenario evaluation. Adoption of this approach would significantly change the deficient landfill permitting approach that is being used today where it is being assumed that meeting the current US EPA Subtitle D post-closure care funding requirements will be protective of public health, groundwater resources, the environment and the interest of those within the sphere of influence of the landfill for as long as the waste in the landfill will be a threat.

The funding of addressing long-term problems associated with public landfills is not much better than private landfills. City councils, county boards of supervisors and other elected bodies that govern the development of landfills today within their region are reluctant to "tax" their constituency to pay for past improper landfilling of waste. Such "taxing" could be readily detrimental to re-election to the governing body. It is for this reason that the long-term costs should be based on revenue developed from tipping fees acquired during the active life of a landfill. As discussed by Hickman (1992, 1995), the funds developed for this purpose must be secured to prevent boards of supervisors and others from using these funds to meet other needs. The dedicated trust appears to be the only reliable instrument that can protect these funds for the period of time that will be needed to meet the long-term financial obligations of today's minimum Subtitle D landfills.

The problems with failing to address the active life and long-term problems of municipal landfills when there is recognition among professionals and others, that the current landfilling approach will not protect public heath, groundwater resources, environment and the interest of those within the sphere of influence of the landfill for as long as the wastes will be a threat, are not new or restricted to Subtitle D landfills. The American Society of Civil Engineers in 1959 (ASCE, 1959) developed a sanitary landfill development guidance manual which discussed that sanitary landfills which were just beginning to be developed in the 1950s as a change from municipal dumps, would likely pollute groundwaters. The classical sanitary landfill was developed without regard to groundwater pollution issues. While groundwater pollution problems associated with the landfilling of wastes were well known for over 40 years, it took until 1991 for the US Congress/federal government to adopt the first national regulations governing the protection of groundwaters from pollution by landfill leachate. Today's generations are facing a legacy of over 40 years of sanitary landfilling where with few exceptions these landfills are now polluting groundwaters.

While states and local political jurisdictions have the option of developing more protective landfills than the minimum national standard, there are few that do so. Further, even when more protective landfill standards are developed, there is often great difficulty achieving reliable enforcement of these standards at the local level. A prime example of this situation occurred in California where the State Water Resources Control Board in 1984, adopted Chapter 15 regulations which have an explicit groundwater protection standard of protecting groundwaters from impaired use for as long as the wastes in the landfill will be a threat. These regulations also specified a minimum liner design of 1 ft of compacted soil with a permeability of less than 1×10^{-6} cm/sec, indicating that the minimum may not be adequate at a particular location. Site-specific evaluations must be made to determine the adequacy of the minimum design to comply with the groundwater protection standard. Chapter 15 is also explicit with requiring that whatever landfill design is adopted, it must protect groundwaters from impaired use for as long as the wastes represent a threat. The regional water quality control board's staff and boards assumed an obviously technically invalid approach that the minimum liner design of 1 ft of compacted clay with a permeability of less than 1×10^{-6} cm/sec would be protective of groundwaters from impaired use by landfill leachate for as long as the wastes represent a threat. A simple Darcy's law calculation shows that this liner system would be breached by leachate in less than a year under design specifications.

Today because of this technically invalid approach, California faces the groundwater pollution legacy caused by nine years (1984 to1993) of landfill construction under conditions where obvious groundwater pollution would occur due to inappropriate siting and design of the landfill containment system. Mulder and Haven (1995) have reported as part of the ongoing State Water Resources Control Board SWAT studies,

> *"Available data indicate no apparent correlation between the percentage of landfills which leaked and any of the different site-specific factors checked, including depth to ground water, average annual precipitation, waste acceptance rate, and rock type. Thus, information collected through the SWAT Program demonstrates that unlined or clay-lined landfills leak, regardless of factors such as climate or site-specific geology."*

In 1993 the state of California like other states, had to adopt minimum Subtitle D single composite liner as the minimum liner design for MSW landfills. Subsequently, without public review, the State Board staff adopted the "position" that the minimum Subtitle D liner design would comply with Chapter 15 requirements of protecting groundwaters from impaired use for as long as the wastes in the landfill would be a threat. This position like the position that the regional board staff adopted in 1984 with respect to a liner composed of 1 ft of compacted clay of protecting groundwater's use for as long as the wastes present a threat, was then and is today obviously technically invalid. Subtitle D landfills now being permitted in California like similar landfills throughout the country will eventually require massive "Superfund"-like funding to clean up the polluted groundwaters that will arise from the failure of the minimum Subtitle D liner cover and groundwater monitoring systems that are being approved today. Further, large amounts of funds will be needed to properly close these landfills to stop future groundwater pollution by them. Since there is inadequate funds being set aside during the active life of the landfill to meet the long-term funding needs including possibly waste exhumation, these funds will have to be derived from future generations.

There are significant problems today gaining funding to properly close the classical sanitary landfills that are now polluting groundwaters because of the high cost of closure in accord with current Subtitle D requirements. There is little likelihood that future boards of supervisors, city councils, etc. will be any more willing to "tax" their constituency to finally pay the true cost of landfilling that occurs some 50 years or so previously associated with today's minimum Subtitle D landfills. The current Subtitle D regulations virtually mandate that eventually "Superfund" sites will be developed at most locations where minimum Subtitle D landfills are developed which will not be addressed any better than today's proper closure of classical sanitary landfills that are polluting groundwaters. Many political jurisdictions are finding great difficulties gaining public funds to properly close existing sanitary landfills to stop further groundwater pollution and to clean-up to the extent possible the existing groundwater pollution. The high costs of constructing the currently required landfill cover, coupled with the lack of revenue source from an active landfill associated with this closure, leads to a common situation of little or nothing being done to comply with regulatory requirements of stopping the pollution of groundwaters by existing sanitary landfills. The same kind of situation will almost certainly occur 50 or more years or so hence when regulatory bodies have great difficulties taxing their constituency to fund public health and environmental protection associated with the failure of today's minimum Subtitle D landfills. It is for this reason that dedicated trusts derived from disposal fees during the active life of the landfill of sufficient magnitude to address all plausible worst-case scenario failures, must become the financial instrument that is used to ensure that funds will be available when needed to provide for true post-closure care of today's minimum Subtitle D landfills.

Closure of Classical Sanitary Landfills

Beginning in the 1950s there was a major shift in municipal solid waste landfilling approaches away from the open dump where the municipal solid wastes were placed in low land value often wetland areas. Frequently burning of the waste was practiced. Severe problems of odor, vermin, vectors, etc. were associated with the municipal dump. In order to control these problems to some degree, a daily cover of a few inches of soil was placed on the waste and the burning of the waste was terminated. When the landfill was filled to capacity, a layer of soil was placed on top of the landfill. There were no liners used in the classical sanitary landfills, nor was there any attempt to create a low-permeability layer in the cover to restrict moisture entering the landfill. The classical sanitary landfills as well as their predecessor, the municipal dump have led to widespread groundwater pollution that at some landfills extends in a groundwater pollution plume for a mile or more from the landfill.

The current regulatory approach for closure of classical sanitary landfills requires the placement of a low permeability cover on the landfill and the development of a groundwater monitoring system to detect pollution of groundwaters by the landfill. Where such pollution is detected, the landfill owner/operator is required to initiate a monitoring program to determine the extent and degree of pollution and a remediation program to clean up to the extent possible the polluted groundwaters. It is understood, however, by Rowe (1991), Lee and Jones (1992), and Lee and Jones-Lee (1994a) that it will not be possible to clean up the polluted groundwaters to the degree necessary to enable the polluted areas of the aquifer to be used again for domestic water supply, and, for that matter, as a water supply for many other purposes, including some high-value agricultural crops. A critical review of the regulatory approach that is allowed today for closure of existing classical sanitary landfills shows that the low permeability clay layer that is allowed in today's classical sanitary landfill closure is widely recognized to be largely ineffective in preventing moisture from entering the landfill within a short period of time after the development of the cover. Even in wet climates, such as Wisconsin, the clay layers that are used have been found to crack within a few years to a sufficient extent to allow ready infiltration of moisture that enters the topsoil layer of the landfill cover through cracks that develop in the clay layer of the cover. Montgomery and Parsons (1994) found cracks up to a 0.5 in wide which extended 35 to 40 in into the clay layer, had developed within three years in a clay layer designed to simulate a landfill cover.

Lee and Jones-Lee (1997b) have discussed the deficiencies in capping landfills and waste management areas with today's RCRA approved caps in preventing further groundwater pollution by the landfill. At best, these caps, based on compacted clay and including a single plastic sheeting layer do little more than postpone when further groundwater pollution will occur. They will not prevent the pollution. The same problem exists with maintaining these covers as discussed above in that the integrity of the low permeability layer is not subject to inspection for cracks by the techniques typically used in landfill cover maintenance.

There are some, including the authors, who question whether the approach currently required for closure of classical sanitary landfills should be continued which involves spending from $0.5-million to $1-million per acre for construction of a landfill cover system that will only postpone for a short period of time when further groundwater pollution occurs at the landfill. This pollution would be the result of the ineffectiveness of the low permeability layer in the cap to prevent significant moisture infiltration into the landfill that generates leachate that can lead to further groundwater pollution at an existing classical sanitary landfill.

Lee and Jones-Lee (1995a) have suggested that rather than spending large amounts of money to construct an ineffective landfill cover associated with the closure of classical sanitary landfills, a more appropriate approach would be to construct a pump and treat operation to intercept the polluted groundwaters generated by the landfill. As a result of natural as well as enhanced moisture addition through the landfill cover, ultimately the wastes in the landfill will be leached to a sufficient degree to produce a non-polluting waste residue. At that time, the pump and treat operations could be terminated.

Typically at landfill permitting hearings, landfill proponents, both public and private, assert to the regulatory agency or review board that once a landfill is closed, it would be possible to develop a park, golf course or some other significant amenity for the region. While golf courses have been developed on landfills, such development is often not without significant problems due to differential settling of the wastes, landfill gas emissions which are adverse to the vegetation that is developed on the landfill cover, etc. Lee and Jones-Lee (1994e, 1995a) have discussed the potential for developing golf courses or other park-like amenities on Subtitle D landfills where they point out that since, with few exceptions, these systems will have to be irrigated to maintain the vegetation, this irrigation, coupled with the plant roots and other physical disturbance of the cover, will likely impair the integrity of the low permeability layer underlying the topsoil layer of the landfill cover, allowing more rapid infiltration. The increased hydraulic loading on the surface due to irrigation will also increase the amounts of moisture entering the landfill, leading to increased leachate generation. It is, therefore unlikely that golf courses, parks or other similar kinds of areas can be developed on minimum Subtitle D landfills and maintain the low permeability of the landfill cover (Lee and Jones-Lee, 1994e).

Wet Cell Technology - Leachate Recycle

There is growing recognition that the "dry tomb" landfilling approach in a minimum Subtitle D landfill is a fundamentally flawed technology that is prone to failure (Lee and Jones-Lee, 1996c). As discussed herein and in the literature (Lee and Jones-Lee, 1995c), it is possible to modify the Subtitle D "dry tomb" landfilling approach to provide for true long-term public health, groundwater resource and environmental protection associated with "dry tomb" landfilling. The costs represent a substantial increase from today's conventionally paid landfilling costs. Lee and Jones-Lee (1993d) estimate that the increased cost in many areas would be in the order of $0.10 to $0.20 per person per day more than is being paid today for minimum Subtitle D landfilling. Even with this expenditure, there is still a significant long-term problem associated with insuring that the post-closure care needed to keep a "dry tomb" type landfill dry forever, will in fact be carried out in perpetuity. This situation has caused a number of individuals to recommend the abandonment of the "dry tomb" landfilling approach in favor of a wet cell- reactor approach.

As discussed by Lee *et al.* (1985) and Lee and Jones (1990b), there are two processes that take place in landfills that are dependent on the moisture content of the wastes. One of these is the fermentation of some of the organic components of the waste to produce landfill gas. The other is the leaching of the wastes to remove the soluble components that become the constituents of concern with respect to leachate pollution of groundwaters. Pohland (1975, 1980) pioneered in the recycle of leachate into MSW landfills for the purpose of enhancing landfill "stabilization." Pacey of EMCON 1975-76, (EMCON 1975-1976) was one of the first to conduct field studies to evaluate the potential benefits of adding moisture to a classical sanitary landfill for the purpose of enhancing fermentation and leaching of the wastes. Pacey found in large-scale field studies that the addition of leachate and/or clean water to a landfill not only enhanced the rate of gas formation, but also for the clean water additions, removed soluble components of the waste that represent a threat to pollute groundwaters.

Christensen and Kjeldsen (1989) presented a review of the basic biochemical processes that occur in landfills in which they discussed the importance of the moisture content of the wastes in enhancing the rate of landfill gas formation. They reported that gas formation was directly proportional to the water content of the waste between 20% and about 80% moisture. Below about 10% moisture, the waste becomes sufficiently dry so that there is insufficient moisture for the biochemical processes that lead to gas formation to be carried out by bacteria. There is no information at this time on the impact of moisture on the leaching of the wastes under unsaturated leachate transport conditions that typically exist in today's landfills. While moisture content of the wastes will influence the rate of water movement through the wastes under unsaturated transport conditions, whether the characteristics of the leachate that is transported under unsaturated conditions changes significantly with moisture content of the waste has not been investigated. It is likely that there is some effect of moisture content, although it may not significantly change the pollution potential of the leachate that ultimately enters the groundwater system underlying a landfill.

Landfill leachate recycle is proposed as a means of accelerating the "stabilization" of wastes through accelerating landfill gas formation. Use of the term "stabilization" in connection with the ability of a landfill to pollute the environment is misleading in that the "stabilized" wastes, i.e. those for which landfill gas production has been carried out to the maximum extent possible, still can have a significant potential for groundwater pollution due to leaching of waste components. This is especially true under conditions in which the "stabilized" wastes are achieved through leachate recycle where leachate collected from the landfill is added back into the landfill to increase the moisture content of the wastes. For many landfill operators, landfill leachate recycle while advocated as a means of increasing the rate of stabilization of a landfill is in fact conducted for the purpose of low-cost disposal of leachate.

There have been a number of reviews on the potential advantages and problems of leachate recycle. Lee *et al.* (1985) discussed not only the advantages of leachate recycle but also some of the significant problems associated with it. Pohland and Harper (1987) reviewed leachate recycle focusing primarily on the advantages of this approach. US EPA in 1995 (USE EPA, 1995) published the proceedings of a landfill bioreactor operation and design conference that focused on the advantages of leachate recycle and how it can be carried out. Recently Reinhart and Townsend (1988) discussed leachate recycle without providing a comprehensive review of the literature on the topic, especially the work devoted to the problems with leachate recycle as being practiced today.

There is considerable controversy about the appropriateness of leachate recycle, especially in today's landfills (both classical sanitary landfills and Subtitle D landfills). While there are numerous publications on the advantages of leachate recycle, few of these discuss the potential problems with practicing leachate recycle in today's classical sanitary landfills as well as minimum Subtitle D landfills. Lee *et al.* (1985) and Lee and Jones-Lee (1994f,g;1995d,e) reviewed the potential benefits and problems associated with leachate recycle. They point out that while leachate recycle can accelerate the rate of landfill gas production, it also increases the hydraulic head within the landfill leading to potentially greater groundwater pollution. It is this situation that led a number of states in the 1980s to ban leachate recycle in MSW landfills (Lee *et al.*,1985). Leachate recycle in a minimum Subtitle D landfill can increase the rate of groundwater pollution by that landfill, making the groundwater problems associated with the pollution more severe.

An issue that is not typically or adequately discussed by many of the proponents of leachate recycle, is the potential impacts of the plastic bags that are used in residential solid waste disposal. The classically discussed benefits of accelerated waste fermentation that have been demonstrated in laboratory studies may not be realized to the same degree in today's landfills due to the fact that much of the solid waste present in a municipal solid waste landfill today is encased in plastic bags that while crushed are not shredded. The plastic bags, while they remain intact – which will be for a long period of time – will inhibit/prevent the recycled leachate and other moisture from interacting with the wastes. Therefore, the predicted short period of landfill gas formation that has been achieved under idealized laboratory conditions, will extend over much longer periods of time, likely 100 or more years. Ham (1975) has reviewed the role of shredding of MSW in landfilling, in which he has noted that it is possible to eliminate the need for daily cover of shredded waste. This approach can significantly increase the amount of waste that can be placed in the landfill and improve the hydraulic characteristics of the landfill.

Another significant deficiency in the literature developed by leachate recycle proponents is the failure to discuss the pollution potential of the fermented waste residues after landfill gas production has ceased. The waste residue arising from a leachate recycle operation still has a significant potential to pollute groundwaters. Lee and Jones-Lee (1993e) recommend that following the recycle period, which can under recommended conditions be on the order of five years or so, clean water washing (leaching) of the wastes should be practiced to remove the soluble components of the non-fermentable residues. It is estimated that an additional five to ten years of clean water washing of the wastes should produce a residue that represents little threat to cause groundwater pollution.

Lee *et al.* (1985) and Lee and Jones-Lee (1995c, 1996b) have recommended that the wet cell reactor approach be conducted in a double composite lined landfill in which the lower composite liner is used as a leak detection system for the upper composite liner. When leachate is found in the leak detection system between the two composite liners, the recycle operations should be terminated and either the wastes should be removed from the landfill or an impermeability leak detectable cap should be placed on the landfill to prevent further moisture from entering the landfill. The fermentation and leaching of the wastes advocated by Lee and Jones-Lee would be carried out within the time frame that the flexible membrane liners used in today's landfills would, with appropriate design, and construction and careful initial waste placement, be expected to perform in an effective manner to collect leachate generated within the landfill in the leachate collection and removal system above the upper composite liner. Adoption of this approach would significantly reduce the potential for the increased hydraulic head associated with leachate recycle and clean water washing of the wastes to lead to groundwater pollution.

The MSW placed in the reactor wet cell landfill should be shredded to enable moisture added to the landfill to readily interact with all components of the wastes. Under these conditions and with adequate bufferlands around the landfill for odor dissipation, it should be possible to operate the landfill without daily cover thereby improving the hydraulic characteristics of the landfill. Leachate recycle should be practiced until landfill gas production has essentially ceased which according to Pacey (EMCON, 1975-76) should be about five years. The actual period of time would be dependent upon the hydraulic loading of the landfill. The leachate recycle period would be followed by a clean water washing-leaching of the wastes in which there is no leachate recycle to remove those components of the wastes that represent a threat to cause groundwater pollution. This approach can lead to a truly stabilized waste residue that represents little threat for landfill gas formation and groundwater pollution. While initially, the costs of this approach are greater than today's minimum Subtitle D landfills, ultimately the cost of this true wet cell reactor approach will be far cheaper than the long-term costs of the minimum Subtitle D landfilling through the elimination of the inevitable Superfund cost associated with most minimum Subtitle D landfills.

Cost of Reliable Landfilling

With the courts overturning the restrictions on where a community can deposit its MSW in a landfill (flow control), the costs (tipping fees) of landfilling of MSW have been decreasing in many areas. This is an artificial decrease in that it is based on only considering the initial disposal costs and ignores the long-term "Superfund"-like costs that will ultimately have to be borne by the residents of a region and likely by the future generations of those that deposit wastes in the landfill from outside the region, i.e., PRPs in the future "Superfund" remediation activities, for most minimum Subtitle D landfills. In order to stay competitive with other landfills, landfill owners, both public and private, are decreasing tipping fees in order to gain a waste stream of sufficient magnitude to meet the financial obligations that exist in the development of the landfill, as well as to gain maximum profit from the operations of the landfill. The true costs of landfilling have been recently discussed by Lee and Jones-Lee (1997a). They include a variety of factors, such as acquisition of adequate bufferlands for control of active life emissions through treatment or dilution. For landfills sited at geologically suitable sites with adequate natural bufferlands to dissipate active life releases and natural protection of groundwaters, the true costs, including long-term costs of developing, operating and closing the landfill can be on the order of $30 to $40 per ton for a minimum Subtitle D landfill. However, more typically the acquisition of a mile or more bufferlands around the waste deposition areas, coupled with the development of a truly protective landfill which would involve the double composite-lined system, leak detectable cover and the development of a dedicated trust of sufficient magnitude to address plausible worst-case scenario failures of the landfill system to contain waste components during the active life and the infinite post-closure care period, would typically cost from $60 to $100 per ton. This translates to about 10 to 20 cents/day/person who contribute waste to the landfill in increased disposal costs over the current costs for minimum Subtitle D landfilling (Lee and Jones-Lee, 1993d). The actual costs depend on the cost of property acquisition and the size of the landfill, its filling rate (tons per day) and the ultimate capacity.

Under today's conditions of a lack of solid waste flow control there are few county boards of supervisors, city councils and others that will cause their constituency to significantly increase their garbage disposal bills. This is especially true when the *New York Times Magazine* through Tierney (1996) and others published inaccurate, unreliable information about the safety of today's landfills and the true long-term costs associated with minimum Subtitle D landfilling (Lee and Sheehan, 1996). Paying the true costs, including the long-term Superfund costs associated with MSW management in landfills, will be a significant factor in reversing the trend today in practicing the 3Rs . Waste reduction, recycling and reuse is economically competitive with protective landfilling.

There is an urgent need for the US EPA to publicly admit that minimum Subtitle D landfilling as promulgated by the Agency in 1991, is a fundamentally flawed technology that should not continue to be practiced. Further, there is need to educate Congress on the need to revise RCRA so that the true wet cell reactor approach for waste treatment is the minimum approach that is used for landfilled MSW. Diaz *et al.* (1997) in a recent review of landfill technology in the United States have summarized MSW management by landfilling today as,

> *"Landfill technology in the United States is currently driven by regulatory requirements and by design and operating practices that conform to the regulations and that are optimized in terms of economy and of minimizing the financial liability of landfill owners and operators."*

Rather than the current practice of developing landfills to meet minimum but often inadequate landfill design, operation, closure and post-closure care regulatory requirements in order to minimize the costs of landfilling, landfills should be developed based on the premise of fully protecting public health, groundwater resources, environment and the interests of those within the sphere of influence of the landfill during the active life and for as long as the wastes in the landfill represent a threat. The current practice which basically started in medieval times of disposal of solid wastes by the cheapest methods possible, must be changed so that the wastes are, in fact, managed in a fully protective manner.

While the landfill owner/operator, both public and private, is often criticized as the basic cause of today's landfill problems, the facts are that the waste management professionals working with public agencies typically within departments of public works, are the root of the problem. They are often forced operate under the premise of keeping waste management costs as low as possible to just meet current minimum regulatory requirements. With few exceptions, minimum regulatory requirements are inadequate for most situations to protect public health, groundwater resources, the environment and the interests of those within the sphere of influence of the landfill. The public waste management officials need to educate their boards of supervisors, city councils and the public on the need to do more than the minimum at most landfill sites if true public health, groundwater resource, environment and those within the sphere influence of landfills are to be protected. Future development of landfills should be based on a site-specific evaluation of the ability of a particular site and proposed design to develop a truly protective landfill. While this approach will significantly increase the cost of MSW waste management by landfilling over that typically paid today, the $0.10 to $0.20 per person per day more than minimum Subtitle D landfilling is readily affordable by most of the public.

Additional Information

Many of the papers and reports developed by the authors cited herein as well as others are available as downloadable files from their web site (https://www.gfredlee.com).

Acknowledgments

This overview review of the deficiencies in today's Subtitle D landfills and recommended alternative approaches for landfilling of wastes is based on over 30 years of work on landfill impacts, specific research devoted to landfill liners and extensive experience gained through public and private consulting activities with various water utilities, municipalities and others devoted to evaluating the potential impacts of landfills on public health, groundwater resources, the environment and the interests of those within the sphere of influence of the landfill. The authors wish to acknowledge the support of all of those who have provided support which has enabled us to become familiar with the properties of landfill containment and monitoring systems, the inappropriate approaches which are being used today for permitting landfills and the approaches that should be used to manage municipal solid wastes in a technically valid, cost-effective, protective manner.

References

Angell, J., "A Pollution Solution, A Landfill Designed to Safeguard the Environment." In: *Land and Water,* pp. 27-29, July/August (1992).

ASCE, "Sanitary Landfill," Report Committee on Sanitary Landfill Practice of the Sanitary Engineering Division of the American Society of Civil Engineers: New York (1959).

Belevi, H. and Baccini, P., "Water and Element Fluxes from Sanitary Landfills," In: *Sanitary Landfilling: Process, Technology and Environmental Impact,* Academic Press: San Diego, pp.391-397 (1989).

Burke, L. and Haubert, A., "Predicting Contaminant Transport from an Inward Gradient Landfill." Proc. Fifteenth Annual Madison Waste Conference, University of Wisconsin Department of Engineering Professional Development, September (1992).

Buss, S.E., Butler, A.P., Johnston, P.M., Sollars, C.J. and Perry, R., "Mechanisms of Leakage through Synthetic Landfill Liner Materials," J. CIWEM, 9:353-359 (1995).

CalRecovery Incorporated, "Landfill Mining Feasibility Study," Submitted to California Integrated Waste Management Board Science Applications International Corporation, Los Altos, California, October (1993).

Cherry, J.A., "Groundwater Monitoring: Some Deficiencies and Opportunities," In *Hazardous Waste Site Investigations: Towards Better Decisions, Proc. 10th Oak Ridge National Laboratories' Life Sciences Symposium,* Lewis Publishers: Gatlinburg, TN (1990).

Cherry, J.A., Personal communication to G.F. Lee, University of Waterloo, Canada (1991).

Christensen, T. and Kjeldsen, P., "Basic biochemical processes in landfills," In: *Sanitary Landfilling: Process, Technology and Environmental Impact,* Academic Press, San Diego, CA, pp 29-49 (1989).

Clay, D., Assistant Administrator, Office of Solid Wastes and Emergency Response, US EPA, Washington, D.C., Personal communication to G. Fred Lee (1991).

Cochran, T., "Offerings in the Offing," Barron's, April 6 (1992).

Daniel, D., "Critical Factors in Soils Design for Covers," In: *US EPA Seminars - Design and Construction of RCRA/CERCLA Final Covers*, US EPA Office of Research and Development, Washington, D.C. CERI 90-540 (1990).

Daniel, D. and Koerner, R., "Landfill Liners from Top to Bottom," Civil Engineering 61:46-69 (1991).

Dellinger, R., Personal communication to G. Fred Lee, G. Fred Lee & Associates, El Macero, CA, (1998).

Diaz, Luis F., Savage, George M., Cal Recovery, Inc. and Ham, Robert K., "Landfill Technology in the United States," *International Solid Waste Association Times* 3:3-15 (1997).

Eden, R., "Toxic Emissions from Different Types of LFG Burners," In: *Proceedings of Sardinia '93 IV International Landfill Symposium*, Sardinia, Italy, pp. 635-636, October (1993).

EMCON, Sonoma County Solid Waste Stabilization Study and Twelve-Month Extension Sonoma County Solid Waste Stabilization Study, Report SW-65d.1, Environmental Protection Agency Office of Solid Waste, Washington, D.C. (1975,1976)

Freeze, R.A. and Cherry, J.A., *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, NJ (1979).

Gintautas, P., Daniel, S. and Macalady, D., "Phenoxyalkanoic Acid Herbicides in Municipal Landfill Leachates," Environ. Sci. & Technol. 26:517-521 (1992).

Gray, D.H., "Diffusion as a Transport Process in Fine-grained Barrier Materials," Geotechnical News 6(2), June (1988).

GSE, "Sensor Damage Detection System" Lining Technology Incorporated, Houston, TX, (undated).

Haitjema, H., "Ground Water Hydraulics Considerations Regarding Landfills," Water Res. Bull. 27(5):791-796 (1991).

Ham, R.K. "The Role of Shredded Refuse in Landfilling." Waste Age 6:22, (1975).

Haxo, H.E. and Lahey, T.P., "Transport of Dissolved Organics from Dilute Aqueous Solutions through Flexible Membrane Liners," Hazardous Wastes & Hazardous Materials 5(4):275-294 (1988).

Hickman, L., "Financial Assurance-Will the Check Bounce?" Municipal Solid Waste News, March (1992).

Hickman, L., "Ticking Time Bombs?" Municipal Solid Waste News, Solid Waste Association of North America, March (1995).

Hirschfeld, S., Vesilind, P.A. and Pas, E.I., "Assessing the True Cost of Landfills," Waste Management & Res. 10:471-484 (1992).

Hodgson, A., Garbesi, K., Sextro, R. and Daisey, J., "Soil-Gas Contamination and Entry of Volatile Organic Compounds into a House Near a Landfill," Air & Waste Mgt. 42:277-283 (1992).

Jones-Lee, A. and Lee, G.F., "Groundwater Pollution by Municipal Landfills: Leachate Composition, Detection and Water Quality Significance," Proceedings of *Sardinia '93 IV International Landfill Symposium,* Sardinia, Italy, pp. 1093-1103 (1993).

Lee, G.F., "Comments on Tisinger and Giroud 'The Durability of HDPE Geomembranes'," Letter to the Editor, Geotechnical Fabrics Report, Minneapolis, MN, Submitted by G. Fred Lee & Associates, El Macero, CA, 4pp (1994).

Lee, G.F. and Jones, R.A., "Use of Landfill Mining in Solid Waste Management," Proc. Water Quality Management of Landfills, Water Pollution Control Federation, Chicago, IL, 9pp, July (1990a).

Lee, G.F. and Jones, R.A., "Managed Fermentation and Leaching: An Alternative to MSW Landfills," Biocycle 31:78-80,83 (1990b).

Lee, G.F. and Jones, R.A., "Managing Solid Wastes with Landfill Mining," Water Environment and Technology, Water Pollution Control Federation 3:32-34 (1991).

Lee, G.F. and Jones, R.A. "Municipal Solid Waste Management in Lined, `Dry Tomb' Landfills: A Technologically Flawed Approach for Protection of Groundwater Quality," Report of G. Fred Lee & Associates, El Macero, CA, 68 pp (1992).

Lee, G.F. and Jones, R.A., "Geosynthetic Liner Systems for Municipal Solid Waste Landfills: An Inadequate Technology for Protection of Groundwater Quality?" Waste Management & Research, 11:354-360 (1993).

Lee, G.F., Jones, R.A. and Ray, C., "Review of the Efficacy of Sanitary Landfill Leachate Recycle as a Means of Leachate Treatment and Landfill Stabilization," Report to the US Army Construction Engineering Research Laboratory, Champaign, IL (1985).

Lee, G.F. and Jones-Lee, A. "Municipal Landfill Post-Closure Care Funding: The 30-Year Post-Closure Care Myth," Report of G. Fred Lee & Associates, El Macero, CA, 19 pp (1992).

Lee, G.F. and Jones-Lee, A., "Landfill Post-Closure Care: Can Owners Guarantee the Money Will Be There?" Solid Waste & Power 7:35-38 (1993a).

Lee, G.F. and Jones-Lee, A., "Subtitle D Municipal Landfills vs Classical Sanitary Landfills: Are Subtitle D Landfills A Real Improvement?" Report of G. Fred Lee & Associates, El Macero, CA (1993b).

Lee, G.F. and Jones-Lee, A., "Environmental Impacts of Alternative Approaches of Municipal Solid Waste Management: An Overview," Report of G. Fred Lee & Associates, El Macero, CA, 52pp (1993c).

Lee, G.F. and Jones-Lee, A., "The Cost of Groundwater Quality Protection in Landfilling," Report of G. Fred Lee & Associates, El Macero, CA, 8pp (1993d).

Lee, G.F. and Jones-Lee, A., "Landfills and Groundwater Pollution Issues: `Dry Tomb' vs F/L Wet-Cell Landfills," In: Proc. of Sardinia '93 IV International Landfill Symposium, Sardinia, Italy, pp. 1787-1796 (1993e).

Lee, G.F. and Jones-Lee, A. "Landfilling of Solid & Hazardous Waste: Facing Long-Term Liability," Proceedings of the 1994 Federal Environmental Restoration III & Waste Minimization II Conference, Hazardous Materials Control Resources Institute, Rockville, MD, pp1610-1618 (1994a).

Lee, G.F. and Jones-Lee, A., "A Groundwater Protection Strategy for Lined Landfills," Environmental Science & Technology 28:584-5 (1994b).

Lee, G.F. and Jones-Lee, A., "Municipal and Industrial Non-Hazardous Waste Landfills Impact on Public Health and the Environment: An Overview," Report to State of California Environmental Protection Agency Comparative Risk Project, Berkeley, CA (1994c).

Lee, G.F. and Jones-Lee, A., "Addressing Justifiable NIMBY: A Prescription for Siting MSW Landfills," Environmental Management Review, Government Institutes Inc., Rockville, MD, 31:115-138 (1994d).

Lee, G.F. and Jones-Lee, A., "Closed Landfill Cover Space Reuse: Park, Golf Course or a Tomb?" Report G. Fred Lee & Associates, El Macero, CA (1994e).

Lee, G.F. and Jones-Lee, A., "Leachate Recycle Process Offers Pros and Cons," World Wastes 37(8):16,19 (1994f).

Lee, G.F. and Jones-Lee, A., "Advantages and Limitations of Leachate Recycle in MSW Landfills," Report G. Fred Lee & Associates (1994g).

Lee, G.F. and Jones-Lee, A., "Overview of Landfill Post Closure Issues," Presented at American Society of Civil Engineers Convention session devoted to "Landfill Closures - Environmental Protection and Land Recovery," San Diego, CA (1995a).

Lee, G.F. and Jones-Lee, A., "Practical Environmental Ethics: Is There an Obligation to Tell the Whole Truth?," Published in condensed form as "Environmental Ethics: The Whole Truth," Civil Engineering, American Society of Civil Engineers 65:6 (1995b).

Lee, G.F. and Jones-Lee, A., "Recommended Design, Operation, Closure and Post-Closure Approaches for Municipal Solid Waste and Hazardous Waste Landfills," Report of G. Fred Lee & Associates, El Macero, CA, 14pp (1995c).

Lee, G.F. and Jones-Lee, A., "Wet Cell Versus Dry Tomb: Pay a Little Now or More Later," MSW Management 5:70,72 (1995d).

Lee, G.F. and Jones-Lee, A., "MSW Landfill Leachate Recycle and Groundwater Quality Protection," Report of G. Fred Lee & Associates, El Macero, CA, November (1995e).

Lee, G.F. and Jones-Lee, A., "Detection of the Failure of Landfill Liner Systems," Report of G. Fred Lee & Associates, El Macero, CA, 13pp (1996a).

Lee, G.F. and Jones-Lee, A., "Landfill Leachate Management: Overview of Issues," MSW Management 6:18-23 (1996b).

Lee, G.F. and Jones-Lee, A., "'Dry Tomb' Landfills," MSW Management 6:82-89 (1996c).

Lee, G.F. and Jones-Lee, A., "Developing Landfills that Protect People: The True Costs," MSW Management 6:18-23, Nov/Dec (1997a).

Lee, G.F. and Jones-Lee, A., "Hazardous Chemical Site Remediation Through Capping: Problems with Long-Term Protection," Remediation 7(4):51-57 (1997b).

Lee, G.F. and Jones-Lee, A., "Unreliability of Groundwater Monitoring at Lined Landfills," HydroVisions 6(3):3,10-12 (1997c).

Lee, G.F. and Jones-Lee, A., "Potential Impacts of the Proposed Minimum Subtitle D Landfills on Agricultural and Greater Area Municipal Resident Interests," Report of G. Fred Lee & Associates, El Macero, CA, August (1997d).

Lee, G.F. and Jones-Lee, A., "Three R's Managed Garbage Protects Groundwater Quality," Presented at California Resource Recovery Association annual meeting, Monterey, CA, May (1997e).

Lee, G.F. and Jones-Lee, A., "Questions that Regulatory Agencies Staff, Boards and Landfill Applicants and their Consultants Should Answer About a Proposed Subtitle D Landfill or Landfill Expansion," Report of G. Fred Lee & Associates, El Macero, CA, April (1997f).

Lee, G.F. and Jones-Lee, A., "Deficiencies in US EPA Subtitle D Landfills in Protecting Groundwater Quality for as Long as MSW is a Threat: Recommended Alternative Approaches," Report of G. Fred Lee & Associates, El Macero, CA (1997g).

Lee, G.F. and Sheehan, W., "MSW Recycling Protects Groundwaters: Reply to `Recycling is Garbage'," Letter to the editor New York Times, HydroVisions 5(3):6 (1996).

Montgomery, R.J., and Parsons, L.J., "The Omega Hills Final Cover Test Plot Study: Three Year Data Summary," presented at the 1989 Annual Meeting of the National Solid Waste Management Association, Washington, D.C. (1994).

Michaels, A., Editor. "Solid Waste Forum," Public Works, p 32, January (1998).

Mulder, H. and Haven, E. Solid Waste Assessment Test (SWAT) Program, Report to the Integrated Waste Management Board, Water Resources Control Board Report 96-ICWP, Sacramento, CA, December (1995).

Nosko, V. and Andrezal, T., "Electrical Damage Detection System in Industrial and Municipal Landfills," Geocontinue 93:691-695 (1993).

Park, J.K., Sakti, J.P. and Hoopes, J.A., "Transport of Organic Compounds in Thermoplastic Geomembranes. I: Mathematical Model," Journal of Environ. Engr. 122(9):800-806 (1996a).

Park, J.K., Sakti, J.P. and Hoopes, J.A., "Transport of Organic Compounds in Thermoplastic Geomembranes. II: Mass Flux Estimates and Practical Implications," Journal of Environ. Engr. 122(9):807-813 (1996b).

Parsons, A. and Davis, P., "A Proposed Strategy for Assessing Compliance with the RCRA Ground Water Monitoring Regulations," *Current Practices in Ground Water and Vadose Zone Investigations,* ASTM American Society for Testing and Materials, Philadelphia, STP 1118, pp. 39-56 (1992).

Parsons, J. and Mulder, J., "Solid Waste Assessment Test (SWAT) Program Report to the Legislature 1989-1990," Water Resources Control Board 90-20CWP, Sacramento, CA, January (1991).

Peggs, I.D., "Leak Location and Flaw Detection Technologies for Quality Assurance and Analysis of Geomembrane Lining Systems," I-Corp International, Boynton Beach, FL (undated).

Peggs, I., "Geosynthetics in Landfills," MSW Management 8(1):23-27 (1998).

Pohland, F.G., "Sanitary Landfill Stabilization with Leachate Recycle and Residual Treatment," U.S. Environmental Protection Agency, Cincinnati, EPA-600/2-75-043 (1975).

Pohland, F.G., "Leachate recycle as landfill management option," J. of Env. Eng. 106(EE6):1057-1069 (1980).

Pohland, F.G. and Harper, S.R., "Critical review and summary of leachate and gas production from landfills," EPA/600/52-86-073, Cincinnati, OH, USA: US Environmental Protection Agency (1987).

Prosser, R. and Janechek, A., "Landfill Gas and Groundwater Contamination," In: Dunn, R. J. and Singh, U.P, (eds) *Proceedings: Landfill Closures...Environmental Protection and Land*

Recovery, American Society of Civil Engineers, Geotechnical Special Publication No. 53, New York, NY (1995).

Reinhart, D. and Townsend, T., *Landfill Bioreactor Design and Operation,* Lewis Publishers, New York (1998).

Robertson, A., "The 'Robertson Barrier Liner' - A Testable Double Liner System," Robertson Barrier System Corp., Vancouver, B.C., Canada (1990).

Rowe, W., "Superfund and Groundwater Remediation: Another Perspective," Environ. Sci. & Technol 25:370 (1991).

Sakti, J.P., Park, J.K. and Hoopes, J.A., "Permeation of Organic Chemicals through HPDE Geomembranes," In: Proceedings of ASCE National Environmental Engineering Conference, ASCE, New York, July (1991).

Savage, G.M., Diaz, L.F. and CalRecovery, Inc., "Landfill Mining and Reclamation," ISWA Times 4:1-4 (1994).

Shusterman, D. "Critical Review: The Health Significance of Environmental Odor Pollution,@ Archives of Environmental Health, 47(1):76-87 (1992).

Tierney, J., "Recycling is Garbage," New York Times Magazine, p. 106, June 30 (1996).

Trotti, J., "1998: A Return to Deep and Enduring Issues," MSW Management, p 6, December (1997).

US EPA, "Solid Waste Disposal Facility Criteria: Proposed Rule," Federal Register 53(168):33314-33422, 40 CFR Parts 257 and 258, US EPA, Washington, D.C., August 30 (1988a).

US EPA, "Criteria for Municipal Solid Waste Landfills," US EPA Washington, D.C., July (1988b).

US EPA, "Solid Waste Disposal Facility Criteria: Final Rule, Part II," Federal Register, 40 CFR Parts 257 and 258, US EPA, Washington, D.C., October 9 (1991).

US EPA Landfill Bioreactor Design and Operation, Seminar Publication: US Environmental Protection Agency, Office of Research and Development, EPA/600/R-95/146 Washington, D.C., September (1995).