

**Overview of Subtitle D Landfill
Design, Operation, Closure and Postclosure Care Relative to
Providing Public Health and Environmental Protection for as Long as the
Wastes in the Landfill will be a Threat**

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This discussion provides information for members of the public and others who are concerned about the appropriateness of using minimum Subtitle D landfills for managing municipal solid and industrial “nonhazardous” wastes, with particular emphasis on providing for true long-term public health and environmental protection from these wastes that are placed in the landfills.

The discussion presented herein is based on the senior author’s experience in investigating the properties of landfill liners and the characteristics of today’s landfills, relative to their ability to prevent groundwater pollution and other environmental impacts for as long as the wastes in the landfill will be a threat. Additional information on the issues discussed herein is available in papers and reports cited as references. The authors have developed a number of papers and reports that discuss the details of the topics summarized below. The most relevant sources of background information on the topics discussed are Lee and Jones-Lee (1994, 1998a,b) and Lee (2002), as well as other sources cited in the references to this paper.

The US EPA has developed a website on landfill safety, which can best be characterized as propaganda, trying to convey to the public that today’s minimum Subtitle D landfills are protective. However, as discussed by Lee (2003a), the US EPA on its website has provided a considerable amount of half-truths or incomplete discussions of issues, especially as relates to long-term protection afforded by a minimum Subtitle D landfill.

Problems with “Dry Tomb” Landfilling Approach

Traditionally, the landfilling of solid wastes has been accomplished at the least possible cost. Initially, urban areas deposited their solid wastes on nearby low-value lands, frequently wetlands, creating a waste dump. This approach was followed by excavation of an area and depositing the wastes in the excavated area. Often the wastes in the dump were burned to reduce volume and some other adverse impacts. Eventually, beginning in some areas in the 1950s, it was determined that there was need to cover the daily deposited wastes with a layer of soil to reduce odors and access to wastes by vermin, flies, birds, etc. This approach led to the development of the “sanitary” landfill. Basically, the sanitary landfill was an excavated area in which the wastes were supposed to be covered each day by a layer of soil. No regard was given to the potential for the wastes in a sanitary landfill to cause groundwater pollution or for the gas generated in the landfill to be a threat to cause explosions and to cause public health and environmental problems. While landfilling in the conventional sanitary landfill was recognized

in the 1950s as leading to the pollution of groundwater by landfill leachate (ASCE, 1959), it was not until the 1980s/1990s that there were national regulations that were designed to control groundwater pollution by landfills. In the 1980s the US EPA and state regulatory agencies adopted the “dry tomb” landfilling approach.

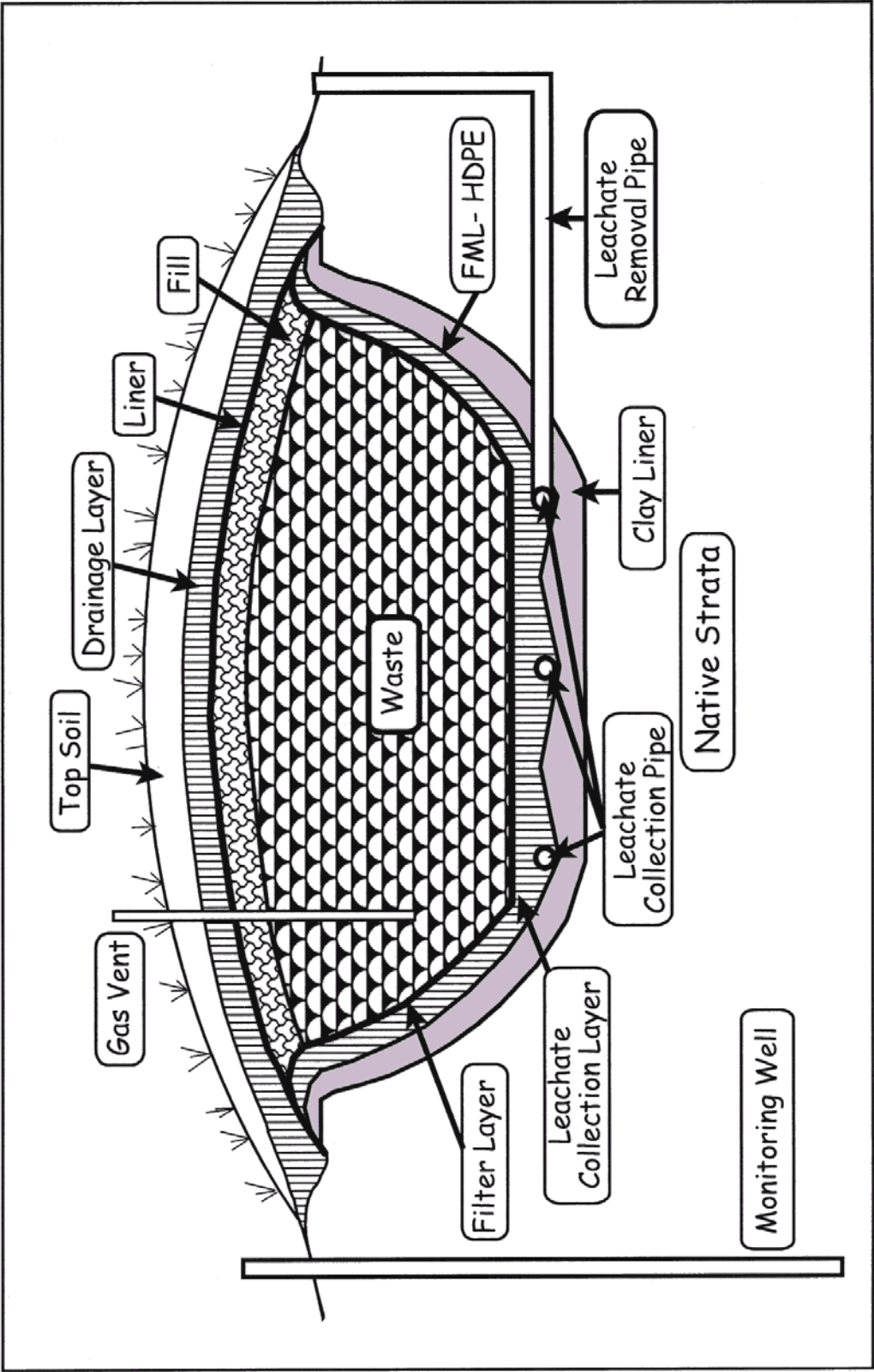
In accordance with current US EPA regulations, solid waste landfills today are of a “dry tomb” design and, in principle, operation. Environmental groups in the early 1980s convinced the US Congress and the US EPA that landfilling should be based on the concept of isolating the waste from water that can generate leachate (garbage juice) that can in turn lead to groundwater pollution by constituents leached from the solid waste. In theory, since one of the primary problems of solid waste landfills that are used to manage municipal or industrial solid waste is the pollution of groundwater by leachate, if the waste can be isolated from water that leads to the formation of leachate, then groundwater pollution by landfills could be prevented. The dry tomb landfilling approach, however, leads to a situation where the wastes that are isolated from the environment in a compacted soil and plastic sheeting “tomb” will remain a threat to cause groundwater pollution and to generate landfill gas.

The dry tomb landfilling approach (see Figure 1), as implemented by the US EPA, is based on the use of a relatively thin plastic sheeting (high-density polyethylene – HDPE) layer and a compacted soil/clay layer to form what is called a “composite” liner. The evolution of this approach began in the 1970s, when compacted soil/clay liners were proposed for waste containment. However, it was soon found that compacted soil/clay has a finite permeability for water/leachate, which means that eventually it is subject to penetration by leachate, which can lead to groundwater pollution. Further, the clay liners were found to be subject to a number of problems that led to their failure to prevent leachate from passing through them at the design characteristics.

The fact that compacted soil layers cannot prevent groundwater pollution by landfill leachate led the US EPA in the early 1980s to adopt the use of a plastic sheeting layer as a liner. However, that approach was soon found to be unreliable, since relatively small holes in the plastic sheeting could lead to high leakage rates through it. The next approach adopted was that of a composite liner, in which the high-density polyethylene plastic sheeting is laid immediately adjacent to the compacted soil/clay layer. This approach can greatly decrease the rate of leakage through the plastic sheeting liner, where there are only a few holes in the plastic sheeting, if the clay and the plastic sheeting layers are in intimate contact.

The evolution of liner and cover systems for landfills – from no liner, to a clay/soil liner, to a plastic sheeting liner, to the current composite liner – was not based on a finding that any of these liners could potentially prevent groundwater pollution by wastes for as long as the wastes in the containment system were a threat. The clay/soil liner was based on using the next least expensive material to no liner. When it was realized that clay/soil liners had significant problems, plastic sheeting was the next least expensive thing to clay/soil. There was never any evaluation that showed that clay/soil or plastic sheeting would be expected to prevent groundwater pollution for as long as the wastes were in the landfill. The same situation applies to the composite liner system that is used today. It is only a matter of time until that liner system

Figure 1
Single Composite Liner Landfill Containment System



fails to prevent leachate from passing through it that can pollute groundwaters, rendering them unusable for domestic and many other purposes.

The US EPA, as part of adopting the RCRA Subtitle D regulations, stated in the draft regulations (US EPA, 1988a),

“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 (1988b) Criteria for Municipal Solid Waste Landfills 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.”

With this background of the ultimate long-term failure of the landfill containment system, it is appropriate to inquire as to why the Agency went ahead with a fundamentally flawed approach for landfilling of wastes. This situation arose out of the fact that environmental groups had filed suit against the US EPA for failure to develop municipal and industrial “nonhazardous” solid waste landfilling regulations. This led the Agency to promulgate the Subtitle D regulations (US EPA, 1991), based on a single composite liner and equivalent landfill cover, even though it was understood in the early 1990s that at best this approach could only postpone when groundwater pollution occurs by landfill leachate. US EPA regulations governing the landfilling of hazardous wastes (Subtitle C) were adopted separately in the 1980s.

The 30-year funding period for postclosure monitoring and maintenance of Resource Conservation and Recovery Act (RCRA) Subtitle C and D landfills that was specified by Congress was one of the most significant errors made in developing RCRA Subtitle C and D landfilling regulations. Unfortunately, those who were responsible for developing this approach did not have an understanding of the elements of how waste-associated constituents in a dry tomb landfill would behave with respect to degradation, transformation, etc. They also did not take into account the fact that the liner components that were proposed (plastic sheeting and clay) have a finite period of time over which they can be effective.

In establishing the original RCRA landfilling regulations, the environmental groups and Congress, apparently with US EPA approval, had no understanding of the length of time that municipal or industrial waste in a dry tomb landfill would be a threat to cause groundwater pollution when moisture (water) infiltrates into the landfill. There was the mistaken idea that 30 years after closure of a dry tomb landfill, the waste in the landfill would no longer be a threat. Those who understand the characteristics of wastes and their ability to form leachate, as well as the processes that can occur in a landfill, realize that 30 years is an infinitesimally small part of the time that waste components in a landfill, especially a dry tomb landfill, would be a threat to cause groundwater pollution through leachate formation. While Congress required that the regulations include provisions to potentially require additional funding at the expiration of the 30-year postclosure care period, the likelihood of obtaining this funding from private landfill

companies, even if they still exist 30 years after a landfill has been closed, or from a public agency that develops or owns a landfill, is remote.

A critical review of the processes that can take place in a landfill that can generate leachate shows that a dry tomb landfill, where there is at least an initial effort to reduce the moisture entering the wastes, will eventually lead to a waste containment system that will not prevent groundwater pollution for as long as the wastes are a threat. The municipal solid wastes (MSW) in a classical sanitary landfill where there is no attempt to prevent moisture from entering the wastes have been found to generate leachate for thousands of years. Freeze and Cherry (1979) have reported that Roman Empire landfills developed over 2,000 years ago are still generating leachate. Belevi and Baccini (1989) have reported, based on a study of Swiss landfills, that lead would be expected to be leached from the landfilled wastes at concentrations above drinking water standards for over 1,000 years. In a dry tomb landfill the wastes will be a threat to generate leachate, effectively forever, and therefore are a threat to cause groundwater pollution well beyond the 30-year postclosure care period established in current landfilling regulations.

Another significant error that was made in developing the dry tomb landfilling approach was that it was assumed that it would be possible to design, construct and operate the landfill containment system so that little or no moisture could enter the landfill once the landfill was closed – i.e., no longer accepting waste – and a landfill cover had been placed on the waste. Further, it was assumed that, even if moisture did get through the low-permeability cover of the landfill, the leachate generated would be collected in a leachate collection system which overlies the single composite liner. Further, the US EPA assumed then (and, unfortunately, still assumes today) that, when a dry tomb landfill generates leachate that passes through the liner into the underlying geological strata and groundwater system, the groundwater monitoring system used would detect this leachate-polluted groundwater while the leachate-polluted groundwater was still on the landfill owner's property. Unfortunately, these assumptions were based on inappropriate analysis, and it is now clear that the dry tomb landfill is a fundamentally flawed technological approach for managing solid waste. As it stands now, the current regulatory approaches allowed by the US EPA and states can at best provide for protection of public health and the environment from hazardous and deleterious components of municipal and industrial wastes for a relatively short period of time compared to the time that the landfilled waste components will be a threat.

Penetration of Moisture through the Landfill Cover into Wastes

Today's Subtitle D landfills (those that accept municipal solid waste and so-called "nonhazardous" industrial waste) are allowed to be closed with a landfill cover consisting of soil above the wastes shaped to serve as the base for a low-permeability plastic sheeting layer, which is overlain by a foot to two feet of a drainage layer. Above the drainage layer is a few inches to a foot or so of topsoil that serves as a vegetative layer. The vegetative layer is designed to promote the growth of vegetation that will reduce the erosion of the landfill cover. In principle, this landfill cover is supposed to allow part of the moisture that falls on the vegetative layer of the landfill to penetrate through the root zone of the vegetation in this layer to the porous (drainage) layer. When the moisture reaches the low-permeability plastic sheeting layer, it is supposed to move laterally to the outside of the landfill (see Figure 1).

Landfill permit applicants and their consultants as well as some regulatory agency staff will claim that the eventual failure of the landfill liner system is of limited significance in causing groundwater pollution, since the landfill cover can keep the wastes dry, and thereby prevent leachate generation. Landfill permit applicants and their consultants, as well as some governmental agency staff who support a single composite liner system, will, at permitting hearings, show a picture of landfill leachate generation once the landfill is closed with a low-permeability cover. This image shows that the leachate generation in the closed landfill is greatly curtailed within a year after the cover is put in place. While they would like to have others believe that that situation will continue to exist in perpetuity, it will not, because of the eventual deterioration of the low-permeability plastic sheeting layer in the landfill cover.

Another deception with respect to landfill covers is that they can be effectively monitored to detect when moisture leakage through the cover occurs. The typical monitoring approach that is advocated by landfill owners and operators and allowed by regulatory agencies, involves a visual inspection of the surface of the vegetative soil layer of the landfill cover. If cracks or depressions occur in this layer, these are filled with soil. Such an approach will not detect cracks in the plastic sheeting layer. As a result, the moisture that enters the drainage layer which comes in contact with the plastic sheeting layer and which, when the plastic sheeting is new and constructed properly, runs off of the landfill, will instead penetrate into the wastes. This could occur during the postclosure care period, and the increased leachate generation would be detected. However, it could also readily occur in year 31 after closure or thereafter, when there could be no one monitoring leachate generation.

Further, even if it were detected, the typical postclosure funding that is allowed does not provide adequate funds to determine where the landfill cover has failed and to repair it. The typical required postclosure funding today does not provide funds to repair the low-permeability layer of a dry tomb landfill cover. It is assumed by the regulatory agencies that the low-permeability plastic sheeting layer in a dry tomb landfill will maintain its integrity throughout the 30-year postclosure care period, even though it is understood that the plastic sheeting layer in a landfill cover is subject to significant stresses due to differential settling of the wastes that can lead to its failure to prevent moisture from entering the wastes.

The high probability of failure of the low-permeability layer of the landfill cover is the reason why Lee and Jones-Lee (1995a) advocate the use of leak detectable covers on landfills, which are operated and maintained in perpetuity – i.e., as long as the wastes are a threat. This approach requires that a dedicated trust fund be developed that is of sufficient magnitude to ensure that, at any time in the future while the wastes are still a threat (typically, forever), the leaks in the cover can be isolated and repaired. This dedicated trust should be of sufficient magnitude to address plausible worst-case failures in each of the landfill containment system components, as well as the monitoring system.

This long-term financial commitment to maintaining a low-permeability cover on the landfill would significantly increase the cost of solid waste management. This is the political reason that regulatory agencies, from the US EPA through the state agencies, do not implement the dry tomb landfilling approach so that it addresses the long-term problems associated with this

landfilling approach. Until this issue is meaningfully addressed, today's dry tomb landfills at best are façades with respect to their ability to protect public health and the environment from landfilled wastes for as long as the wastes in the landfill will be a threat.

The situation is that no political entity, from the federal administration in power through the federal Congress, state governors and legislatures, to county Boards of Supervisors, wants to be responsible for causing those who generate solid waste to have to pay for the true cost of its management/disposal. It is estimated that solid waste disposal that is truly protective of public health and the environment would double to triple the cost of solid waste management. Instead of increasing everyone's cost of solid waste management by 15 to 25 cents per person per day, the political entities are opting for short-term protection, and passing these costs on to future generations in terms of lost groundwater resources and adverse impacts to the health, welfare and interests of those in the vicinity of the landfills. Today's cheaper-than-real-cost solid waste management is strongly contrary to effective conservation and reuse of solid waste components. Lee and Jones-Lee (2000) have discussed the importance of recycling/reusing as much of the components of solid waste as possible as a resource conservation measure and for protection of groundwater resources, public health and the environment, under the conditions where the true cost of landfilling of solid waste in dry tomb landfills is paid as part of disposal fees.

Leachate Collection and Removal System

The key to preventing groundwater pollution by a dry tomb landfill, as well as a leachate recycle (so-called "bioreactor") landfill, is the ability to collect all leachate that is generated in the landfill in the leachate collection and removal system. Leachate collection and removal systems, however, as currently designed, are subject to many problems. In principal, leachate that is generated in the solid waste passes through a filter layer underlying the waste which is supposed to keep the solid waste from infiltrating into the leachate collection system (see Figure 1). The leachate collection system consists of gravel or some other porous medium, which is designed to allow leachate to flow rapidly to the top of the HDPE liner. Once it reaches the sloped liner, it is supposed to flow across the top of the liner to a collection pipe, where it will be transported to a sump, where the leachate can be pumped from the landfill. According to regulations, the maximum elevation of leachate ("head") in the sump is to be no more than 1 ft. However, leachate collection systems are well known to be prone to plugging. Biological growth, chemical precipitates, and "fines" derived from the wastes all tend to cause the leachate collection system to plug. This, in turn, increases the head of the leachate above the liner upstream of the area that is blocked. While there is the potential to back-flush some of these systems, this back-flushing will not eliminate the problem.

The basic problem with leachate collection systems' functioning as designed is that the HDPE liner, which is the base of the leachate collection system, develops cracks, holes, rips, tears, punctures or points of deterioration. When the leachate that is passing over the liner reaches one of these points, it starts to pass through the liner into the underlying clay layer. If the clay layer is in intimate contact with the HDPE liner, the rate of leakage through the clay is small. If, however, there are problems in intimate contact between the clay and HDPE liner, such as a fold in the liner, then the leakage through the HDPE liner hole can be quite rapid. Under these conditions, the leachate spreads out over the clay layer and can leak at a substantial rate through the clay.

The theoretical rate of leakage through a clay liner, if it is constructed properly and has, at the time of construction, a permeability of 10^{-7} cm/sec with 1 ft of head, is about 1 in/yr. Therefore, since the clay liners should be a minimum of 2 ft thick, leachate in the areas of the liners where there is 1 ft of head will penetrate through holes in the HDPE and the clay liner in about 25 years. There are several reasons, however, why the penetration through the clay liner could be much more rapid. These include desiccation cracking of the clay associated with the vadose zone transport of the moisture that is used to achieve optimum moisture density at the time of clay liner construction, which moves by gravity out of the clay into the underlying strata.

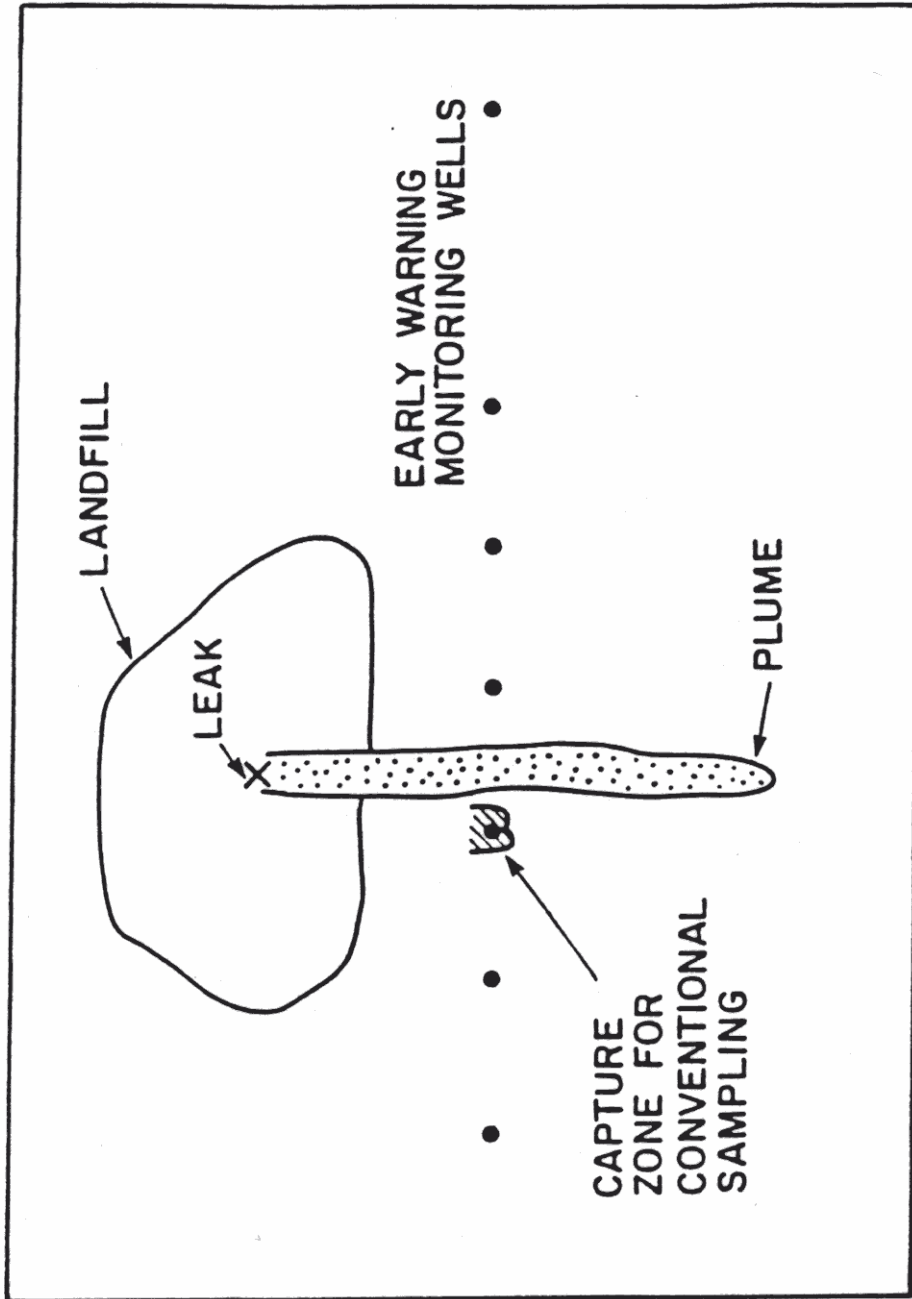
Groundwater Monitoring

The US EPA Office of Solid Waste Emergency Response senior staff have repeatedly indicated that the ultimate failure of HDPE liners to prevent leachate from passing through the liner into the underlying groundwaters does not mean that the Subtitle D regulations are fundamentally flawed. They have pointed out that the regulations are explicit in requiring that a groundwater monitoring system be developed so that, when leachate-polluted groundwaters first reach the point of compliance for groundwater monitoring, they are detected by the groundwater monitoring system with sufficient reliability so that a remediation program can be initiated. The point of compliance for groundwater monitoring at Subtitle D landfills is specified as being no more than 150 meters from the downgradient edge of the waste deposition area, and must be on the landfill owner's property.

It was pointed out by Cherry (1990) that initial leakage through HDPE-lined landfills will be through areas where there are holes, rips, tears or points of deterioration of the HDPE liner. As shown in Figure 2, this will lead to relatively narrow plumes of polluted groundwaters at the point of compliance for groundwater monitoring. The typical groundwater plume in a sand, gravel or silt aquifer system will likely be on the order of 10 to 20 ft wide at the point of compliance. The basic issue that must be addressed is whether these narrow plumes will be detected by the groundwater monitoring well array at the point of compliance. A casual, much less sophisticated review of this situation shows that, typically, federal and state regulatory agencies allow monitoring wells to be placed 100 or more feet apart at the point of compliance. Each monitoring well has a zone of capture of 1 ft, which means that, if the wells are 200 ft apart, there is 198 ft between wells where a plume of leachate-polluted groundwater can pass and not be detected. This situation is recognized as one where the typical groundwater monitoring approach used for Subtitle D landfills is a façade with respect to reliably implementing Subtitle D regulations for detecting liner failure.

It is because of the unreliability of groundwater monitoring systems based on vertical monitoring wells at the point of compliance that some states (such as the state of Michigan) require that a double composite liner be used at municipal solid waste landfills, where the lower composite liner represents a leak detection system for the upper liner (see Figure 3). While this approach is not foolproof in always being able to detect when both liner systems fail, it has a much greater probability of detecting when the upper composite liner fails, since leachate that passes through that liner will be collected in a leak detection system between the two composite liners. This situation represents the primary basis for the recommendation (Lee and Jones-Lee,

Figure 2
Leakage from HDPE Lined Landfill
(Adapted from Cherry, 1990)



1998a) that all Subtitle D landfills consist of a double composite liner with a leak detection system between the two liners.

A key issue that needs to be addressed as part of establishing the postclosure funding for a Subtitle D landfill is the development of a dedicated trust fund of sufficient magnitude to take action at any time in the infinite future when leachate is detected in the leak detection system between the two composite liners to stop further leachate generation by repairing the cover or exhuming the wastes and placing them in another landfill. As discussed by Lee and Jones-Lee (1995a), failure to provide this funding could readily mean that, when leachate is detected in the leak detection system between the two composite liners, no action will be taken, since there are no funds available to properly address the failure of the upper composite liner.

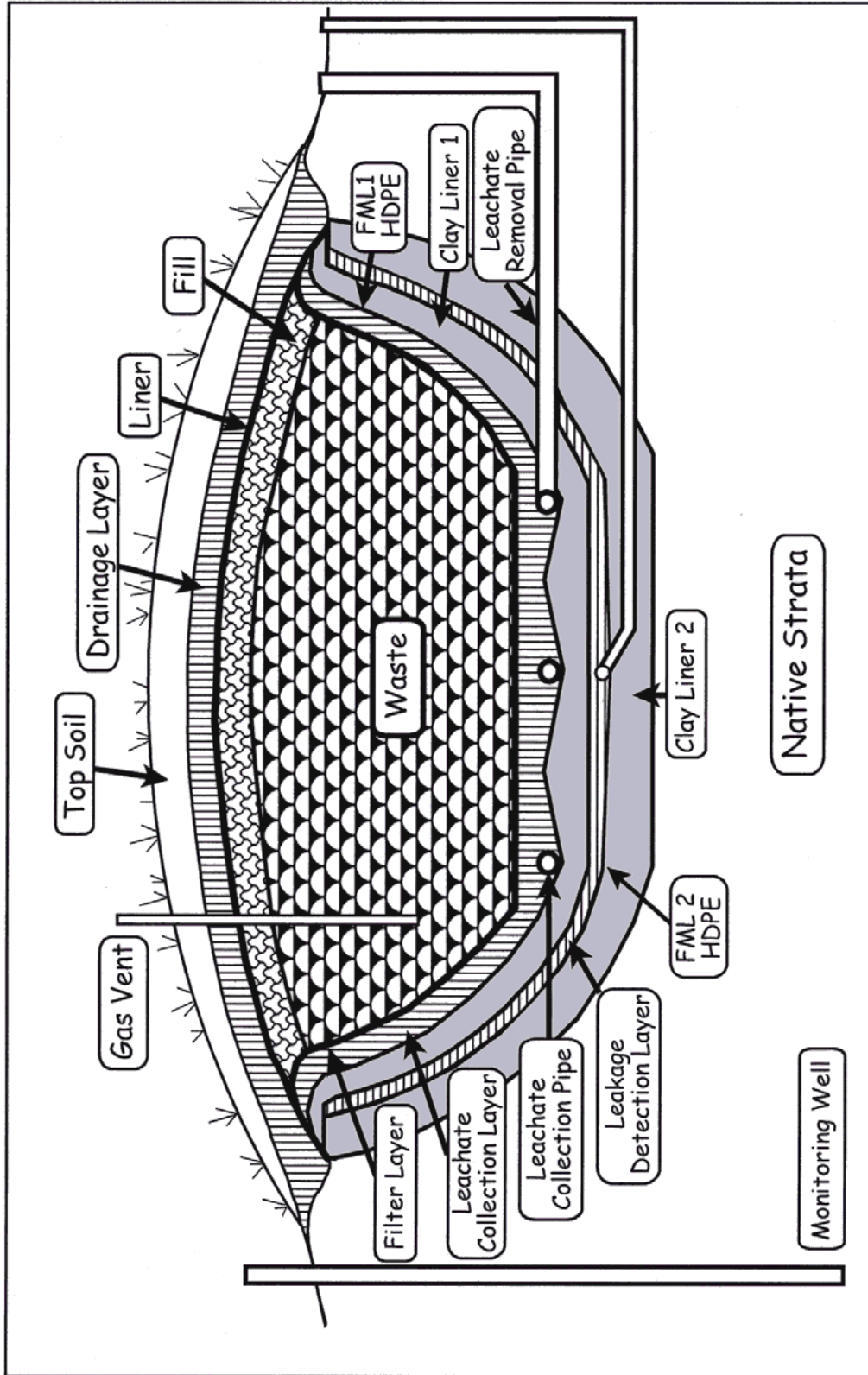
Landfill Gas

Some organics in wastes can serve as a source of food for bacteria will, in a landfill environment, produce methane and CO₂ (landfill gas). Landfills will also release a number of other volatile chemicals, including highly hazardous VOCs and odorous compounds, which are a threat to the health and welfare of those within the sphere of influence of the landfill. This sphere can extend for several miles, depending on the topography of the area and the tendency for atmospheric inversions to take place.

While landfill advocates will claim that the approaches used today of providing daily cover of the wastes will reduce the gaseous releases from landfills, the facts are that they do not eliminate them. Further, when landfill owner/operators become sloppy in operations, greater-than-normal landfill gas emissions occur. These emissions are typically detected through landfill odors. Basically, if an adjacent or nearby property owner/user can smell the landfill, then there is inadequate buffer land between the landfill and adjacent properties, which should make it necessary for the landfill owner/operator to either acquire adjacent buffer land or to use more than the minimum approach for controlling gaseous releases from the landfill. It would be important to control land use within this area so that releases from the landfill would not be adverse to the land use. For example, agriculture in these areas should be restricted, since releases from the landfill could contaminate the crops.

While there are some who attempt to minimize the significance of smelling landfill gas on adjacent properties as only being an aesthetic problem, in fact, as discussed by Shusterman (1992), it is now known that noxious odors can cause illness in people. Therefore, odors should be controlled so that they do not trespass across the landfill adjacent property owner's property line. So long as landfill owners attempt to use adjacent properties for their waste disposal buffer zones, and regulatory agencies allow this, there will be justified NIMBY ("not in my back yard") issues by adjacent property owners. Lee and Jones-Lee (1994) have discussed many of the issues that lead to a justified NIMBY, the most important of which is malodorous landfill gas emissions. One of the major problems with current US EPA and many state landfilling regulations is that they allow the deposition of wastes in the landfill without adequate buffer land between where the wastes are deposited and adjacent property. Often at least a mile and, in some situations, several miles of buffer land is needed to dissipate odors as well as airborne hazardous chemicals.

Figure 3
Double Composite Liner Landfill Containment System



According to Anderson (pers. comm., 2004), the US EPA estimates that a well designed, maintained and operated landfill gas collection system will collect only about 75 percent of the landfill gas emissions. The percentage of collection will deteriorate significantly over time, due to development of cracks in the landfill cover and the problems that develop in the ability of the landfill gas collection system to collect and transport landfill gas from all parts of the landfill to a point where it can be extracted and managed.

A significant error that is made in landfill development and expansion applications is that the landfill applicant and its consultants, and the regulatory agencies, allow predictions of landfill gas production based on incorrect assessments of how landfill gas production will play out over the years in a “dry tomb” landfill. The key to landfill gas production is the ability of the fermentable components of the wastes to contain sufficient moisture so that bacteria can convert the some of the organic fraction of the wastes into landfill gas (methane and CO₂). Therefore, the rate of moisture penetration through the cover and the mixing of this moisture with the waste components control the rate and duration of landfill gas production.

Lee and Jones-Lee (1999) have discussed the fact that, since much of the municipal wastes that are placed in Subtitle D landfills are contained within plastic bags, and since these plastic bags are only crushed and not shredded, the crushed bags will “hide” the fermentable components of the waste that can lead to landfill gas formation. The net result is that, rather than landfill gas production following the classic generation rates and durations that were developed based on unbagged wastes or situations where much of the wastes in the landfill were able to interact with the moisture that enters the landfill during the first decade or so of landfill operation, the period of landfill gas production will be extended until the plastic bags decompose. This can readily be many decades, to a hundred or more years.

“Bioreactor” Landfills

The bioreactor landfilling approach is being offered as a solution to the significant problems associated with dry tomb landfilling of municipal solid wastes and industrial solid wastes that contain organics that can lead to the formation of landfill gas. In a bioreactor landfill, rather than trying to keep the wastes dry, moisture, usually in the form of leachate, is added to the landfill to promote waste “stabilization.” It has been known for over 25 years that the addition of moisture, such as leachate, to a landfill accelerates the rate of landfill gas production. This knowledge has led to “leachate recycle” as a means of enhancing the rate of “stabilization” of the landfill. By “stabilization” it is meant that the wastes no longer produce landfill gas (methane and CO₂) through the biochemical reactions of bacteria utilizing some of the organic components in wastes as a source of energy. Further, addition of moisture accelerates the rate of settling of the wastes.

Some landfill owner/operators who advocate leachate recycle support this approach as a less expensive method of disposal of leachate, rather than having to haul it to a local domestic wastewater treatment plant. The US EPA has jumped on the bioreactor bandwagon, where conference proceedings have been published on the advantages of this approach. Further, articles in solid waste trade magazines and books have been published advocating the merits of the bioreactor landfill. Those reviewing this literature could be led to believe that this is a viable

approach to follow; however, as discussed by Jones-Lee and Lee (2000), there are significant problems with it. Unfortunately, the literature on this topic is biased, in that those writing in support of it generally fail to discuss the well known problems associated with it.

First, as discussed by Jones-Lee and Lee (2000), leachate recycle increases the amount of leachate in the landfill that must be managed and, therefore, that can leak through the liner system. Leachate recycle should only be used in a double composite lined landfill where, as discussed herein, there is an opportunity to detect when the upper composite liner fails to prevent leachate from migrating through it.

A second problem with leachate recycle is that much of the waste that is placed in municipal solid waste landfills is contained in plastic garbage bags. While these bags are crushed – i.e., run over by landfill compacting equipment – they are not shredded, and therefore “hide” some of the waste from the moisture until the bag decomposes. Basically, this means that the period of time over which landfill gas can be generated by municipal solid wastes is much longer (decades, to possibly a 100 years or so), compared to the situation if the wastes were placed in the landfill in such a way as to enable all of the recycled leachate to come in contact with the wastes. This would require either removal of the wastes from the garbage bags prior to deposition in the landfill or shredding of the bags.

Another problem with leachate recycle is that there are components in the municipal solid waste that are a threat to generate leachate, which is a threat to groundwater quality, even after all of the gas has been generated. Jones-Lee and Lee (2000) recommend that, after the fermentation of the wastes has stopped, leachate recycle should stop, and the wastes should be “washed” leached with clean water, in order to remove the salts and other leachable inorganic and organic constituents. During this washing process, the leachate that is generated is not recycled – i.e., it is removed and treated before disposal outside the landfill..

Geosynthetic Liner as a Substitute for Two Feet of Clay

Landfill developers, with the approval of state and federal regulatory agencies, are allowing the substitution of a so-called “geosynthetic” liner for 2 ft of clay in a Subtitle D landfill. These geosynthetic liners are thin layers of bentonite clay encased in a woven material to provide some structure to the thin layer of clay. There are a number of reasons why this approach is not acceptable in terms of providing equivalent protection of 2 ft of clay compacted to a permeability of 10^{-7} cm/sec. In support of this approach, those who advocate it claim that the advective permeability of 10^{-9} cm/sec for geosynthetic liners is a significant advantage over the 10^{-7} cm/sec permeability of the clay layer. However, such claims are misleading and represent either a distortion of what is known or a lack of understanding of diffusion processes. As was pointed out by Daniel and Shackelford (1989), diffusion-controlled processes become the dominant factor controlling rates of migration of chemical constituents through liners when the advective permeability is about 10^{-8} cm/sec. The 10^{-9} cm/sec advective permeability claim for geosynthetic liners does not represent the rate of migration through the liner. The migration is controlled by diffusion, which is a factor of 10 or more times greater than the predicted advective permeability.

A second area of concern with respect to geosynthetic liners is that their extremely thin character makes them subject to structural failure. Great care must be exercised in developing the base for these geosynthetic liners, or else there will be structural failure of the thin liner layer. Overall, geosynthetic liners should be used as an add-on to the regular clay liner, not as a substitute for it.

Permeation of Solvents

One of the issues that the US EPA and other regulatory agencies continue to ignore in developing Subtitle D landfills is that low molecular weight solvents, such as can be purchased in a hardware store, including the components of gasoline, can pass through an intact (without holes) HDPE liner in a short period of time. As discussed by Lee and Jones-Lee (1998a), it has been found that solvents can pass through HDPE liners in a few days. The process is called “permeation,” where the solvents dissolved in water can pass through an HPDE liner by dissolving into the organic matrix and then out of the matrix on the downgradient side. Permeation has been known since the late 1980s as a potential mechanism for transporting solvents that are allowed in the municipal solid waste stream as “nonhazardous” waste. This issue has been investigated in detail by Park, et al. (1996a,b). The regulatory agencies have ignored this situation, since it would mean that they would have to admit that HPDE liners are not effective barriers for preventing pollution by some important MSW constituents.

Postclosure Monitoring and Maintenance

Subtitle D regulations require that a small amount of assured funding for postclosure monitoring and maintenance be available for a period of 30 years. Some regulatory agencies will allow the landfill company to be self-insured or insured through an insurance company that is backed by a landfill company. Such approaches should not be allowed, since landfill companies are amassing large liability due to the ultimate failure of the landfill liner system and the pollution of groundwaters that will occur as a result of this failure. It is well understood that, ultimately, private landfill companies will not likely be able to comply with Subtitle D regulations for funding remediation. The amount of postclosure monitoring and maintenance funding that is currently required is grossly inadequate compared to the funding levels that could be necessary during the 30-year mandatory postclosure period.

Recently the US EPA (Bonaparte, et al., 2002) has claimed, based on an inappropriate technical approach, that the landfill liner systems being developed today will maintain their integrity for 1,000 years. Koerner, in Bonaparte, et al. (2002), has erroneously stated that municipal solid wastes would only be a threat to generate leachate in a dry tomb landfill for 200 years. The conclusion from the Bonaparte, et al. (2002) review is that today’s minimum Subtitle D landfills will, based on this analysis, be protective of groundwater from landfill leachate. However, as discussed by Lee (2002), this analysis is flawed from several perspectives. Municipal solid waste in a dry tomb landfill has components that will be a threat to cause groundwater pollution effectively forever. Inorganic solid waste in a dry tomb landfill will also be a threat to cause groundwater pollution forever. Further, the prediction of how long the plastic sheeting layer in a single composite liner will be an effective barrier to leachate transport through it of 1,000 years is based on an inappropriate use of the Arrhenius equation. Wastes in Subtitle D dry tomb landfills will be a threat to cause groundwater pollution after the HDPE

liners that are used in these landfills are no longer effective barriers to prevent groundwater pollution by reliably collecting all leachate generated in the landfill.

Another significant deficiency with the US EPA contractors' assessment of the ability of minimum Subtitle D landfills with a single composite liner to collect all leachate generated within the landfill for hundreds to 1,000 or more years is that there is no assured funding available for operation of the leachate collection system for 970 of the 1,000 years. Further, there is no assurance that there will be funds available to properly analyze and manage the leachate that is collected for the 970 years after the current minimum 30-year postclosure funding terminates. While Subtitles D (MSW) and C (hazardous waste) provide that the Regional Administrator may extend the postclosure care period, the likelihood of that being effective for public and, especially, private landfills is small. Private landfill companies are building up massive liability associated with the development of Subtitle D landfills, and will not likely be in business 50 or so years from now when there is need to establish funding for the postclosure care period during which the US EPA contractors claim that the liners will be effective in collecting leachate. These same postclosure funding issues apply to landfill gas collection system maintenance, treatment, etc. Even public agencies will have difficulty gaining support for spending funds on a publicly owned landfill that was closed 30 years previously, which, with high-quality construction, has caused no problems. This is yet another reason why the minimum Subtitle D landfilling approach is flawed.

Lee (2003b) has provided a discussion of the importance of solid waste management regulatory agencies' requiring that landfill owners, whether public or private, prepare for the inevitable failure of the landfill containment system and provide funding to address this failure. An elementary examination of these issues leads to the conclusion that the 30-year postclosure assured funding period mandated in RCRA was a significant error on the part of the US Congress, which is recognized not only in the technical community, but also by various groups or individuals who have reviewed this issue. For example, the GAO (1990), in the Executive Summary of its report "Funding of Postclosure Liabilities Remains Uncertain," under a section labeled "Funding Mechanisms Questionable," concluded that,

"Owners/operators are liable for any postclosure costs that may occur. However, few funding assurances exist for postclosure liabilities. EPA only requires funding assurances for maintenance and monitoring costs for 30 years after closure and corrective action costs once a problem is identified. No financial assurances exist for potential but unknown corrective actions, off-site damages, or other liabilities that may occur after the established postclosure period."

Further, the US EPA Inspector General (US EPA, 2001) in a report, "RCRA Financial Assurance for Closure and Post-Closure," developed similar conclusions:

"There is insufficient assurance that funds will be available in all cases to cover the full period of landfill post-closure monitoring and maintenance. Regulations require postclosure activities and financial assurance for 30 years after landfill closure, and a state agency may require additional years of care if needed. We were told by several state officials that many landfills may need more than 30 years of post-closure care."

However, most of the state agencies in our sample had not developed a policy and process to determine whether post-closure care should be extended beyond 30 years, and there is no EPA guidance on determining the appropriate length of post-closure care. Some facilities have submitted cost estimates that were too low, and state officials have expressed concerns that the cost estimates are difficult to review.”

As discussed by Lee (2003b), the deficiencies in the 30-year postclosure care funding approach are well understood, but for political reasons, the US EPA has been unwilling to address this issue. Since it appears that the US EPA will not revise the national regulations on this issue (30 years of minimal postclosure care funding), state regulatory agencies will need to adopt an *ad infinitum* assured funding approach in order to protect the state’s groundwater resources and the health and welfare of those who live or work near a landfill.

Hazardous versus Nonhazardous Waste Classification

One of the most significant deficiencies in the US EPA RCRA program is the approach that was used to classify waste as hazardous versus nonhazardous. The typical approach that is used by regulatory agencies and landfill proponents is to say that no hazardous wastes are being added to a Subtitle D landfill. However, that is said based on the fact that an arbitrary and often not protective approach is used to define “hazardous” waste. An understanding of the basis of this classification shows that the US EPA’s approach allows substantial amounts of hazardous chemicals to be added to so-called “nonhazardous” waste (Subtitle D) landfills. Further, the US EPA’s classification system provides for no recognition of so-called “nonhazardous” waste containing constituents which are highly detrimental to the use of the groundwaters that are polluted by leachate from such wastes, rendering the waters unusable for domestic and many other purposes. As discussed by Jones-Lee and Lee (1993), the presence of municipal solid waste and other waste leachate with no “hazardous” chemicals above the US EPA criteria used to make the distinction between hazardous and nonhazardous can cause the water supply well to have to be abandoned because of the aesthetic problems of taste and odor, color, iron, manganese, hydrogen sulfide, corrosion, scaling, etc.

The most significant problem with the US EPA’s classification of hazardous versus nonhazardous waste is the use of the leaching test – originally, EP-tox test, and now the toxicity characteristic leaching procedure (TCLP). The test is patterned after dredged sediment elutriation. While the dredged sediment elutriation conditions make sense for dredged sediment open-water disposal, similar conditions have no validity for the leaching of constituents in a solid waste landfill. The liquid-to-solid ratios used, redox conditions, pH and exposure surface area of the solid particles are all highly arbitrary. The EP-tox test, now TCLP, is a political test designed to limit the size of the hazardous waste stream that must be managed as hazardous waste. The tests have little or nothing to do with properly evaluating chemicals that could affect groundwater quality.

The interpretation of what constitutes excessive leaching in the EP-tox test and TCLP is another example of an arbitrary approach on the part of the US EPA in defining hazardous waste. The allowed attenuation factor (5-to-1 dilution is assumed) will, for some hydrogeological groundwater systems, be overprotective, and for others, underprotective. Yet the characteristics

of the hydrogeology of the site are not taken into account in interpreting the results of the test to determine whether a waste can be placed in a nonhazardous waste landfill.

Widespread Nature of Hazardous Chemicals in the Environment

There are a variety of hazardous chemicals that have been in the environment for considerable periods of time but have only recently been discovered as widespread contaminants. An example of inadequate definition of constituents of concern occurs with perchlorate. Perchlorate is an inorganic chemical that moves rapidly through groundwater systems. Perchlorate has been a contaminant of groundwaters associated with rocket fuels. For years the US EPA and state regulatory agencies did not examine groundwaters for perchlorate because it was not on the Priority Pollutant list. However, it is known to be hazardous to public health. There are situations, such as associated with Aerojet Inc. near Sacramento, California, where the company polluted groundwaters by chlorinated solvents and perchlorate. The regulatory agencies, in their limited scope of defining constituents of concern, allowed Aerojet to pump the chlorinated-solvent-polluted water from the aquifer, airstrip it, and then inject it back into the aquifer. This approach allowed widespread contamination of groundwaters and the loss of a number of municipal water supply wells because of perchlorate pollution of the groundwaters.

Perchlorate is being found as a pollutant in surface and groundwaters in areas not associated with rocket fuel use. Silva (2003) of the Santa Clara Valley Water District in the southern San Francisco Bay region of California, has discussed the potential for highway safety flares to be a significant source of perchlorate (ClO_4^-) contamination to water, even when the flares are 100-percent burned. According to Silva,

“A single unburned 20-minute flare can potentially contaminate up to 2.2 acre-feet [726,000 gallons] of drinking water to just above the California Department of Health Services’ current Action Level of 4 $\mu\text{g}/\text{L}$ [for perchlorate].”

It should be noted that California’s Office of Environmental Health Hazard Assessment (DHS, 2003) is conducting an evaluation of the hazards of perchlorate in drinking water. The 4 $\mu\text{g}/\text{L}$ current action level is based on the detection limit. It is possible that the OEHHA evaluation will result in a decrease in the action level for perchlorate in drinking water.

Silva (2003) points out that, *“More than 40 metric tons of flares were used/burned in 2002 alone in Santa Clara County.”* Silva also indicates that fully burned flares can leach up to almost 2,000 μg of perchlorate per flare. Perchlorate from highway flares could readily be a contaminant in soils and existing landfills. Without monitoring for perchlorate, it is not possible to know if this is a problem. Perchlorate is just one of the 85,000 or so chemicals that are in use today that could cause public health and environmental impacts associated with landfills.

Another widespread “new” pollutant was discussed by Hooper (2003) of the Hazardous Materials Laboratory, Department of Toxic Substances Control, California EPA. In his abstract, he states,

“Over the past 25 years, tens of thousands of new chemicals (7 chemicals per day) are introduced into commerce after evaluation by USEPA. Few (100-200) of the 85,000

chemicals presently in commerce are regulated. We have reasons to believe that a much larger number than 200 adversely affect human health and the environment.”

As an example of unidentified hazardous chemicals in the environment, Hooper discussed finding PBDE (polybrominated diphenyl ether) in human breast milk. Archived human breast milk shows that this is a problem that has been occurring for over 20 years. According to McDonald (2003) of California Environmental Protection Agency, Office of Environmental Health Hazard Assessment,

“Approximately 75 million pounds of PBDEs are used each year in the U.S. as flame retardant additives for plastics in computers, televisions, appliances, building materials and vehicle parts; and foams for furniture. PBDEs migrate out of these products and into the environment, where they bioaccumulate. PBDEs are now ubiquitous in the environment and have been measured in indoor and outdoor air, house dust, food, streams and lakes, terrestrial and aquatic biota, and human tissues. Concentrations of PBDE measured in fish, marine mammals and people from the San Francisco Bay region are among the highest in the world, and these levels appear to be increasing with each passing year.”

PBDEs are similar to PCBs and are considered carcinogens. Some of the PBDEs are being banned in the US and in other countries.

It not be assumed that if a groundwater that has been polluted by MSW leachate that has been found to meet drinking water standards (MCLs) is safe to drink since it could readily contain hazardous chemicals that are not known or regulated under current regulatory requirements.

Addressing Situations where the Regulatory Agencies Permit the Development of a Landfill that will not be Protective of Groundwater Quality for as Long as the Wastes are a Threat

It is the authors' experience that, even though the issue of the inability of a “dry tomb” landfill to provide reliable groundwater quality protection for as long as the wastes in the landfill will be a threat are well understood, there is little likelihood that many regulatory agencies will require that landfills will be protective throughout this period. It is suggested that the approach to take under these conditions is to consider that the groundwaters that could be polluted by the landfill are part of the landfill – i.e., an attenuation zone is, *de facto*, allowed. The key issue, then, is to site landfills so that the polluted groundwaters that occur do not surface at springs or into existing surface waterbodies. Further, and most importantly, no water supply production wells should be allowed to be developed within the zone of attenuation, forever.

It is suggested that this zone of attenuation should extend – for homogeneous, fairly well-defined aquifer systems – for at least two, and preferably three miles down groundwater gradient from the landfill. If the situation should develop where new, large production wells are constructed at some time in the future which could influence the groundwater gradient associated with the landfill, then there will be need to extend the area of potential impact of polluted groundwaters to consider the production well influence. If the groundwater hydrology within

several miles of the landfill is not well defined, because of fractured rock, cavernous limestone, sandy lenses, etc., then the distance of the attenuation zone should be extended to five miles or so from the area where wastes are deposited. Since the zone of attenuation is, *de facto*, part of the landfill, the landfill owner should be required to compensate those whose lands lie within the overlying attenuation zone, because of the loss of the ability to use the groundwaters at any time in the future, for domestic and other purposes.

If this approach cannot be achieved, then it is recommended that those concerned about groundwater quality protection and the health, welfare and interests of those potentially impacted by the landfill require that the landfill owner commit to funding in perpetuity a third-party comprehensive groundwater monitoring program of all production wells within the potential sphere of influence of the landfill. This monitoring program should be conducted by an independent third party, to insure, as much as possible, that reliable results are produced, and are not biased by the landfill owner/operator or regulatory agencies.

The monitoring program should be specifically designed to detect incipient changes in groundwater quality characteristics, considering the variability of the groundwater characteristics in the zone of potential influence and the characteristics of the aquifer. It should not be a program that is designed to detect when the concentration of a pollutant exceeds a drinking water MCL. It should also be understood that the monitoring parameters may be just an indicator of potential problems from unmonitored parameters – i.e., constituents of the 85,000 or so chemicals in use every day that are not monitored today in a groundwater pollution monitoring program.

Evidence for Subtitle D Landfill Liner Failure

Supporters of minimum Subtitle D landfill containment systems, including US EPA representatives, claim that minimum Subtitle D landfill liner systems must be working, since there is no recorded evidence that a single composite liner system has failed. This statement is more of the unreliable information (propaganda) that some within the US EPA and state regulatory agencies, as well as minimum Subtitle D landfill proponents, are providing the public who are not knowledgeable in these issues. Someone who is knowledgeable knows that, unless there is extremely sloppy construction which leads to groundwater pollution under the landfill in the short period of time since Subtitle D landfills have been required to be developed (about 10 years) and, by a stroke of luck, a groundwater monitoring well happened to be in the path of the leachate plume that was created by the landfill liner failure, it would not be expected that groundwater pollution from Subtitle D landfills would yet be evident.

If the landfill is operated in accordance with design and regulatory requirements, it should take at least 25 years for the leachate to penetrate through the two feet of clay that is part of a composite liner. The rate of penetration through the clay at 10^{-7} cm/sec, with one foot of head, is about an inch a year. Therefore, unless the clay layer develops desiccation cracks (which are possible), which match to points of deterioration/failure in the HDPE liner, the pollution of groundwaters underlying a single composite lined landfill should not yet be occurring. Further, even with sloppy construction and failure of the clay liner to perform as designed, the likelihood of the groundwater monitoring system, with monitoring wells spaced hundreds of feet apart, to detect the failure, is remote.

It has been found that in some double composite lined landfills with a leak detection system between the two composite liners, the upper composite liner has failed within a few years after construction. This has been found because leachate has been detected in the leak detection layer between the two composite liners. It is important to note that it is possible, through high-quality construction and liner inspection, and careful placement of the waste, to achieve a single composite liner that will be protective of the underlying groundwaters for a period of time – possibly several decades. There is no question about the fact, however, that at some time in the future the single composite liner system will fail, and groundwater pollution will occur by constituents which are hazardous/deleterious to the use of the groundwaters for domestic purposes – i.e., will cause the well to have to be abandoned because of landfill leachate pollution of the groundwater.

Therefore, the failure to see evidence of liner system failure in minimum Subtitle D single composite lined landfills at this time is no basis to conclude that there will not be groundwater pollution by these landfills at some time in the future while the wastes in the landfill are still a threat.

Landfill Siting Issues

The US EPA, as part of the development of Subtitle D landfill regulations, failed to address one of the most important issues that should be addressed in developing a minimum Subtitle D landfill – namely, the siting of the landfill at geologically suitable sites for a landfill of this type. While the Agency does require that minimum Subtitle D landfills not be sited too close to airports, where there could be major bird problems for aircraft, or too near an earthquake fault or within a flood plain, the Agency did not address the issue of siting minimum Subtitle D landfills where the underlying geological strata do not provide natural protection of the groundwaters from pollution by landfill leachate when the landfill liner systems eventually fail. In accordance with current regulations, minimum Subtitle D landfills can be sited over highly important aquifers that serve as a domestic water supply source for an area. They can also be sited in fractured rock and cavernous limestone areas, where it is impossible, through the use of vertical monitoring wells, to reliably monitor the pollution of groundwaters by landfill leachate.

The Agency, in developing Subtitle D landfill regulations, also failed to address one of the most important reasons why landfills lead to a justified NIMBY. US EPA Subtitle D regulations allow the deposition of wastes very near the landfill property owner's property line. Under these conditions, the landfill gases, blowing paper, birds, rodents, vermin, etc., associated with the landfill can readily gain access to adjacent properties, and thereby be adverse to the interests of the owners/users of those properties. It is well established that landfill gas can readily travel a mile or more from a landfill, and thereby be adverse to the adjacent property owners' use of their properties. It is recommended that at least a mile, and preferably two miles, of landfill-owned buffer lands exist between the area where wastes are deposited and adjacent property owners' property lines. This buffer land is used to dissipate the releases from the landfill on the landfill owner's property. Such an approach will eliminate or greatly minimize the trespass of waste-derived materials from the landfill onto adjacent properties.

Hazards of Living/Working near Landfills

Frequently there are questions about the potential hazards of using a closed landfill as a playfield for children, constructing a school or playground adjacent to a closed (inactive) landfill, or purchasing residential property near an active and/or closed landfill. The public is justifiably concerned about the hazards of living next to, constructing a school next to, or constructing a playfield on a former landfill. Landfills, even those that contain so-called “nonhazardous” wastes, contain a variety of hazardous chemicals that, if not properly managed, can pollute groundwaters, soil and the atmosphere and therefore be a threat to those using properties near the landfill.

An issue of concern is whether those who live near landfills show evidence of adverse health effects. It is known from a number of studies conducted by the Centers for Disease Control (Anderson, pers. comm., 1999) that some populations living near landfills have shown a greater incidence of some diseases. Elliott, *et al.* (2001) have reported that children of people living near landfills in England tend to have a higher rate of birth defects than the general population. A review of the various studies that have been conducted, however, reveals that the epidemiological approach for discerning health effects associated with populations living near landfills is not sufficiently sensitive to reliably determine whether releases from the landfill are at least in part responsible for the health effects. A complicating factor is that those living near landfills frequently are economically disadvantaged and of a different ethnic mix than the general population. Further, data that have been developed on this issue have often been devoted to former (closed) landfill situations, where there is far greater limiting of landfill emissions than will occur, at least initially, with today’s Subtitle C and D landfills.

It should not be assumed that a former landfill – or for that matter, a currently active landfill – is not a significant threat to public health and the environment. It has been the authors’ recommendation that at least one mile of buffer land, owned by the landfill owner, should exist between a landfill and adjacent properties. This one mile distance should be adequate in most situations to dissipate releases from the landfill to either groundwater or the atmosphere, although there are situations where groundwaters more than a mile from the landfill have been polluted by landfill wastes.

Recommended Approach. The recommended approach for utilizing landfill covers and areas adjacent to landfills for situations where children can be exposed to waste-derived constituents should involve a detailed, third-party, independent review of the magnitude of the releases that are occurring from the landfill to the atmosphere, to surface water runoff and to groundwater. This should require at least a one-year detailed monitoring effort that is conducted from the perspective of trying to find problems. This perspective is important since, in many cases, studies sponsored by landfill owners, as well as the studies conducted by consultants who typically work for potential site developers, are biased toward not finding problems – i.e., doing the minimum necessary to get by current regulatory agency requirements.

There is need for the site investigations to be conducted by a third-party managed team, where the management team has a proper balance of individuals who are knowledgeable and interested in full protection of public health and the environment. This does not mean that the team should be dominated by what are sometimes called “environmental activists.” Some

individuals who operate in this arena tend to distort the technical information available, and thereby have limited credibility in striking a proper balance.

Professional Ethics Issues

It is appropriate to inquire why there is not greater discussion of the significantly flawed approach of Subtitle D landfilling. It is the authors' experience that these issues are well-understood by many of those in regulatory agencies and in the landfill consulting community; however, as discussed by Lee and Jones-Lee (1995b), there is a significant professional ethics issue associated with the permitting of landfills, where those who develop landfills for public and private agencies do not discuss these problems, since it would mean that their firm would not gain further work from landfill developers.

Landfill permitting in the US is conducted in an adversarial arena, where landfill applicants and their consultants only discuss the positive aspects of a proposed landfill, and do not discuss the problems associated with the landfill. This provides regulatory agencies responsible for permitting landfills with an unreliable information base upon which to make decisions on the permitting of a landfill. Lee and Jones-Lee (1995b) recommend that the current adversarial landfill permitting approach be replaced by a publicly conducted interactive peer review process, where both the positive and negative aspects of a proposed landfill can be discussed. Adoption of this approach would greatly improve the reliability of the information provided to regulatory agencies as part of permitting of landfills.

Improving Landfilling

There are a number of approaches that members of the public potentially impacted by a landfill can work toward achieving, which will improve the ability of landfills to provide containment of the wastes for as long as the wastes in the landfill will be a threat. These are briefly summarized below.

Siting. The landfill should be sited so that it provides, to the maximum extent possible, natural protection of groundwaters when the liner system fails. Siting landfills above geological strata that do not have readily monitorable flow paths for leachate-polluted groundwaters should be avoided. Of particular concern are fractured rock and cavernous limestone areas, as well as areas with sandy lenses.

Design. The landfill should be a double composite lined landfill, with a leak detection system between the two liners.

Closure. A leak detectable cover should be installed on the landfill which will indicate when the low-permeability layer of the landfill cover fails to prevent moisture from entering the landfill.

Monitoring. The primary monitoring of liner leakage should be based on the double composite liner, where the lower composite liner is the leak detection system for the upper composite liner. If vertical monitoring wells are used, then the spacing between the vertical monitoring wells at the point of compliance should be such that a leak in the HDPE liner caused by a 2-ft-wide rip, tear or point of deterioration at any location in the landfill would be detected based on the plume that is generated at the point of compliance with a 95 percent reliability.

Landfill Gas Collection. For those landfills that contain wastes that can produce landfill gas, a landfill gas collection system should be designed, installed and maintained for as long as the wastes in the landfill have the potential to generate landfill gas. The landfill gas collection system should be designed to have at least a 95 percent probability of collecting all landfill gas generated at the landfill.

Maintenance. The maintenance of the landfill cover, monitoring system, gas collection system, etc., should be conducted for as long as the wastes in the landfill will be a threat, with a high degree of certainty of detecting landfill containment system and monitoring system failure.

Funding. The funding for closure, postclosure monitoring, maintenance and groundwater remediation should be established at the time the landfill is established, in a dedicated trust fund of sufficient magnitude to address plausible worst-case scenario failures for as long as the wastes in the landfill will be a threat. Unless appropriately demonstrated otherwise, it should be assumed that the period of time for which postclosure care funding will be needed will be infinite.

Adoption of these approaches (or as many of them as possible) will significantly improve the ability of landfills to protect groundwater quality, public health and the environment for as long as the wastes in the landfill will be a threat.

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