Expected Performance of the Pottstown Landfill Containment and Monitoring Systems

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Summary of Pottstown Landfill Closure/Post Closure Issues

Landfill Liner Integrity Issues
There is a finite period of time during which the plastic sheeting upper composite liner and lower plastic sheeting secondary liner used in the Pottstown Landfill can be expected to function as designed to collect leachate and thereby prevent it from polluting groundwater. In time, the upper composite liner will fail; if the lower plastic sheeting secondary liner is still functioning without significant holes and areas of deterioration, it can indicate when the upper primary liner has failed. If the leachate that is collected in the leak detection zone is detected and action is taken to prevent water from entering the landfill through the cover, forever, the further groundwater pollution by the Pottstown Landfill can be prevented. However, if the plastic sheeting liner of the leak detection zone has significantly deteriorated, the leachate that has passed through the upper composite liner will pass through the leak detection zone into the underlying fractured rock aquifer system under the landfill and additional groundwater pollution by the Pottstown Landfill will occur.

Long Term Functioning of the Leachate Collection and Removal System
The leachate collection system that has been installed at the post-1991 sections of the Pottstown Landfill can be effective in collecting leachate generated in the landfill. However, over time the leachate collection and removal system at this landfill will fail to function as designed due to deterioration of the plastic sheeting layer in the upper (primary) composite liner. Leachate will pass through holes in the plastic sheeting and then penetrate through the underlying clay layer in the composite liner. It is not possible to repair the landfill liner system and the associated leachate collection and removal system as a result of the fact that they are buried under the wastes. If failure of the leachate collection and removal system is properly monitored/detected, action can be taken to repair the areas of the landfill cover that are allowing moisture to pass through the cover to generate leachate.

Expected Performance of the Landfill Cover
A properly constructed and maintained landfill cover that includes a plastic sheeting layer can be effective in preventing moisture from entering the landfill and therefore keep the wastes dry. When dry the wastes do not generate leachate or landfill gas. In a dry tomb type landfill, drying out of the wastes leads to a dormant period with respect to landfill

gas and leachate generation. However, the integrity of the low permeability layer of the cover is subject to many stresses; eventually it deteriorates and allows moisture to enter the wastes which allows the renewed generation of leachate and landfill gas. This can happen a short time after landfill closure, or be postponed for many decades after landfill closure. A reliable landfill closure plan for the Pottstown Landfill must include monitoring of leachate and landfill gas generation as long as the wastes in the landfill have the potential to generate leachate and gas when moisture is introduced into the wastes. Also, the landfill cover must be routinely inspected for areas of stressed vegetation that is indicative of landfill gas migration through the cover. Renewed landfill gas and/or leachate generation after a dormant period with little or no leachate generation is an indication that moisture has been entering the landfill. Under those conditions, the landfill owner must be required to locate the area of the cover that is no longer preventing moisture from entering the landfill and repair the low permeability layer of the cover. This process will have to be repeated as needed for as long as the wastes in the landfill are a threat.

Reliability of Groundwater Monitoring

The geology/hydrogeology of the area under and near the Pottstown Landfill is extremely complex. Because of the fractured rock aquifer system underlying the landfill, it is very difficult, if not impossible, to use vertical monitoring wells around the perimeter of the landfill to reliably monitor initial failure of the upper composite liner and leak detection zone. As discussed above, it is not possible to rely on the leak detection zones to reliably monitor upper liner failure for as long as the wastes in the landfill will be a threat. There is need for Waste Management to conduct a quantitative assessment of the number and locations of groundwater monitoring wells that would be needed to reliably detect leachate-polluted groundwater when it first reaches the point of compliance for groundwater monitoring.

Landfill Gas Emissions

Landfill gas emissions from the Pottstown Landfill are a significant threat to cause explosions and to be a health threat to those in the sphere of influence of the landfill. This landfill has already had severe offsite landfill derived and associated odors. There have also been uncontrolled releases of landfill gas below the soil surface onto adjacent properties. As part of developing the final Pottstown Landfill closure plan, there will be need to gain better control of landfill gas generation through controlling the moisture that enters the landfill through the cover, and the offsite migration of landfill gas.

Landfill Post Closure Funding Issues

There are several important Pottstown Landfill closure issues that the Committee needs to address with DEP regarding long term funding of the postclosure care. These include,

- DEP should clarify its current approach of requiring that Waste Management provide assured funding for only 30 years after closure.
- DEP needs to clarify how it will better ensure that funds will be available from Waste Management to perform postclosure monitoring and maintenance (including replacement of landfill cover) and for groundwater pollution remediation for as long as the wastes in the landfill will be a threat.

- What are the conditions under which DEP might grant Waste Management a Certificate of Closure and thereby relieved it of further postclosure care?
- Should a Certificate of Closure be issued to Waste Management while the wastes in the Pottstown Landfill are still a threat to generate landfill gas and/or leachate upon contact with water, how will DEP detect landfill liner failure and leak-detection-zone failure after that point?
- How will the needed postclosure care be funded and implemented if/when Waste Management is no longer able to provide the needed funding?

Bioreactor Landfill Operation

The conversion of the Pottstown Landfill to a bioreactor landfill could potentially reduce the magnitude of the long term threat of releases from the Landfill. It is unclear whether DEP will allow an MSW landfill such as the Pottstown Landfill to be converted from a dry tomb type landfill to a bioreactor landfill. It may take a change in DEP regulations to permit this change in mode of operation for the Pottstown Landfill. This issue needs further review as a means to better manage a large part of the landfill gas and leachate that can be potentially generated in the Pottstown Landfill.

Additional information on each of these and other issues are discussed in this report.

Location of the Pottstown Landfill and Its Setting

Figures 1 and 2 present maps showing the location of the Pottstown Landfill and the area near the landfill. As shown, this landfill is situated in an urban setting with limited buffer lands between the landfill and residential properties. The limited buffer land between waste deposition and adjacent properties has led to significant offsite landfill odors and other impacts that have been adverse to residents of the area.

According to NUS (1991) the landfill property is approximately 440 acres in area; 178 acres had been permitted for landfill use as of late 1990. The subject area of concern consists of the approximately 80-acre "old landfill" (pre-Waste Management) and an adjacent 3-acre leachate-collection impoundment; both are located in the southwestern portion of the site along Sell Road. Office and maintenance buildings are located off Sell Road in the southwestern corner of the site. The landfill is surrounded by a chain-link fence.

The site is adjacent to a perennial stream known locally as Goose Run (unnamed on the topographic map), which flows from north to south along the western border of the site and into Manatawny Creek 0.3 stream mile downstream of the site. Manatawny Creek flows into the Schuylkill River 2.5 stream miles downstream of the site. This stream system provides a possible migration pathway for surface water contamination downstream of the landfill area.

The Pottstown Landfill has been constructed in several phases. Each phase has had its own landfill liner and cover. Figure 3 presents a map of the landfill, as developed by NUS in 1991. The area has been operated as a solid waste landfill since 1932, when the Rinehart Dump began operations on the original 10-acre parcel; at that time, the parcel was part of a farm owned by the Rinehart family. In 1972, SCA Services of Pennsylvania, Inc. purchased the Pottstown Landfill from the Rinehart family and obtained a state of Pennsylvania permit that included the use of an asphalt and clay liner. Waste Management purchased the Pottstown Landfill from SCA Services in 1984. Waste Management covered over the "old landfill" and continued landfilling in a "double liner system" consisting of a compacted soil base for the bottom liner. The new facility included newly upgraded leachate- and runoff-control systems and a gas-recovery system which has been operational since 1989. According to NUS (1991), in all, a 40-acre portion of the "old landfill" was unlined and a 15-acre portion was lined with sprayed-on asphalt. It is not known whether the remainder was lined; it may have been lined with "elastomeric" material.

The leachate-collection impoundment was constructed at an unknown time before 1977 and is believed to have been decommissioned in 1980; by 1985, the area had been relined. While the impoundment was in existence, leachate was pumped out into trucks and taken to the Pottstown sewage treatment plant. Before Waste Management constructed the leachate pretreatment plant in 1988, and after the decommissioning of the leachate-collection impoundment, leachate was piped directly into the Pottstown sewerage system. Wastes known or suspected to have been landfilled at the site include municipal solid wastes, wastewater treatment sludges, industrial sludges (including some containing arsenic, chromium, chlorinated pesticides, aromatic hydrocarbons, and other hazardous constituents), pharmaceutical manufacturing wastes, paint wastes, ammunition wastes, incinerator ash, and asbestos. (NUS 1991)

Figure 1

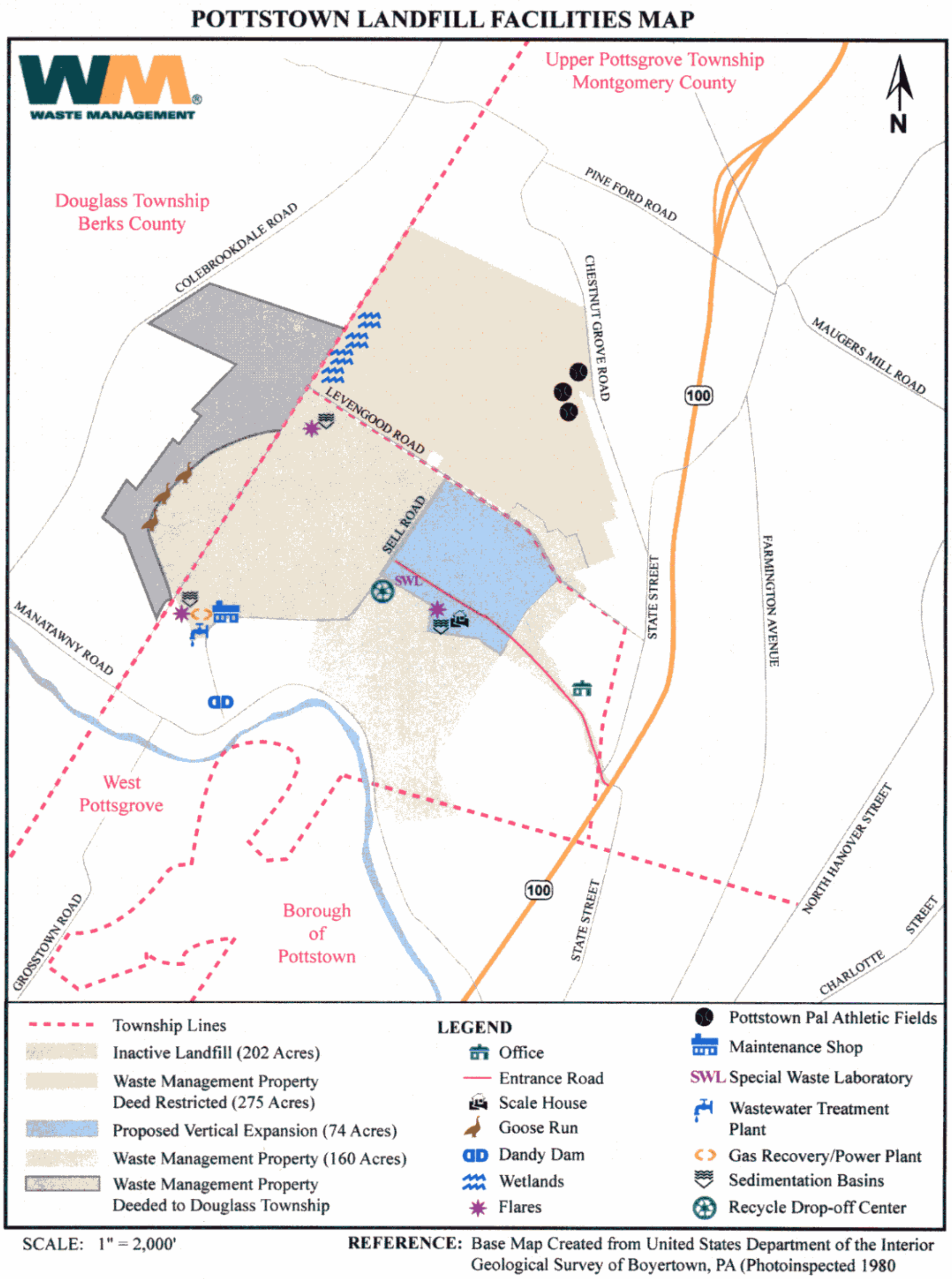
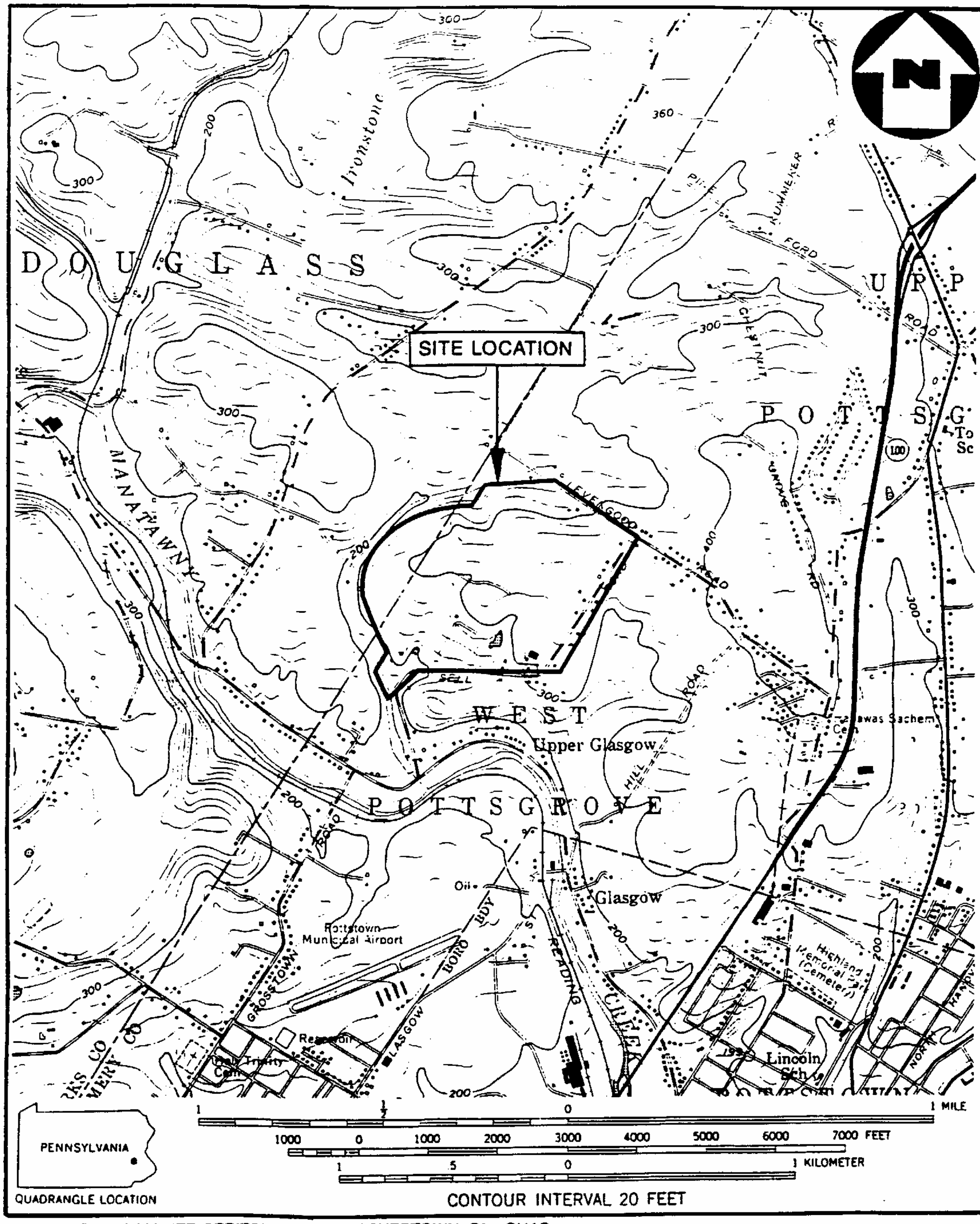


Figure 2



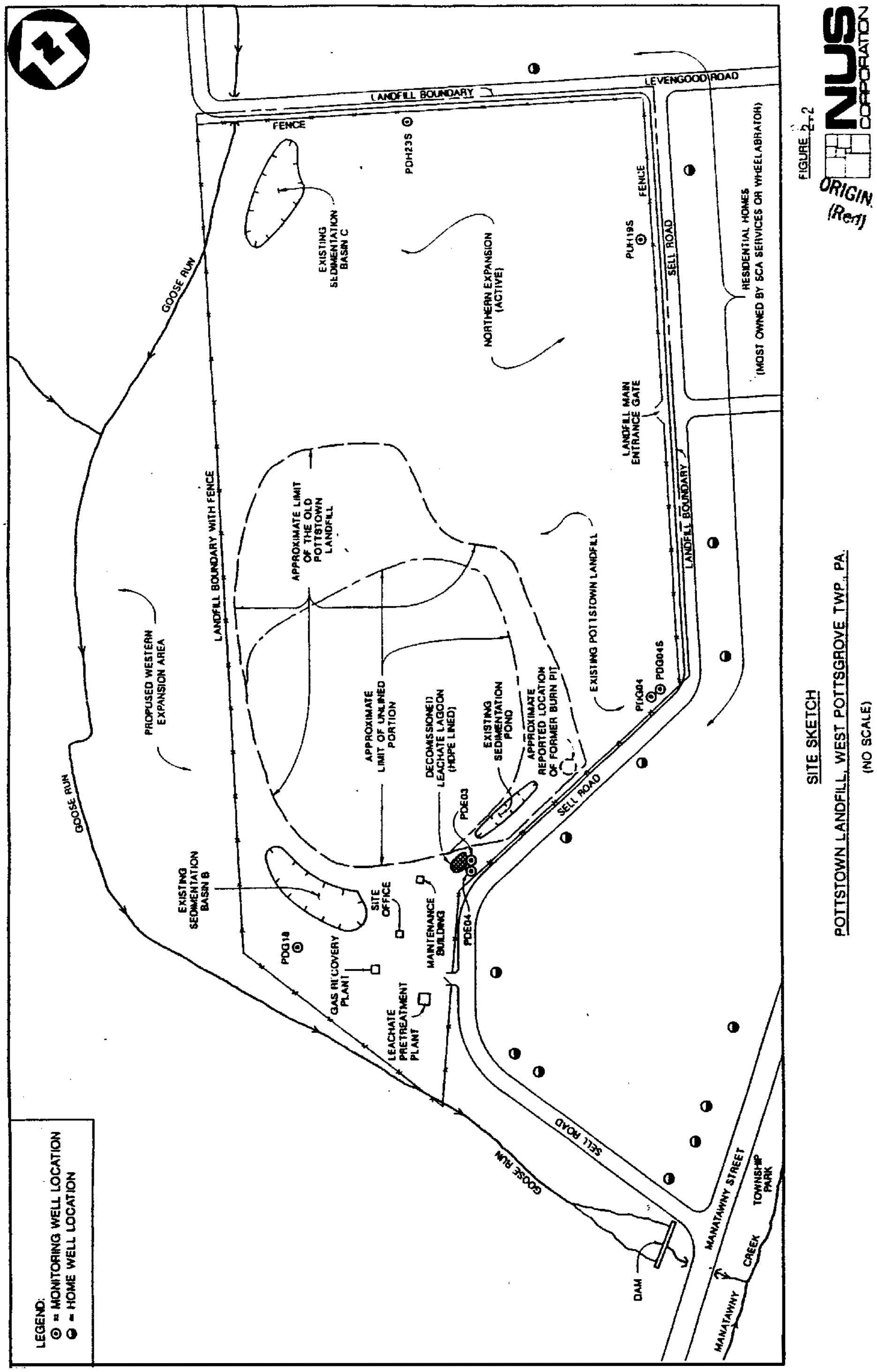
SOURCE: (7.5 MINUTE SERIES) U.S.G.S. BOYERTOWN, PA., QUAD.

SITE LOCATION MAP
POTTSTOWN LANDFILL, WEST POTTSGROVE TWP., PA.
SCALE 1: 24000

FIGURE 2.1

NUS CORPORATION

Figure 3


LEGEND:
⊙ = MONITORING WELL LOCATION
● = HOME WELL LOCATION
LANDFILL BOUNDARY
LEVENGOOD ROAD
FENCE
PDH23S
EXISTING SEDIMENTATION BASIN C
NORTHERN EXPANSION (ACTIVE)
PUH19S
SELL ROAD
RESIDENTIAL HOMES (MOST OWNED BY SCA SERVICES OR WHEELABRATOR)
GOOSE RUN
LANDFILL MAIN ENTRANCE GATE
LANDFILL BOUNDARY WITH FENCE
APPROXIMATE LIMIT OF THE OLD POTTSTOWN LANDFILL
EXISTING POTTSTOWN LANDFILL
PROPOSED WESTERN EXPANSION AREA
APPROXIMATE LIMIT OF UNLINED PORTION
DECOMMISSIONED LEACHATE LAGOON (HDPE LINED)
EXISTING SEDIMENTATION POND
APPROXIMATE REPORTED LOCATION OF FORMER BURN PIT
PUG04
PDG04S
PDE03
EXISTING SEDIMENTATION BASIN B
SITE OFFICE
MAINTENANCE BUILDING
PDE04
PDG18
GAS RECOVERY PLANT
LEACHATE PRETREATMENT PLANT
DAM
MANATAWNY STREET
MANATAWNY CREEK
TOWNSHIP PARK
SITE SKETCH
POTTSTOWN LANDFILL, WEST POTTSGROVE TWP., PA.
(NO SCALE)
FIGURE 2-2
NUS CORPORATION

How Long Will the Wastes in the Pottstown Landfill Be a Threat

Lee and Jones-Lee (2004a, 2005) recently reviewed the factors that control how long municipal solid wastes (MSW) in classical sanitary landfills and in "dry tomb" type landfills will be a threat. As they discussed, classical sanitary landfills, where there is no attempt to prevent moisture from entering the wastes, have been found to generate leachate for thousands of years. In their book, Groundwater, Freeze and Cherry (1979) of the University of British Columbia and the University of Waterloo, Ontario, Canada, discussed the finding that landfills developed in the Roman Empire about 2,000 years ago are still producing leachate. Belevi and Baccini (1989), two Swiss scientists who have examined the expected contaminating lifespan of Swiss MSW landfills, have estimated that waste in Swiss landfills will leach lead in concentrations above drinking water standards for over 2,000 years.

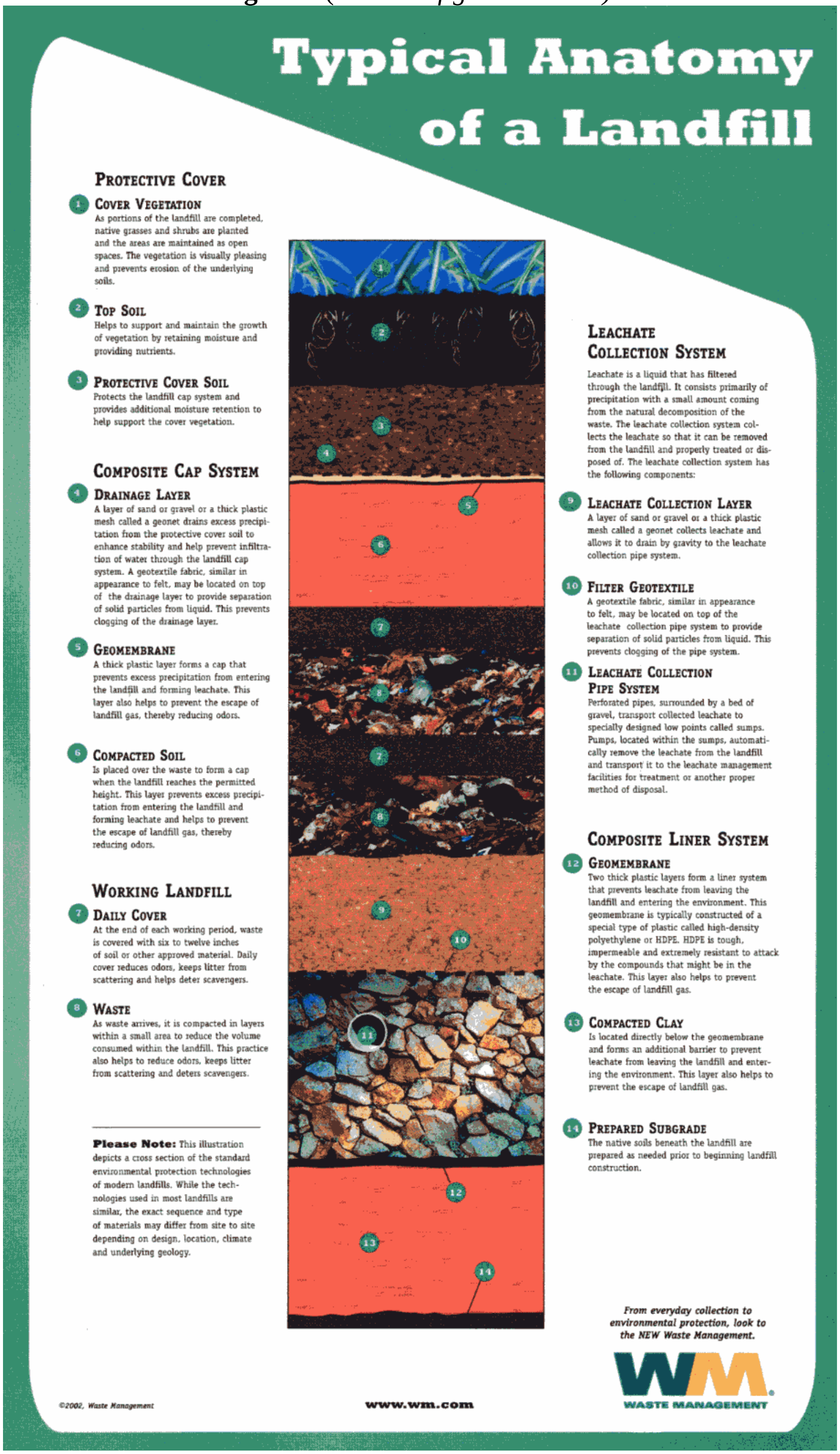
A key difference between those situations and the Pottstown Landfill is that the latter is a "dry tomb" type landfill in which an attempt is made to isolate the wastes from moisture, which delays and prolongs the fermentation and leaching of the wastes. The wastes in the Pottstown Landfill will therefore be a threat to groundwater resources for long periods of time, effectively forever. These issues are discussed further in the papers, "Landfilling of Solid & Hazardous Waste: Facing Long-Term Liability" (Lee and Jones-Lee, 1994), "Landfill Leachate Management," (Lee and Jones-Lee, 1996) and "Groundwater Pollution by Municipal Landfills: Leachate Composition, Detection and Water Quality Significance" (Jones-Lee and Lee, 1993).

Expected Performance of the Pottstown Landfill Containment and Monitoring Systems

As part of the October 20, 2004 tour of the Pottstown Landfill, Waste Management provided the Pottstown Landfill Closure Committee members with a briefing document containing an overview of the landfill characteristics (Waste Management, 2004). Included in that document was a figure (provided herein as Figure 4) that shows what it called the "Typical Anatomy of a Landfill." The briefing document also included statements pertaining to what Waste Management expected for the performance of the landfill containment and monitoring systems. A discussion of some of the claims made about the expected performance of landfill containment system components (liner, leachate collection and removal system, landfill gas collection and disposal system, landfill cover, and stormwater runoff control and treatment system) as well as the groundwater and landfill gas migration monitoring systems, in relation to what is known about the realistic expectations, are discussed below.

One of the postclosure issues of primary concern to the Pottstown Landfill Closure Committee is the potential for this landfill to generate leachate that is a threat to pollute groundwater and surface waters impairing the beneficial uses of these waters for as long as the wastes in this landfill will be a threat. Also of concern is the potential for landfill gas that is generated in the landfill to migrate offsite and be a threat to those near the landfill. Waste Management (2004) stated with regard to the protection that is provided by the Pottstown Landfill,

Figure 4 (*view this figure at 200%)*



“*Groundwater Monitoring Wells*

PA DEP requires only 1 upgradient and 3 downgradient monitoring wells.”

“Double-Lined Synthetic System

Protects Groundwater by forming impermeable layers and seals disposal cell to capture leachate for collection and treatment.”

“6” layer of Daily Cover soil or state-approved alternate

controls odors, birds, and animals”

“Final Cap System

controls odors

prevents stormwater infiltration”

These quoted statements leave the distinct impression that the Pottstown Landfill is benign and does not pose a threat to public health or the environment indefinitely. However, as discussed below, the reality is that the wastes in the Pottstown Landfill will be a threat to generate leachate and landfill gas for a very long period of time, effectively forever. Even if the landfill containment systems are installed and maintained flawlessly, landfill containment systems have a finite period of time during which they can be expected to function as intended. As long as the wastes are kept dry, leachate and gas generation is postponed; the capacity for releases for neither is eliminated. The actual expected performance of the Pottstown Landfill containment and monitoring systems can fall far short of the claims made by Waste Management, during the postclosure period. Further, there is only assured postclosure funding for 30 years after the landfill no longer accepts wastes. Therefore, there is the potential for significant environmental contamination to occur at sometime in the future. To provide the Committee with an understanding of a realistic expectation of the performance of the landfill containment systems and monitoring systems from the perspective of landfill gas migration and leachate pollution of groundwater, the following discussion is presented.

Figure 5 presents a detailed breakdown of the components of the Pottstown Landfill liner system that has been installed since Waste Management purchased the landfill. The compacted soil base of the Pottstown Landfill liner system is overlain by “non-woven geotextile” (see Figure 5) that separates the secondary plastic sheeting liner (secondary liner) from the soil base. One of the problems with the PA landfilling regulations is that it allows the incorporation of the geotextile between the secondary plastic sheeting liner and the compacted soil base. This arrangement destroys the composite liner characteristics of the secondary liner; in order to achieve the double composite liner level of protection the plastic sheeting layer must be in intimate contact with underlying compacted clay/soil liner. Daniel (1990) summarized the properties of composite liners verses double liners. He pointed out that a true composite liner – with the plastic sheeting liner in contact with the compacted soil/clay liner – limits the area of the compacted soil through which leachate that penetrates through holes in the plastic sheeting liner, can migrate. In the Pottstown Landfill, placement of geotextile between the plastic sheeting and the compacted soil layer allows leachate that penetrates through the holes, rips, tears and/or points of deterioration in the plastic sheeting liner, to pass into the geotextile space between the plastic sheeting and the compacted soil layer. It then spreads out over the compacted soil layer. This allows a larger area for leachate to pass through the

Figure 5


Liner System
CONSTRUCTION AND QUALITY CONTROL
Woven Geotextile is a woven fabric that allows liquid to pass through while keeping sediments out, similar to a strainer.
Coarse Gravel is used around the drainage pipes to enhance the free flow of liquids.
Collection Pipe is used to carry liquids to a central collection point.
Primary Liner is a 60 mil. high-density polyethylene selected for its chemical resistance and durability.
Secondary Liner is the same material as the primary liner; all liner seams are welded and then tested by an independent laboratory. This secondary liner further enhances the system's ability to protect the environment.
Non-Woven Geotextile acts as a cushion for the secondary liner as would carpet padding.
Fine Gravel is an 18-inch layer of natural round stone that protects the liner system and allows the free flow of liquids.
Non-Woven Geotextile acts as a cushion for the primary liner, as would carpet padding.
Bentonite Layer is a dry, man-made clay layer that responds to moisture by swelling and sealing. This material further enhances the primary liner's reliability.
Non-Woven Geotextile is a high-strength fabric used to separate the clay layer and the GEONET.
GEONET is a flow medium made of high-density polyethylene that allows liquids to flow and monitoring of the systems.
Compacted Soil is the material that makes up the foundation of the landfill. After careful site evaluation, all unsuitable materials are removed and replaced with a quality structural-grade material that is compacted in place. This minimizes potential settlement of the landfill.
From everyday collection to environmental protection, look to the NEW Waste Management.
WASTE MANAGEMENT
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compacted soil layer than would occur if the plastic sheeting and compacted soil were in intimate contact in a true composite liner design. The net effect of this problem is that the secondary liner can leak at a higher rate through holes that develop in the plastic sheeting secondary liner than would occur if a true composite liner design had been required in the secondary liner design.

The primary function of the secondary plastic sheeting liner is to serve as the base for a leak detection zone (whisper zone). In principal, any leakage of leachate that penetrates through the upper composite liner (primary plastic sheeting liner and bentonite layer in Figure 5) will proceed downward to the secondary plastic sheeting liner and then be transported down slope to a sump where the leachate can be pumped out. The presence of any leachate in the leak detection zone is a clear indication that the primary liner system has failed; then action must be taken to prevent further moisture from entering the landfill through the cover. If such action is not taken, the leachate in the leak detection zone will, in time, penetrate through the secondary liner and begin polluting the groundwater system underlying the landfill. This, in turn, will lead to offsite groundwater pollution if the monitoring wells fail to detect the leachate-polluted groundwater at the point of compliance for groundwater monitoring or if there a lack of action to stop leachate generation when leachate-polluted groundwater is detected at the point of compliance for groundwater monitoring.

While PA regulations allow the design of the leak detection zone with a plastic sheeting secondary liner separated from the compacted soil layer, such a design has important implications for the reliability of leak detection zone to transmit leachate on the plastic sheeting layer to a leak detection zone sump where it can be removed/monitored. The greater rates of leakage of the plastic sheeting layer in the PA DEP allowed secondary liner system design means that there is a greater potential for leachate that reaches the secondary plastic sheeting liner to pass through the liner and then escape from the landfill into the underlying groundwater system.

Another potential problem with the Pottstown Landfill leak detection zone is that a geonet used to allow the leachate that passes through the primary liner rather than a layer of porous sand that is used in some leak detection zones. Municipal solid waste leachates contain chemicals that tend to form precipitates that tend to plug leachate transmission layers. Also, biological growths can develop in the leachate transmission layer such as a geonet or sand layer. This plugging would tend to be more significant in thin leachate transmission layers such as geonets. The plugging of the geonet layer used in the leak detection zones in the liner system that is used in some sections of the Pottstown Landfill would tend to make the leak detection zone system less likely to indicate when the upper primary liner systems has failed.

The current understanding of HDPE plastic sheeting liners is that they deteriorate through free radical attack on the polyethylene polymer chains that make up the backbone of the plastic sheeting layer. Free radical attack is believed to be associated with hydroxyl radicals derived from oxygen. It is more likely that oxygen will be in contact with the secondary plastic sheeting layer than the primary plastic sheeting layer. To the extent that this occurs, this could lead to more rapid deterioration of the secondary plastic sheeting layer than the primary plastic sheeting layer. Therefore there is a greater probability that the leak detection system will fail to transmit leachate that passes through the upper composite liner, to the leak detection zone sump.

If a true double composite liner system were used as the base of the leak detection zone, the potential for oxygen-derived radicals to reach the secondary plastic sheeting layer would be reduced and the leak detection zone would work more in accord with its design function. The deficiencies in the leak detection zone design allowed in PA mean that there is a greater probability that the leak detection zones used in various sections of the Pottstown Landfill will not provide reliable information on when the primary liner systems has failed by allowing leachate to pass through it.

Overlying the geonet in the Pottstown Landfill leak detection zone is geotextile (see Figure 5) which is overlain by a bentonite layer. The bentonite layer is a thin layer of bentonite clay. It is allowed as the equivalent of two feet of compacted clay with a permeability of equal to or less than 1×10^{-7} cm/sec. While states allow the substitution of a very thin bentonite layer for two feet of compacted clay, as discussed by Lee and Jones-Lee (2005) there are several reasons that such a substitution may not, in the long term, provide the same degree of protection as a two-foot-thick clay layer. This issue is discussed further below.

The primary plastic sheeting liner (Figure 5) is of the conventional, minimum design allowed by US EPA Subtitle D for a high density polyethylene (HDPE) liner in municipal solid waste landfills. Lee and Jones-Lee (2005) reviewed the current information on the long term stability of such liners. The following section is derived from their review.

Expected Performance of Subtitle D Landfill Liner System. Lee and Jones-Lee (2005) have discussed the characteristics and expected performance of the typical Subtitle D landfill liner containment system and monitoring system. This is the liner system used as the upper (primary) liner at the Pottstown Landfill. As discussed, it is possible to construct a single composite landfill liner system that will not leak sufficient leachate at the time of construction at a rate to pollute large amounts of groundwaters. However, ultimately the plastic sheeting layer of such a landfill liner will deteriorate to the point at which it will be ineffective in collecting leachate to enable its removal from the landfill in the leachate collection/removal system. This deterioration will eventually allow transport of leachate through the liner on its way toward the groundwater resources, that could be used for domestic or other water supply purposes, hydraulically connected through a vadose (unsaturated) zone. Further, compacted soil (clay layers) used in landfill liners are well-known to experience increased permeability with time over that which was designed and originally constructed.

Lee and Jones (1992) and Lee and Jones-Lee (1998a) have presented reviews of the literature on what is known about the properties of plastic sheeting flexible membrane liners (FML) and clay liners to prevent landfill leachate from passing through them for as long as the wastes in the landfill will be a threat. Peggs (1998) has discussed the inevitable failure of plastic sheeting layers used in landfill covers and liners. Shackelford (1994) has presented a comprehensive review of the potential for waste and compacted soil interactions that alter the hydraulic conductivity of liners. Table 1 summarizes some of the causes of failure of landfill plastic sheeting and clay liners.

Table 1
Causes of Liner Failure

Plastic Sheeting FMLs	**Soil/Clay Liners**
Holes at Time of Liner Construction	Desiccation Cracks
Holes Developed in Waste Placement	Differential Settling Cracks
Stress-Cracks	Cation Exchange Shrinkage (for Expandable-Layer Clays)
Free-Radical Degradation	Inherent Permeability
Permeable to Low-Molecular-Weight Solvents – Permeation	Interactions between leachate and the clays
Inherent Diffusion-Based Permeability	
Finite Effective Lifetime – Will Deteriorate and Ultimately Become Non-Functional in Collecting Leachate and as a Barrier to Prevent Groundwater Pollution	*Highly Permeable – Allow Large Amount of Leakage under Design Conditions and Subject to Cracking and Other Failure Mechanisms*

Liner Failure Inevitable. Hsuan and Koerner (1995) have reported on the initial phase of long-term (10-year) studies underway at that time devoted to examining the rates of deterioration of flexible plastic membrane liners. The focus of the Hsuan and Koerner work was the breakdown of the polymers in the plastic sheeting liners. They predicted that such breakdown will begin to occur due to free radical polymer chain scission (liner breakdown) in 40 to 120 years. Those estimates were indicated by Koerner to consider only some of the mechanisms that could cause breakdown; it is possible that breakdown could begin earlier. Even if the breakdown of the plastic sheeting polymers took 100 years or so, ultimately the plastic sheeting in the flexible membrane liners will break down, leading to an inability to prevent large amounts of leachate from passing through the liner, causing groundwater pollution in the landfill area.

One of the approaches that has been used by Koerner and his associates in an attempt to predict long-term stability of HDPE plastic sheeting liners is the application of the Arrhenius equation. This equation is used in physical chemistry to estimate the effects of temperature on the rates of reactions. In some of Koerner's publications, he has made predictions, based on estimates made using the Arrhenius equation and short-term elevated temperature liner deterioration studies, that the HDPE liners should be serviceable for hundreds to a thousand or so years, but that they eventually will break down. The US EPA (Bonaparte et al., 2002) has released a report that claims that a single composite landfill liner can be expected to have a service life of "1,000 years." A critical review shows that the technical basis for his estimate is an Arrhenius equation extrapolation of a few studies on liner stability that were conducted for short periods of time at elevated temperatures compared to landfill temperatures. This approach for extrapolation is highly speculative and likely to be unreliable. That report continues to support the US EPA (1988a,b) conclusion about the eventual failure of the landfill liner system and its leading to groundwater pollution. While the length of time that the landfill liner will delay groundwater pollution is unknown, there is no doubt that a single composite landfill liner system will eventually fail, and groundwater pollution will occur, when the landfill is sited at locations where there is high-quality groundwater underlying the landfill.

In the US EPA (Bonaparte et al., 2002) report, Koerner made a significant error in claiming that the municipal solid wastes in a Subtitle D dry tomb landfill will only be a threat for about 200 years. There is no technical validity for that estimate. It is obvious that in a "dry tomb" landfill, a number of the normal components of MSW will be a threat forever – not just 200 years. The metals, salts, and many organic compounds that are typically present in MSW that produce hazardous and otherwise deleterious leachate will be a threat forever. In that report the US EPA is attempting to support the continued use of single composite lined landfills for MSW management by claiming the wastes will only be a threat for 200 years, and the liner will work perfectly for 1,000 years. Such claims are fundamentally flawed.

Needham et al. (2003) reported on a study commissioned by the Environment Agency of the UK on the long-term service life of HDPE geomembrane liners. They concluded,

> " *the service life HDPE liners depends upon the rate of generation of holes in the liner and the acceptability of leachate or gas leakage at a particular site. A thorough review of physical damage, material degradation processes and the development of holes by stress cracking has been undertaken. A conceptual model of hole generation in six stages throughout the service life of an HDPE liner is presented. Electrical leak location surveys are seen to be effective means of identifying holes caused by physical damage during liner installation and waste disposal, and permitting their repair. Degradation of the HDPE liner is controlled by the liner exposure conditions, the activation energy of the antioxidant depletion process and the oxidative resistance of the material. Where the liner is subjected to long-term stresses, stress cracking will lead to the development of holes, and the rate of cracking will increase once oxidation of the liner commences.*"

Rowe et al. (2003) has reported on the failure of an HDPE-lined leachate lagoon. They stated,

> *"A geomembrane – compacted clay composite liner system used to contain municipal solid waste (MSW) landfill leachate for 14 years is evaluated. Field observations of the geomembrane revealed many defects, including holes, patches, and cracks.*
>
> ***

> *"Contaminant modelling of the entire lagoon liner suggests that the geomembrane liner most likely stopped being effective as a contaminant barrier to ionic species sometime between 0 and 4 years after the installation."*

It is evident that under some situations there can be rapid failure of HDPE liners that are used in waste management including landfill leachate lagoons and liners.

Minimum Subtitle D landfills include a composite liner composed of a flexible membrane liner (FML) (plastic sheet) and a compacted soil layer or geosynthetic clay layer (GCL) below it. While in concept a composite liner can provide greater postponement of leakage than the sum of the two liner components, the true composite character is difficult to achieve in practical applications (Lee and Jones, 1992), since it requires that the plastic sheeting liner be in intimate contact with the compacted soil layer. There are, however, significant problems in achieving this degree of contact in the construction of a composite liner.

The clay layer beneath the FML is compacted to achieve a prescribed, initial design permeability, which means that even when new, the soil/clay layer will transport leachate at the design permeability. Workman and Keeble (1989) discussed the time it takes leachate to breach a clay layer used as a liner. Through Darcy's Law calculations it is found that a compacted soil layer provides only a short term slowing of the leakage of leachate through the liner; one foot of clay compacted to 10^{-7} cm/sec permeability (design permeability), with one foot of head, will be breached in less than ten years. There is increasing evidence that in addition to general permeability, such liners leak through imperfections that are created at the time of liner construction. Further, compacted clays used as liners are subject to desiccation cracking, cation exchange shrinking, cracking due to differential settling, impacts of chemicals, etc., creating additional points through which leachate can leak, and allowing transport of leachate through the liner at a rate greater than expected based on the design permeability.

Desiccation Cracking of Liner. The desiccation cracking of clay liners arises from the fact that, in order to achieve the design permeability, it is necessary to add water to the clay to typically achieve slightly wetter than optimum moisture density. In time, however, due to unsaturated transport of the water added to the clay, the clay can dry out, leading to shrinkage and desiccation cracks. This situation is readily observed in some soils, where during periods of low precipitation, soils will crack.

Cation Exchange-Related Failure. Some types of clays used in landfill liners, with an expandable lattice structure, exhibit strong shrink/swell properties, dependent on the type of cation on the clay's ion exchange sites. With sodium at the exchange site, the clay is in a swollen state. However, in contact with water with high calcium/magnesium compared to sodium concentrations, the calcium and magnesium will replace the sodium on the clay, and the clay will shrink, leading to higher permeability and possible failure through cracking. Auboiroux et al. (1999) has investigated the impact of calcium exchange for sodium in bentonite geosynthetic clay liner for landfills and stated, "*Results suggest that while GCL's may be considered as useful materials for reinforcing compacted clay layers at the base of landfills, they should not be considered as "equivalent" to compacted clay layers, at least in terms of pollutant breakthrough times.*"

In a study of the use of a GLC as a liner to enhance the cover over a reservoir, James et al. (1997) reported that,

"*The evidence demonstrates that calcium from calcite, contained in the GCL bentonite, exchanged with sodium and, in so doing, contributed to shrinkage and cracking.*"

Jones-Lee and Lee (1993) presented a summary of the concentrations of various ions present in leachates from 83 US landfills. The data show that some MSW leachates have higher concentrations of calcium than sodium. In fact, the overall average calcium concentration for all of the landfill leachates investigated was higher than the sodium concentration. This means that, for some compacted clay liners, the low advective permeability (rate of penetration) at the time of installation of the liner will increase as the sodium on the clay is replaced by calcium, and the clay shrinks from its original characteristics at the time of construction. This shrinking can lead to ion exchange cracking of the compacted clay liner.

Desiccation cracking and ion exchange cracking of compacted clay layers in a composite liner have been known since the late 1980s. However, neither the US EPA nor state regulatory agencies has adequately considered these issues in evaluating the prospective performance of a single composite liner. Both of these phenomena can lead to a much more rapid rate of leachate penetration through the composite liner than is typically assumed.

Permeation through the Liner. An important issue that needs to be considered is that the plastic sheeting HDPE liner will allow dilute solutions of organic solvents, such as those that can be purchased in hardware stores for household use, to pass through an intact (no holes) liner. Many of these solvents are carcinogens and can be readily transported through groundwater systems. The phenomenon in which organics pass through intact plastic sheeting layers is known as permeation and has been recognized in the landfill liner literature since the late 1980s (Haxo and Lahey, 1988). Permeation is a chemical transport process in which low molecular weight organics dissolve into the plastic liner and exit on the downgradient side. Sakti et al. (1991) and Park et al. (1996), at the University of Wisconsin, Madison, reviewed the available information on permeation of landfill liners by solvents and have conducted extensive research on it. They found that an HDPE liner would have to be over three inches thick to prevent permeation of certain organics through it for a period of 25 years. Buss et al. (1995) reviewed the information on the mechanisms of leakage through synthetic landfill liner materials. They discussed the importance of permeation of organics through plastic sheeting liners as a landfill liner leakage mechanism that does not require deterioration of the liner properties for leakage to occur. The US EPA and other regulatory agencies continue to ignore this mechanism of landfill liner leakage.

<u>*Diffusion Can Be Important*</u>. Daniel and Shackelford (1989) have reviewed the inherent leakage rates of plastic sheeting layers and clay liners. They pointed out that even though plastic sheeting layers can have low permeabilities to water at the time of construction – on the order of 10^{-12} cm/sec compared to clay liners which have a permeability of about 10^{-7} cm/sec – the thin layer of plastic that is used, coupled with its inherent chemical diffusion coefficients, cause plastic sheeting liners of the type used in Subtitle D landfills to have diffusion-controlled breakthrough times for waste components of about two to three years. The clay liner in the landfill cells, however, would be expected to have diffusion-controlled breakthrough times of about 10 years.

The diffusion of solid waste components through plastic sheeting liners discussed by Daniel and Shackelford occurs through a different mechanism than the permeation of organic solvents (VOCs) through HDPE liners discussed above. As stated by Daniel and Shackelford (1989),

> *"No material is impervious, and the question of which liner is more effective, like most questions, is ultimately related to one of economics and the realities of construction practices."*

Basically, regulatory agencies, such as the US EPA which has set the national minimum standard for landfill design, have been adopting landfill liner systems that will clearly, in time, fail to prevent groundwater pollution. As part of adopting the RCRA Subtitle D regulations, the US EPA recognized this; it stated, (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 stated,

> *"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."*

<u>*Potential Problems with Geosynthetic Clay Liner*</u>. Some landfill developers have proposed to use a single composite liner for a landfill consisting of a 60 mil HDPE plastic sheeting layer and geosynthetic clay liner. While some states, including PA, allow the substitution of a geosynthetic clay liner for the two feet of clay specified in US EPA Subtitle D regulations, such practice can allow more rapid failure of the composite liner than if the two feet of compacted clay had been used. The US EPA (2001a) reviewed the properties of geosynthetic clay liners and discussed a number of the potential advantages and potential problems with substituting a geosynthetic clay liner for two feet of compacted clay. A key problem with geosynthetic clay liners is that they are so thin that they have limited structural integrity and will allow rapid penetration of leachate through the liner by diffusion. While landfill applicants and their consultants, and unfortunately some regulatory agencies, will claim that the permeability of a geosynthetic clay liner of

10^{-9} cm/sec under 1 ft of head will control the rate of leachate passing through the liner, in fact because of diffusion it can pass through more rapidly.

A bentonite clay layer was incorporated into the Pottstown Landfill by Waste Management in 1984. One of the issues that has not been addressed by the US EPA and others is the potential for cation exchange reactions (cations are positively charged ions) between the leachate and the sodium bentonite clay used in a geosynthetic clay liner; these reactions could lead to higher permeability of the geosynthetic clay liner. As discussed above bentonite clay has significant shrink/swell properties that are impacted by the type of cation that is on the clay's ion exchange sites. With sodium at the exchange site, the clay is in a swollen state. However, when the clay comes in contact with water with high calcium/magnesium compared to sodium concentrations, the calcium and magnesium will replace the sodium on the clay. This replacement causes the clay to shrink, leading to higher permeability and possible failure through cracking. As discussed above, Jones-Lee and Lee (1993) found that leachate data show that some MSW leachates have higher concentrations of calcium than sodium. This means that for many (if not most) geosynthetic clay liners, the low advective permeability at the time of installation of the liner will increase as the sodium on the bentonite clay is replaced by calcium, and the clay will shrink from its original characteristics at the time of construction.

Overall, it is clear that there is a finite period of time during which the plastic sheeting upper composite liner and lower plastic sheeting secondary liner used in the Pottstown Landfill can be expected to function as designed to collect leachate and thereby prevent it from polluting groundwater. In time, the upper composite liner will fail; if the lower plastic sheeting secondary liner is still functioning without significant holes and areas of deterioration, it can indicate when the upper primary liner has failed. If the leachate that is collected in the leak detection zone is detected and action is taken to prevent water from entering the landfill through the cover, forever, the further groundwater pollution by the Pottstown Landfill can be prevented. However, if the plastic sheeting liner of the leak detection zone has significantly deteriorated, the leachate that has passed through the upper composite liner will pass through the leak detection zone into the underlying fractured rock aquifer system under the landfill and additional groundwater pollution by the Pottstown Landfill will occur.

Leachate Collection and Removal System Characteristics

The key to preventing groundwater pollution by a dry tomb type landfill is the ability to collect all leachate that is generated in the landfill in the leachate collection and removal system. The leachate collection and removal system overlies the primary plastic sheeting liner. As shown in Figure 6, the leachate collection and removal system consists of perforated plastic pipe that is embedded in gravel. 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 6). The leachate collection system consists of gravel or some other porous media, 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. This plugging, in turn, increases the head of the leachate above the liner upstream of the area that is blocked.

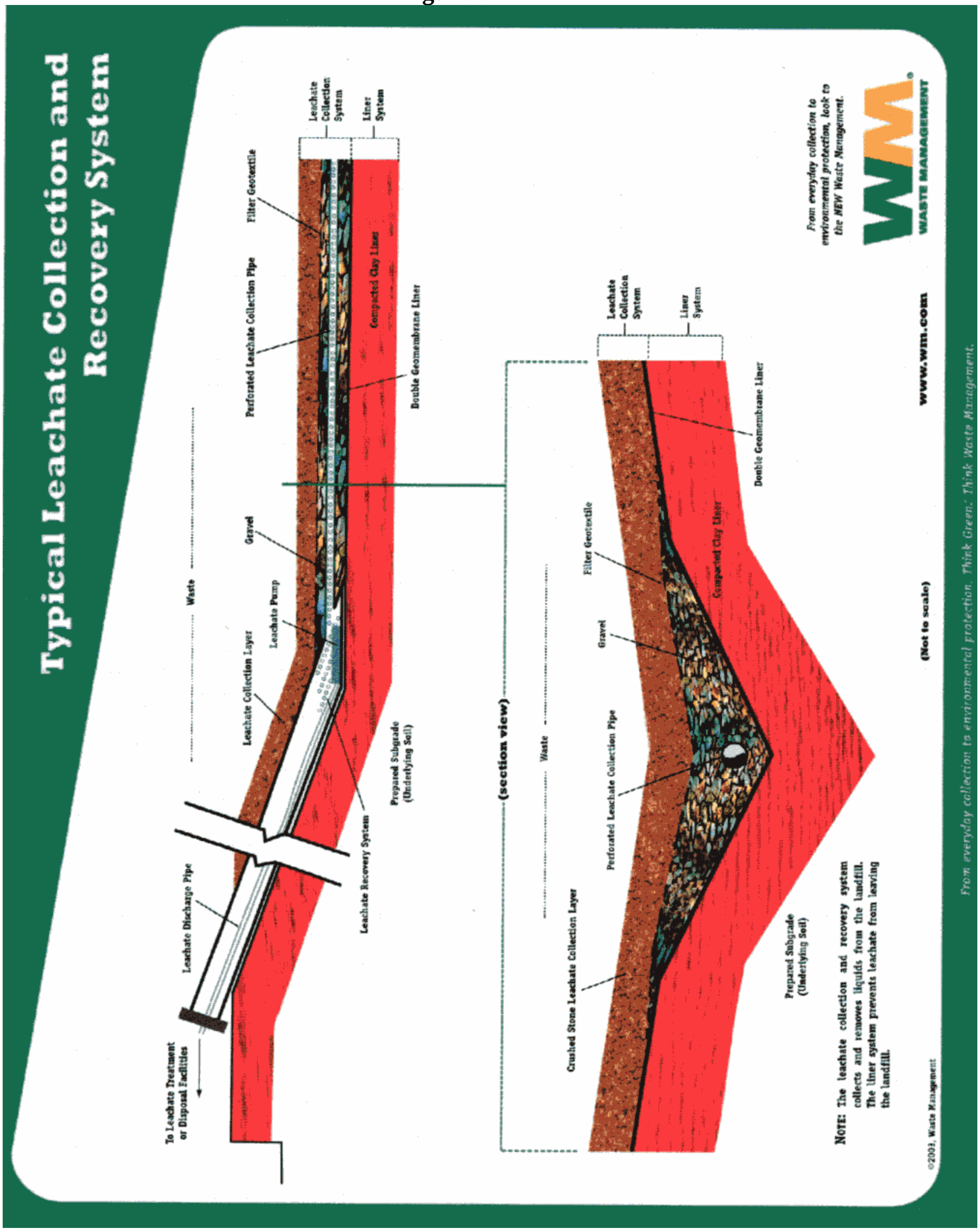
The basic problem with leachate collection systems' functioning as designed is that the HDPE liner, which is the base of the leachate collection system, develops cracks, holes, rips, tears, punctures and points of deterioration. When the leachate that is passing over the liner reaches one of these points, 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 deficiencies in the 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 rapid. Under these conditions, the leachate spreads out over the clay layer and can leak at a substantial rate through the clay.

Plugging of Leachate Collection Systems. An issue that is not adequately addressed in landfill applications is that municipal landfill leachate is well-known to cause plugging of the leachate collection and removal system, thereby allowing greater than one foot of head on the liner on the upgradient side of the plugged area. This plugging arises from chemical precipitation and biological growths. The buildup of head (leachate depth) on the liner leads to greater rates of leakage than would occur if the depth of leachate were less than the one foot allowed in Subtitle D regulations. While some landfills contain provisions to backflush the leachate collection pipe to try to reduce clogging, such

backwashing will not necessarily eliminate build-up of leachate head on the plastic sheeting liner. Waste Management has incorporated the capability to backflush the leachate collection pipes in the various sections of the Pottstown Landfill. If backflushing has been done, this is an indication of plugging of the leachate collection system.

Overall, the leachate collection system that has been installed at the post-1991 sections of the Pottstown Landfill can be effective in collecting leachate generated in the landfill. However, over time the leachate collection and removal system at this landfill will fail to function as designed due to deterioration of the plastic sheeting layer in the upper (primary) composite liner. Leachate will pass through holes in the plastic sheeting and then penetrate through the underlying clay layer in the composite liner. It is not possible to repair the landfill liner system and the associated leachate collection and removal system as a result of the fact that they are buried under the wastes. If failure of the leachate collection and removal system is properly monitored/detected, action can be taken to repair the areas of the landfill cover that are allowing moisture to pass through the cover to generate leachate.

Figure 6



Typical Leachate Collection and Recovery System
Leachate Collection System
Liner System
Filter Geotextile
Perforated Leachate Collection Pipe
Compacted Clay Liner
Double Geomembrane Liner
Gravel
Waste
Leachate Pump
Leachate Collection Layer
Prepared Subgrade (Underlying Soil)
Leachate Recovery System
Leachate Discharge Pipe
To Leachate Treatment or Disposal Facilities
(section view)
Crushed Stone Leachate Collection Layer
NOTE: The leachate collection and recovery system collects and removes liquids from the landfill. The liner system prevents leachate from leaving the landfill.
(Not to scale)
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Landfill Cover
Waste Management (2004) provided the Pottstown Landfill Closure Committee with Figure 7 showing the Pottstown Landfill final cap for part of the landfill. The cover that Waste Management is now using for newer parts of the landfill is consistent with typical Subtitle D landfill covers. Starting from the top, it consists of a two foot thick vegetative soil layer. Under lying the top soil layer is a drainage layer. Underlying the drainage layer is a geocomposite drainage layer which is underlain by a 40 mil HDPE plastic sheeting layer. The plastic sheeting layer of the cover rests on geotextile layer that is placed on a soil layer that is used to shape the area above the wastes so that it is more suitable for placement of the final 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 beneath, it is supposed to move laterally to the outside of the landfill.

A significant problem with landfill covers of this type is that they cannot 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. However, as discussed by Lee and Jones-Lee (1995, 1998a, 2005), since the low-permeability layer (plastic sheeting) is buried below a topsoil layer and a drainage layer, it is not possible to detect when the plastic sheeting layer deteriorates sufficiently to allow moisture that enters the topsoil and drainage layer to pass into the landfilled wastes. Those cracks or depressions that are observed in the topsoil layer 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 and comes in contact with the plastic sheeting layer will penetrate into the wastes rather than run off the landfill as it could when the plastic sheeting is new and constructed properly. Breeches in the plastic sheeting could occur at any time during the postclosure care period. If the leachate collection system is still functioning when it does, the increased leachate generation would be noticed there. However, if the leachate collection system is not functioning adequately, or if no one is monitoring leachate generation (as would occur if postclosure care is limited to a period less than when the wastes in the landfill are still a threat to generate leachate) that collects in the leachate collection system would not be removed and would pollute groundwater.

Christensen and Kjeldsen (1989) published a paper entitled, "Basic Biochemical Processes in Landfills," that discussed the importance of moisture in controlling landfill gas production. As they reported (see Figure 8), when the moisture content of the waste is about 20%, landfill gas production greatly slows down/stops. The same applies to leachate generation. However, the onset of a dormant-dry period does not mean that the wastes in the landfill are no longer a threat to generate landfill gas and leachate.

As discussed by Lee and Jones (1991), the pattern of MSW decomposition in a dry tomb type landfill is significantly different from that in the classical sanitary landfill. If the plastic sheeting layer in the cover of a dry tomb landfill is installed properly, the wastes in the landfill will dry out, and fermentation and leaching of the wastes will stop, until moisture, again, enters the landfill through the cover. Lee and Jones (1991) developed Figure 9 to illustrate the expected landfill gas production in a dry tomb type landfill. A similar relationship was developed by the California Integrated Waste Management Board staff (CIWMB, 2004).

While, with good quality construction of the landfill cover, it is possible to shut off the moisture supply to a landfill, over time the plastic sheeting layer in the cover will decay due to free radical attack and rupture due to differential settling stresses; at some unpredictable time in the future, these failings and deterioration will allow moisture to enter the wastes again. As discussed by Lee and Jones-Lee (2005) in their paper, "Flawed Technology of Subtitle D Landfilling," the decay/rupture of the plastic sheeting cannot be readily observed because the plastic sheeting layer in the cover is buried under several feet of top soil and a drainage layer. As a result, the breeches of the plastic sheeting layer in the cover cannot be identified and repaired as needed to keep the wastes dry.

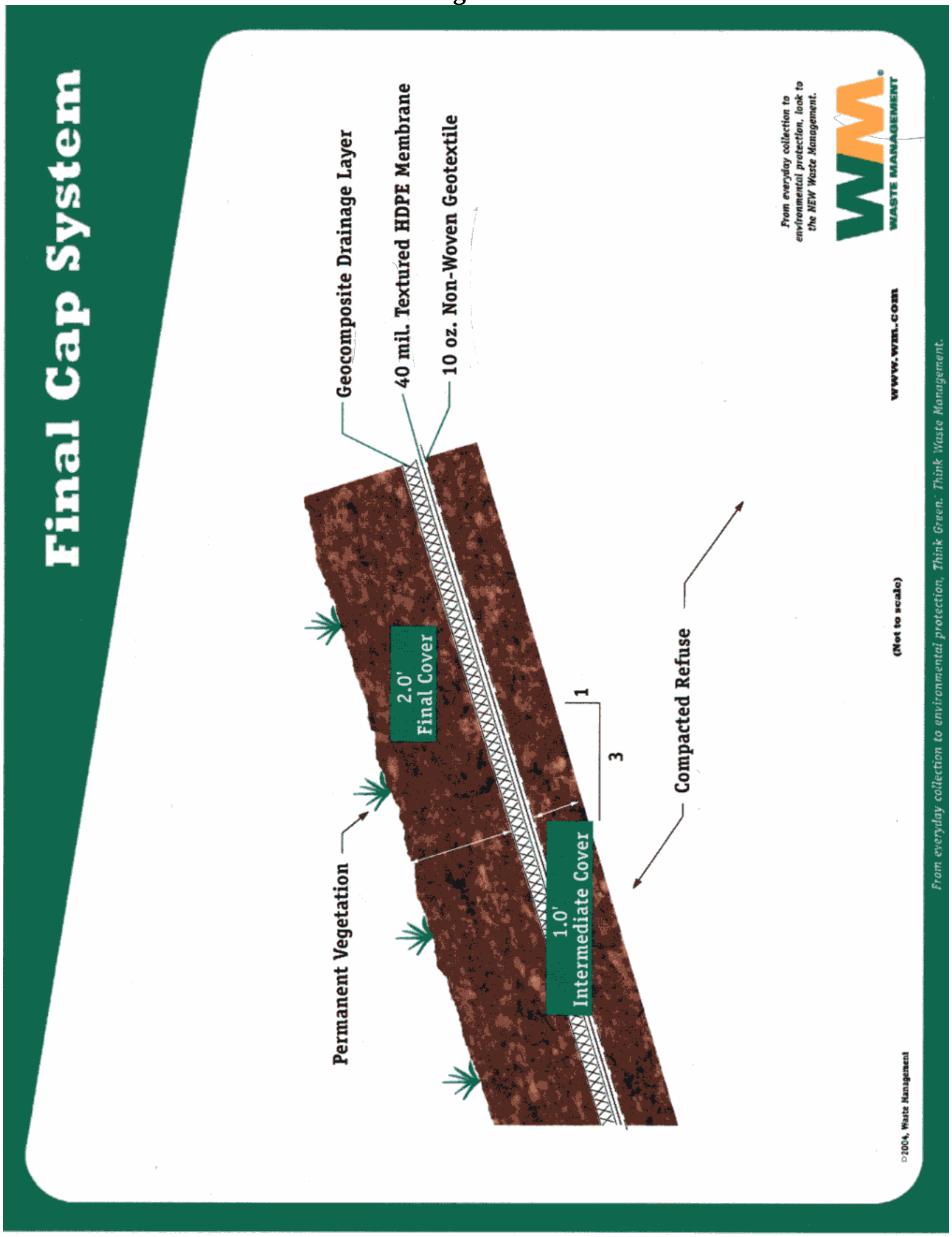
Unless a landfill owner agrees to install, operate, and maintain a leak-detectable cover for the landfill in perpetuity, the landfill cover system will fail to prevent entrance of moisture into the landfill and generation of leachate even if it meets regulatory requirements at the time of installation.

Leak-Detectable Covers. The high probability of failure of the low-permeability layer of the landfill cover is the reason that Lee and Jones-Lee (1995) advocate the use of leak-detectable covers that are operated and maintained in perpetuity – i.e., as long as the wastes in the landfill 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), leaks in the cover can be isolated and repaired.

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

Typically landfill developers' consultants, including those working for Waste Management at the Pottstown Landfill, use the HELP model to try to predict the rate at which moisture will enter the landfill through the cover. A critical review of the HELP model calculations shows that a key component of these calculations of the amount of percolation of water through the cover into the wastes is the assumed permeability of the low-permeability layer of the cover. Typically landfill consultants assume that the

Figure 7



Final Cap System
Geocomposite Drainage Layer
40 mil. Textured HDPE Membrane
10 oz. Non-Woven Geotextile
Permanent Vegetation
2.0'
Final Cover
1.0'
Intermediate Cover
1
3
Compacted Refuse
(Not to scale)
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Figure 8. Impact of Moisture on Landfill Gas Formation
(from Christensen and Kjeldsen, 1989)

44 *Christensen and Kjeldsen*

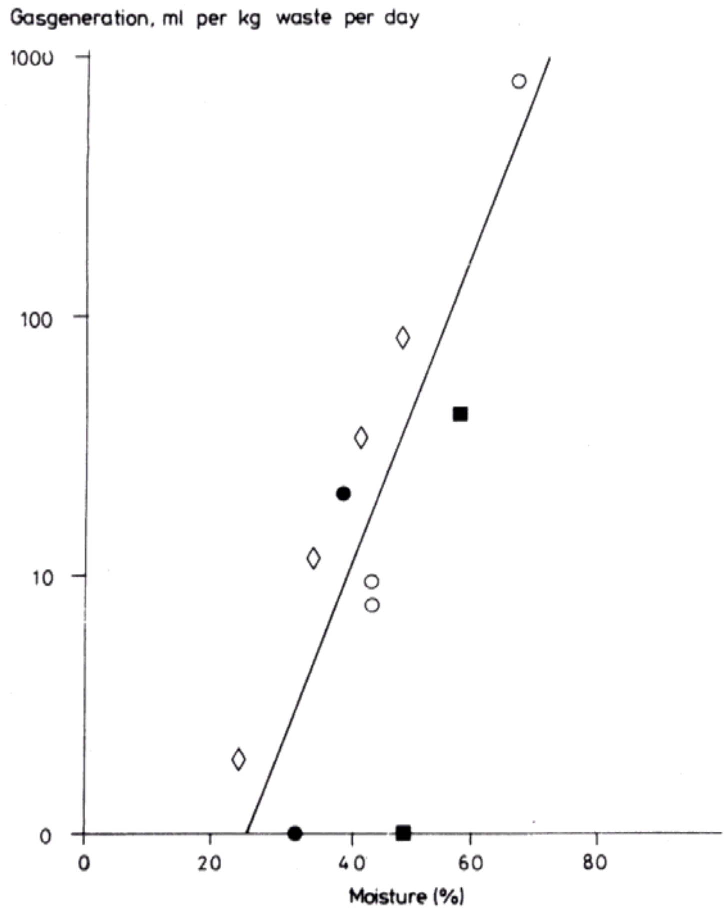
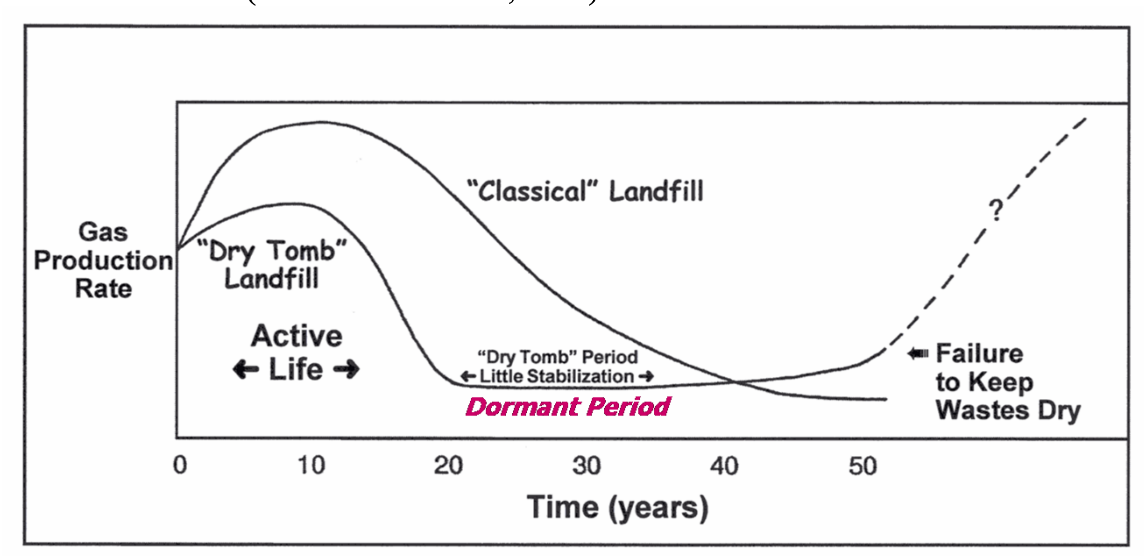


Figure 8. Gas generation rates as a function of moisture content. After Rees (1980a).

construction of the cover will achieve the design permeability. Further, and most importantly, they assume that the design permeability of the cover will be maintained over the period of postclosure care (30 years) and throughout the period that the wastes in the landfill will be a threat. However, no information is provided on the permeability of the cover over the period of time that the wastes in the landfill will be a threat – i.e., effectively, forever.

Figure 9. Comparison of Pattern of Landfill Gas Generation over Time at Classical Sanitary Landfill and "Dry Tomb" Landfill
(from Lee and Jones, 1991)



Part of the Pottstown Landfill has a soil cover. In the late 1980s/early 1990s, the US EPA conducted a series of seminars on RCRA/CERCLA landfill design issues. One was devoted to "Design and Construction of RCRA/CERCLA Final Covers" (US EPA, 1990). Included in the seminar notes was a section developed by Dr. David Daniel, then of the University of Texas, Austin (Daniel, 1990), which discussed "Critical Factors in Soils Design for Covers." In the appendix to his presentation, Dr. Daniel presented a paper by Montgomery and Parsons (1989), which summarized the results of a three-year study conducted in cooperation with the state of Wisconsin on the performance of various types of landfill soil covers. The Montgomery and Parsons study was conducted on three different 40ft x 40ft test plots near Omega Hills, Wisconsin, near Milwaukee. Daniel (1990) summarized the results and reported that after three years,

- *"Upper 8 to 10 in. of clay was weathered and blocky*
- *Cracks up to ½ inch wide extended 35 to 40 inches into the clay*
- *Roots penetrated 8 to 10 inches into clay in a continuous mat, and some roots extended into crack planes as deep as 30 in. into the clay".*

Daniel also discussed problems with soil/clay covers' being able to withstand stress-strain relationships associated with differential settling of the wastes under the cover. He pointed out that differential settling can readily lead to cracks in the soil cover.

It is likely that the cover in those parts of the Pottstown Landfill that are covered by a clay/soil cover and are generating leachate and landfill gas, has developed cracks that are allowing moisture to enter the wastes. Those parts of the Pottstown Landfill with clay/soil covers will likely need to have a new cover installed that contains a plastic sheeting layer to shut off the moisture supply to the wastes.

Overall a properly constructed and maintained landfill cover that includes a plastic sheeting layer can be effective in preventing moisture from entering the landfill and therefore keep the wastes dry. When dry the wastes do not generate leachate or landfill gas. In a dry tomb type landfill, drying out of the wastes leads to a dormant period with respect to landfill gas and leachate generation. However, the integrity of the low permeability layer of the cover is subject to many stresses; eventually it deteriorates and allows moisture to enter the wastes which allows the renewed generation of leachate and landfill gas. This can happen a short time after landfill closure, or be postponed for many decades after landfill closure. A reliable landfill closure plan for the Pottstown Landfill must include monitoring of leachate and landfill gas generation as long as the wastes in the landfill have the potential to generate leachate and gas when moisture is introduced into the wastes. Also, the landfill cover must be routinely inspected for areas of stressed vegetation that is indicative of landfill gas migration through the cover. Renewed landfill gas and/or leachate generation after a dormant period with little or no leachate generation is an indication that moisture has been entering the landfill. Under those conditions, the landfill owner must be required to locate the area of the cover that is no longer preventing moisture from entering the landfill and repair the low permeability layer of the cover. This process will have to be repeated as needed for as long as the wastes in the landfill are a threat.

Groundwater Monitoring Reliability Issues

Lee and Jones-Lee (1993b, 1998b and 2005) presented comprehensive reviews of groundwater quality monitoring issues for Subtitle D landfills. As they pointed out, a fundamental problem with typical groundwater monitoring programs for minimum Subtitle D landfills is that they have been developed based on perceptions of leakage from **unlined** landfills, without proper consideration of the manner in which **lined** landfills leak and pollute groundwater. Conventional, unlined sanitary landfills are expected to leak leachate over a considerable part of the bottom of the landfill. Therefore, even though the lateral spread of a plume of leachate-contaminated groundwater can be limited depending on aquifer characteristics (Cherry, 1990), the plume of leachate-contaminated groundwater in some types of geological/ hydrogeological strata would move as a wide front downgradient of the unlined landfill (see Figure 10). Under those conditions, close well-spacing downgradient of the landfill may not be critical for the detection of groundwater contamination by leachate. However, this is not the character of initial leakage from plastic sheeting lined landfills.

Initial Liner Leakage Can Produce Narrow Plumes of Leachate-Polluted Groundwater. Bumb et al. (1988) and Glass et al. (1988) discussed the fact that the initial leaking of leachate from lined landfills will occur from point sources in the liners, rather than uniformly from the landfill bottom as may be expected from unlined landfills. The initial leaks will occur from holes, rips, tears and points of deterioration in the plastic sheeting liner. That fact changes the reliability of groundwater monitoring based on the wide plume of leachate expected from an unlined landfill in a uniformly porous aquifer system. In a study of the lateral dispersion of leachate plumes from lined landfills, Smyth

(1991) of the Waterloo Centre for Groundwater Research, University of Waterloo, reported that a 0.6-m (2-ft)-wide point-source tracer spread laterally to a width of only about 2 m (6 ft) after traveling 65 m (213 ft) in a sand aquifer system. Thus it is clear that leakage from point sources such as holes in plastic sheeting liners can move downgradient as narrow "fingers" of leachate (Figure 11) rather than in the traditionally assumed fan-shaped plumes. This means that conventional wells used for monitoring of the pollution of groundwaters caused by lined landfills must be placed close enough together at the point of compliance to detect narrow fingers of leachate if the monitoring program is to comply with Subtitle D requirements for the detection of incipient groundwater pollution from waste management units at the point of compliance.

The typical groundwater monitoring well used today has a four- to eight-inch diameter borehole and are spaced hundreds of feet apart. Such wells are normally purged prior to the quarterly or so sampling by removal of three to five borehole-volumes of water. Thus, the zones of capture for such monitoring wells are on the order of a foot around each well for wells located in sand and clay aquifers. Since the lateral spread of a finger of leachate-contaminated groundwater from a lined landfill is dependent on aquifer characteristics and can be minimal, especially for leaks arising on the downgradient edge of the waste deposition area, monitoring wells that are spaced hundreds of feet apart at the downgradient edge of some lined landfills have a low probability of detecting the fingers of leachate produced by leaks in the liner system. Those fingers of leachate could travel long distances before groundwater pollution by the landfill is detected.

Parsons and Davis (1992) discussed issues of monitoring well spacing and zones of capture of monitoring wells associated with waste management units. As they discussed in order to have a high probability of detecting leachate leakage from a waste management unit, the spacing of standard monitoring wells at the point of compliance must be such that zones of capture overlap. Thus, in order to be effective in achieving the groundwater monitoring performance standard of Subtitle D, for some landfills, conventional vertical groundwater monitoring wells need to be spaced no more than a few feet apart along the downgradient edge of the landfill, creating a "picket fence" of wells.

The problems of the unreliability of groundwater monitoring in plastic sheeting lined landfills to detect groundwater pollution before widespread offsite groundwater pollution has occurred are well-recognized. A number of states, including Michigan in its Rule 641, require double composite liners for municipal solid waste landfills. These liners are similar to those required for hazardous waste landfills. They also require that a leak-detection system be used between the two composite liners to determine when the upper composite liner has failed. The state of PA adopted a version of this approach with its leak detection zone under the primary composite liner. The double composite approach, in which the lower liner is a pan lysimeter for the upper composite liner, is a far more reliable monitoring approach for detecting liner leakage than the single composite liner with wells spaced along the point of compliance.

The ability to define the shape and movement of a contaminant finger-plume developed from a lined landfill depends on the hydrogeological characteristics of the aquifer-strata. In homogeneous, isotropic "sand" systems, the vertical and horizontal spread of point source discharges/leaks in the liner from a given point can be estimated with some degree of reliability. However, the hydrogeology of many locations in which landfills are sited is sufficiently complex so that predictions of the spread of a leachate plume are fairly unreliable. The presence of fractured bedrock, fissures, cavernous calcareous strata, and non-isotropic lenticular aquifers (such as former river beds) make predictions of the spread of leachate highly questionable.

Various reports (see the Waste Management (2002) application for the vertical expansion of the Eastern Landfill) have been developed on the geology/hydrogeology of the areas underlying and near the Pottstown Landfill. Those reports discuss the characteristics of the fractured rock aquifer system that underlies the landfill. There is general agreement among experts in groundwater hydrology and groundwater monitoring that the monitoring of some fractured rock aquifers for incipient leachate pollution for landfill leachate polluted groundwater from dry tomb type landfills is nearly impossible. For example, Haitjema (1991) from the University of Indiana stated,

> *"An extreme example of Equation (1) (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."*

Even if a monitoring well intercepts a fissure/crack, the leachate in that fissure system is not necessarily reliably sampled during groundwater monitoring. Because the amount of water extracted during sampling is typically quite small, the zone of capture around the monitoring well, even in a fracture, is often limited. Thus, leachate-contaminated groundwater can be present in a fracture without its being detected by the monitoring programs typically used. Therefore, in addition to misconceptions about the nature of the spread of leachate from lined landfills, incomplete or unreliable assessment of the geological features of the subsurface system and complex hydrogeology can further reduce the probability that the groundwater monitoring well array will intercept any initial plume of leachate-contaminated groundwater at the point of compliance for the MSW landfill monitoring program.

From a review of Waste Management's (2002) proposal for expansion of the Eastern Area of the landfill, there are appropriate questions about the ability of the two primary downgradient monitoring wells to detect leachate-pollution of the groundwaters in fractures that can occur at any location underlying the Eastern Area Expansion. Similar problems exist for the Western Expansion of the initial landfill. Since, as discussed

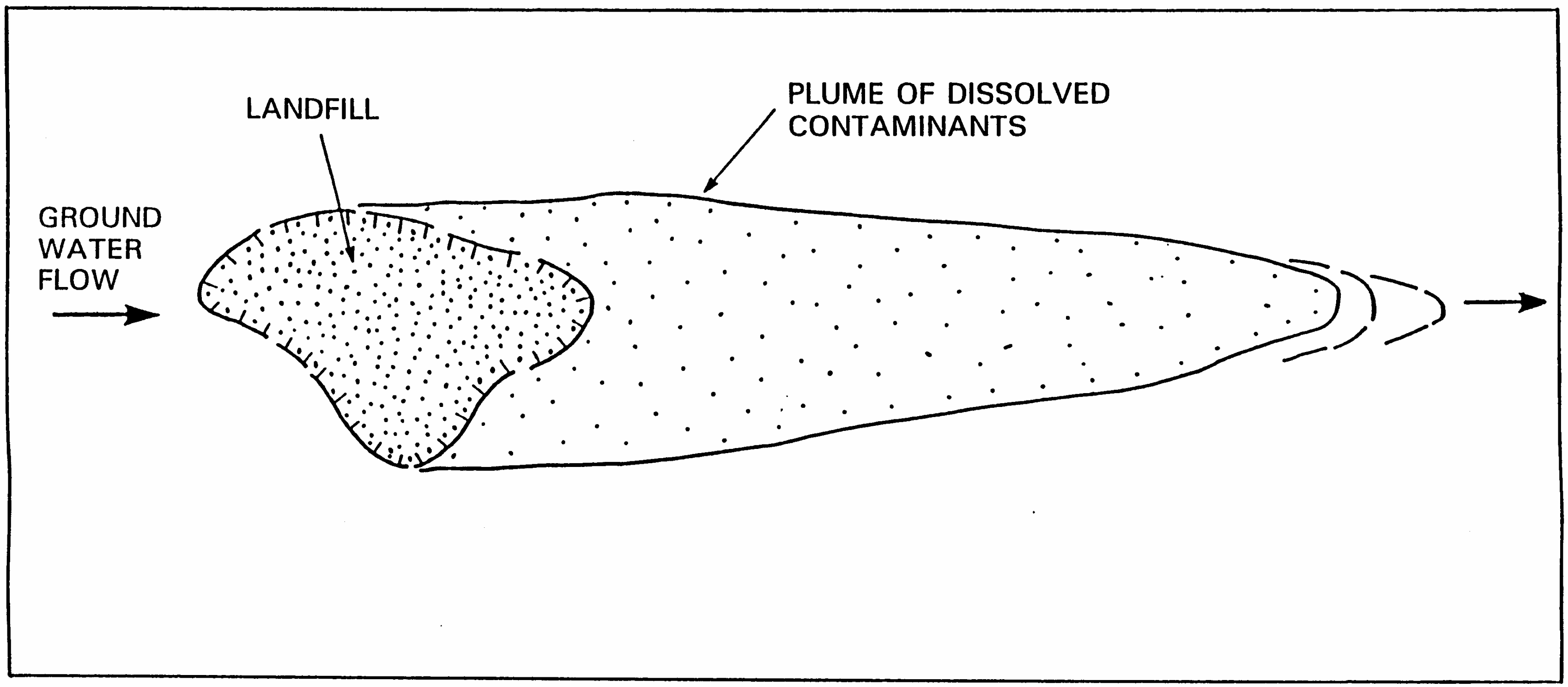


Figure 10. Pattern of Landfill Leakage – Groundwater Contamination – from Unlined Landfills
(after Cherry, 1990)

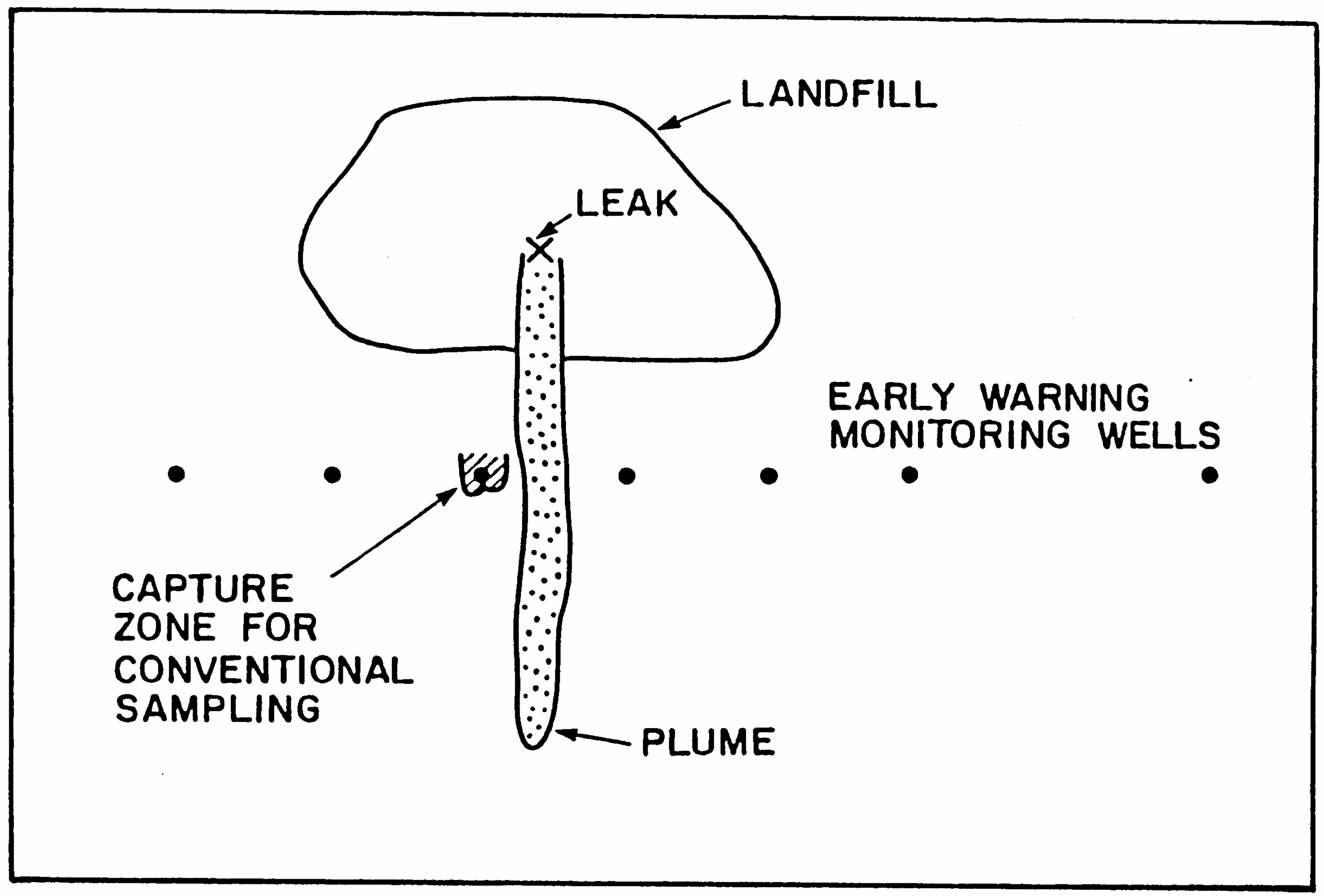


Figure 11. Pattern of Landfill Leakage – Groundwater Contamination- from Lined Landfills (after Cherry, 1990)

above, it is possible that the leak-detection zone under the landfill will fail to reliably indicate when the primary composite liner for the landfill fails, it is important that an evaluation be made as part of the development of the final closure plan, to determine the reliability of the existing monitoring well array to detect leachate-polluted groundwater that has passed through the upper composite liner and out of the leak-detection zone without being transported to the leak-detection-zone sump where the leak would be recognized. It is suggested that as part of developing the final closure plan, Waste Management employ a consultant who could make a reliable evaluation of monitoring well spacing required to produce at least a 95% probability of detecting leachate that passes through the bottom of the leak-detection zone into the underlying groundwater aquifer fractures and then downgradient of the landfill.

Another issue that needs to be considered in developing a groundwater monitoring program for the closed Pottstown Landfill is the potential for new production wells just outside of the landfill to change the overall groundwater flow direction downgradient of parts of the landfill. A program should be established as part of the permitting of new production well(s) in the area that would evaluate the potential of a proposed well(s) to influence the magnitude or direction of groundwater flow that could change the potential reliability of the groundwater monitoring wells that are incorporated into the final closure plan for the Pottstown Landfill.

Evaluation of Leachate Density. According to Cherry (pers. comm., 1991) leachate from municipal landfills can contain sufficient amounts of salt to cause them to be somewhat more dense (heavier per unit volume) than the groundwaters of the area. This would cause a finger-plume of leachate to sink along its horizontal trajectory until it becomes sufficiently diluted so that its density matches that of the area groundwater. The hydrogeology and the groundwater characteristics of the area beneath and downgradient from a landfill must be defined with a high degree of certainty as part of permitting a landfill groundwater monitoring system if a potentially meaningful groundwater monitoring program is to be developed to detect landfill liner leakage. Particular attention needs to be given to the depth of monitoring well screens that are designed to intercept the layer of leachate-polluted groundwater. The vertical position of the leachate plume that will occur at the point of compliance for groundwater monitoring should be predicted as part of permitting a landfill. Based on this prediction, the screening of monitoring wells to detect the maximum concentration of the leachate-polluted groundwaters at the point of compliance should be determined. A nested well sampling of various depths should be used to provide confirmation of the predictions.

Some regulatory agencies allow monitoring wells that include well screening length over a substantial depth of the aquifer. Substantial long-screened monitoring wells could withdraw from the aquifer large amounts of water that is not likely polluted by landfill leachate, thereby diluting the leachate-polluted water. This could impair or defeat the ability to reliably detect a leachate plume that occurs in a narrow vertical band underlying the point of compliance for groundwater monitoring. This is a potential problem at the

Pottstown Landfill. A nested well sampling of various depths should be used, rather than a long screen well.

Overall, the geology/hydrogeology of the area under and near the Pottstown Landfill is extremely complex. Because of the fractured rock aquifer system underlying the landfill, it is very difficult, if not impossible, to use vertical monitoring wells around the perimeter of the landfill to reliably monitor initial failure of the upper composite liner and leak detection zone. As discussed above, it is not possible to rely on the leak detection zones to reliably monitor upper liner failure for as long as the wastes in the landfill will be a threat. There is need for Waste Management to conduct a quantitative assessment of the number and locations of groundwater monitoring wells that would be needed to reliably detect leachate-polluted groundwater when it first reaches the point of compliance for groundwater monitoring.

Landfill Gas and Airborne Emission Problems.
Municipal solid wastes and some industrial "non-hazardous" wastes contain organic compounds which, in a landfill in the presence of moisture, are converted by bacteria to methane and carbon dioxide (landfill gas). The presence of methane in landfill gas represents an explosion hazard and contributes to global warming. There have been situations in which subsurface migration of landfill gas to adjacent properties has resulted in explosions in dwellings on adjacent properties. In order to detect subsurface migration of methane, landfill developers have proposed to take measures to ensure that the concentration of methane gas generated by the landfill does not exceed 25 percent of the lower explosive limit (LEL) for methane in landfill structures and that the concentration of methane gas does not exceed the LEL for methane at the landfill property boundary.

While controlling landfill gas emissions to 25 percent of the lower explosive limit for methane if adequately implemented, could eliminate the potential for explosions, it would mean that appreciable concentrations of landfill gas could develop at the landfill/adjacent property owners' property line. This situation is strongly contrary to the health, welfare and interests of adjacent property owners/users.

Monitoring for landfill gas reliably can be complex. As landfill gas is generated within the landfill, it attempts to migrate in all directions, escaping where it can through the bottom, sides and top surfaces. Some landfill developers install gas monitoring wells every 1000 feet or so and test them quarterly for the presence of methane using monitoring probes installed in soil between the landfill unit and the property boundary or on-site structures (office, maintenance, and scale). The spacing of landfill gas monitoring wells 1,000 feet apart is grossly inadequate to detect landfill gas migration through the subsurface soil under the conditions that exist at many landfills. The escape of landfill gas from a landfill will not be uniform across all areas of the landfill liner system that is used on the subsurface sides of the landfill. It will occur in areas where the liner has failed due to landfill construction problems, landfill operation problems and points of deterioration in the liner. This can lead to the development of plumes of landfill gas that can pass between monitoring wells spaced 1,000 feet or so apart. As discussed by Hodgson et al. (1992), this, in turn, can be a threat to those who construct dwellings near the landfill property line. There is need to evaluate the adequacy of the current landfill gas migration monitoring well array that exists at the Pottstown Landfill to determine if it is adequate to detect landfill gas migration before it leaves the landfill property.

The production of landfill gas is a result of the fermentation of materials in the landfill; fermentation requires moisture. The rate of landfill gas production is thus dependent on the moisture content of the wastes; dry wastes produce little landfill gas. Landfill developers typically present estimates of the period of time that landfill gas will be generated in a proposed dry tomb landfills that presume the presence of moisture for fermentation. As discussed by Lee and Jones-Lee (1999b) these estimates typically ignore the fact that once the landfill is closed and the low permeability cover is installed, the rate of landfill gas generation will be greatly reduced as the wastes dry out. As discussed above, landfill gas generation can resume when the low permeability layer in the cover no longer keeps moisture out of the wastes.

Another issue that is not adequately addressed in the permitting of dry tomb Subtitle D landfills is that much of the wastes placed in today's landfills is in plastic bags. 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. Landfill gas production in today's landfills does not follow the classic generation rates and durations that were developed based on unbagged wastes or on situations in which 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. Rather, the period of landfill gas production will be prolonged, until the plastic bags decompose and allow exposure of their contents to moisture in the breeched landfill. This can readily be many decades, to a hundred or more years.

Prosser and Janechek (1995) have discussed the fact that gaseous emissions from landfills are a threat to cause groundwater pollution. These gaseous emissions contain a variety of volatile hazardous chemicals that are a threat to cause cancer and other diseases in those living/using areas near a landfill. However, the groundwater pollution caused by landfill gas will not likely be detected by the groundwater monitoring wells since gas migration can be in a direction different from down groundwater gradient. The Pottstown Landfill has already caused problems with migration of landfill gas, apparently arising from the old landfill; the landfill gas has caused groundwater pollution by vinyl chloride, a potent human carcinogen.

While landfills designs incorporate landfill gas collection systems, even at the time of construction such systems are not fully effective in preventing landfill gas and other volatile waste components from escaping from the landfill through the landfill cover. Further, over time, the reliability of landfill gas collection systems deteriorate or even become nonfunctional. This deterioration can lead to large-scale, uncontrolled releases of landfill gas through the landfill cover and liner system.

Landfill Odor Control Problems and Impacts. One of the components of landfill gas that is especially of concern to those living or working near a landfill is the malodorous compounds present in the gas. Municipal solid waste landfills are notorious for causing severe odor problems that can extend to considerable distances (sometimes miles) from the landfill. Offsite, landfill-derived odors have been a severe problem at the Pottstown Landfill. Landfill developers routinely claim at permitting hearings, that the landfill operator will place daily and intermediate cover over the wastes and that additional control of odors will be achieved through limiting the size of the tipping face. Some landfill developers also state that if odor increases, additional cover material will be placed over the offensive material and/or an US EPA approved deodorizer will be installed to control the odor. In addition, when the landfill closes, the thick final landfill cover will further "control the odors." While typically landfill proponents will make such claims about controlling odors, as part of attempting to gain a permit, frequently landfills with grossly inadequate buffer lands, such as the Pottstown Landfill will cause odors on adjacent properties.

The trespass of landfill odors onto adjacent properties is sometimes characterized as a "nuisance." The fact is, however, that landfill odors represent significant health hazards. Shusterman (1992), a physician with the California Department of Health Services, published a paper on the health threat posed by odorous conditions for those who experience obnoxious odors.

In addition to the health impacts of landfill odors, landfill gas releases, odorous or not, are known to contain carcinogens and other chemicals that are a threat to human health. Landfill odors on adjacent properties are a good indicator that there are compounds in the air that are a threat to health; the absence of odors is not an indication of the absence of hazardous airborne chemicals derived from the landfill.

With respect to using US EPA approved deodorizers to "control the odor," such an approach is often not effective. Further, and more important, while a deodorizer can potentially mask offsite odors, it does not control the hazardous chemicals that are present in the landfill gas emissions that reach offsite properties. One of the major problems with controlling landfill odors is that regulatory agencies are often not effective in achieving the control of landfill odors so that they do not occur on adjacent properties.

Overall, landfill gas emissions from the Pottstown Landfill are a significant threat to cause explosions and to be a health threat to those in the sphere of influence of the landfill. This landfill has already had severe offsite landfill derived and associated odors. There have also been uncontrolled releases of landfill gas below the soil surface onto adjacent properties. As part of developing the final Pottstown Landfill closure plan, there will be need to gain better control of landfill gas generation through controlling the moisture that enters the landfill through the cover, and the offsite migration of landfill gas.

Inadequate Postclosure Monitoring and Maintenance

Specifying a 30-year funding period for postclosure monitoring and maintenance of Resource Conservation and Recovery Act Subtitle C and D landfills was one of the most significant errors Congress made in developing those landfilling regulations. Those who were responsible for developing this approach did not have an understanding of how waste-associated constituents would degrade/transform in a dry tomb-type landfills put forth in those regulations. The US Congress General Accounting [now, "Accountability"] Office (GAO, 1990) concluded in the Executive Summary of its report, "Funding of Postclosure Liabilities Remains Uncertain," under a section labeled "Funding Mechanisms Questionable,"

> *"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, in a report entitled, "RCRA Financial Assurance for Closure and Post-Closure," the US EPA Inspector General (US EPA, 2001b) 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 noted by John Skinner, Executive Director of the Solid Waste Association of North America (SWANA) and a former US EPA official in the Office of Solid Waste and Emergency Response (Skinner, 2001),

> *"The problem with the dry-tomb approach to landfill design is that it leaves the waste in an active state for a very long period of time. If in the future there is a breach in the cap or a break in the liner and liquids enter the landfill, degradation would start and leachate and gas would be generated. Therefore, dry-tomb landfills need to be monitored and maintained for very long periods of time (some say perpetually), and*

someone needs to be responsible for stepping in and taking corrective action when a problem is detected. The federal Subtitle D rules require only 30 years of post-closure monitoring by the landfill operator, however, and do not require the operator to set aside funds for future corrective action. Given the many difficulties of ensuring and funding perpetual care by the landfill operator, the responsibility of responding to long-term problems at dry-tomb landfills will fall on future generations, and the funding requirements could quite likely fall on state and local governments."

Typically landfill owners, including Waste Management for the Pottstown Landfill, propose to only be responsible for providing the financial assurance for closure; post closure and corrective action for the 30-year minimum period. In a series of published articles (entitled, "Financial Assurance-Will the Check Bounce?" "Ticking Time Bombs?" "No Guarantee," "A Broken Promise Reversing 35 Years of Progress"), Hickman (1992, 1995, 1997, 1998) former executive director of SWANA, discussed the inadequacy of approaches for postclosure funding under Subtitle D regulations. Lee and Jones-Lee (1992, 1993a,b, 2004a, c, 2005) and Lee (2003) have also published a number of reviews on the need for longer-term postclosure care, as well as the use of more reliable financial instruments to provide funding during the postclosure care period than is typically provided today.

As part developing a final closure plan for the Pottstown Landfill there is need to define a process to ensure that Waste Management will provide postclosure care for as long as the wastes in this landfill will be a threat. That care needs to include:

- Monitoring the groundwater monitoring wells and the gas monitoring wells,
- Removing leachate from the leachate collection sumps,
- Repairing the cover as it erosions and it fails to prevent moisture from entering the landfill,
- Cleaning out the leachate collection system to rid chemical and biological plugging of this system,
- Operating and maintaining the landfill gas collection and management systems,
- Performing groundwater remediation when the pollution of groundwater by landfill leachate is discovered in a monitoring well, or in an offsite production well,
- Replacing the domestic water supply sources for nearby property owners/users when the groundwaters that they are using for domestic water supply are polluted by landfill leachate, and
- Funding the liability for lawsuits that will result from developing and permitting a landfill that will can pollute groundwater during the time that the wastes in the landfill will be a threat.

Lee and Jones-Lee (2005) recommend that since the wastes in a dry tomb landfill will be a threat to generate leachate and landfill gas for well-beyond the 30 years of minimum postclosure monitoring and maintenance specified under RCRA, regulatory agency staff should estimate the period of time that postclosure funding will be needed (including providing the technical basis for developing that estimate), how much funding will be needed to address all plausible worst-case failure scenarios for the landfill cover, bottom liner, and groundwater and gas monitoring systems, and the source of the funds for the required postclosure monitoring, maintenance and groundwater pollution remediation. This estimate can be used to develop the magnitude of postclosure funding that will be needed.

The state of PA landfill closure regulations do not carry the RCRA Subtitle D 30-year minimum post closure funding requirements. There is no time limit in the PA regulations for landfill owners to provide for postclosure care/funding. Since the waste in the Pottstown Landfill will be a threat to cause groundwater pollution forever, and since Pennsylvania regulations require monitoring, maintenance, and remediation when the containment system fails at any time in the future, there will likely be need for post-closure funding forever. One of the issues that must be addressed as part of closing the Pottstown Landfill is the assurance that funds will be available indefinitely to monitor and maintain the landfill leachate and gas collection and management systems.

In 1994, DEP worked with Waste Management to develop closure funding worksheets. The closure/post-closure funding estimates developed at that time were based on a 30-year period for post-closure. DEP has indicated that the requirements for postclosure funding will be periodically reviewed and adjusted/extended as needed. Since 30 years is an infinitesimally small portion of the time that funding will be needed to provide post-closure care for the Pottstown Landfill, the Committee will need to work with DEP and Waste Management to develop the post-closure funding assurance that will actually be needed for the Pottstown Landfill.

An important issue that will need to be considered in developing the post-closure funding is the potential for Waste Management to become no longer viable, and hence unable to fund post-closure activities over the infinite period during which funding will be needed. Companies like Waste Management are building up massive liabilities by constructing and operating dry tomb-type landfills that are ultimately going to pollute groundwaters in the vicinity of the landfills. This will lead to the equivalent of Superfund sites at many, if not most, of the municipal landfills that have been closed, that are being closed, and that are still operating at this time. The issue of the long-term financial stability of garbage companies, including Waste Management, was discussed by Cochran (1992) in *Barron's*. There it was stated,

> *"Legal liability in this* [solid waste management] *field is significant and uninsurable. Illustrating the risks, WMX* [Waste Management Inc.] *has agreed to pay WMII* [Waste Management International] *$285 million over 50 years for 'certain environmental costs and liabilities which may be suffered by the Company' because of past practices, and which are 'both probable of incurrence and capable of reasonable estimation.' The amount for known problems exceeds WMII's total earnings for its corporate history."*

The Committee needs to address how it will ensure that funding of the Pottstown Landfill postclosure care will be provided, if Waste Management is no longer able to provide the required funding for as long as the wastes in the landfill will be a threat. For planning purposes this period of time should be considered to be infinite.

Another area of concern in the PA regulations is that DEP can issue a Certificate of Closure to Waste Management which would relieve Waste Management from further funding of postclosure care. Private landfill companies including Waste Management are attempting to convince federal and state agencies that it is possible to predict, based on landfill monitoring, the end of the postclosure care period. However, as discussed by Lee and Jones-Lee (2005), the information being provided by Waste Management consultants, including Waste Management corporate staff, is unreliable for making these predictions. Basically those making such claims are ignoring the characteristics of dry tomb landfills which act to halt generation of landfill gas and leachate after an effective cover is installed on the landfill, and postpone their generation until after the containment is breeched.

Those who do not understand, or want to mislead regulatory agencies, claim that once landfill gas and leachate generation is no longer apparent after closure the waste in the dry tomb landfill is stabilized and there is, therefore, no longer need for further postclosure care/funding. However, this dormant phase only lasts as long as the landfill cover is effective in keeping the wastes dry. As the low permeability layer in the landfill cover deteriorates and allows moisture to enter the wastes, landfill gas and leachate generation can resume. It will be important that the Committee develop an approach to address the potential for DEP to issue a Certificate of Closure for the Pottstown Landfill while the wastes in the landfill are still a threat to generate leachate and/or landfill gas upon addition of water.

Another approach for detecting the failure of the landfill liner and groundwater pollution at the Pottstown Landfill is monitoring Goose Run and other nearby streams for evidence of landfill pollution. Hydrogeological studies at this landfill have shown that shallow groundwater discharges to Goose Run; thus it would be expected that some of the leachate-polluted groundwater would surface in Goose Run and other nearby streams. DEP has required that surveys be conducted of the benthic invertebrate organism communities in those tributaries; the numbers and types of organisms present in the sediments upstream of the landfill, adjacent to the landfill, and downstream of the landfill are monitored periodically. Thus far, the monitoring reports have not indicated an apparent effect of the landfill on the numbers and types of benthic invertebrates in those small streams that could be impacted by groundwater pollution by the landfill. However, that may not be the case during the post-closure period.

Goose Run and the unnamed tributary(s) that is down-groundwater-gradient from the Eastern Expansion area should continue to be monitored in perpetuity. It will be important to continue the monitoring of those benthic organism populations indefinitely as part of the monitoring system for the eventual failure of the Pottstown Landfill liner system. This requirement should be incorporated into the post-closure plan.

Overall, there are several important Pottstown Landfill closure issues that the Committee needs to address with DEP regarding long term funding of the postclosure care. These include,

- DEP should clarify its current approach of requiring that Waste Management provide assured funding for only 30 years after closure.
- DEP needs to clarify how it will better ensure that funds will be available from Waste Management to perform postclosure monitoring and maintenance (including replacement of landfill cover) and for groundwater pollution remediation for as long as the wastes in the landfill will be a threat.
- What are the conditions under which DEP might grant Waste Management a Certificate of Closure and thereby relieved it of further postclosure care?
- Should a Certificate of Closure be issued to Waste Management while the wastes in the Pottstown Landfill are still a threat to generate landfill gas and/or leachate upon contact with water, how will DEP detect landfill liner failure and leak-detection-zone failure after that point?
- How will the needed postclosure care be funded and implemented if/when Waste Management is no longer able to provide the needed funding?

Bioreactor Landfill

In an attempt to address some of the deficiencies environmental and public health protection afforded by dry tomb landfilling, attempts are beginning to be made to convert some dry tomb landfills into so-called bioreactor landfills. In this approach, leachate generated in the landfill is added back into the landfill (leachate recycle) to enhance and hasten the fermentation of the wastes. As part of its proposed expansion, Waste Management has mentioned the possibility of adopting that approach at some time in the future for the Pottstown Landfill. With proper precaution and adequate waste leaching, this approach has the potential to aid in managing the landfill gas and leachate that can be generated if the wastes in this landfill are not kept dry.

Leachate recycle is being used in some areas to eliminate, or greatly reduce, the cost of leachate management by treatment at a local public owned treatment works (POTW). Jones-Lee and Lee (2000) have discussed advantages and drawbacks of bioreactor landfills and noted that if properly conducted, the addition of moisture to a closed landfill can be an important component in producing non-polluting waste residues. Jones-Lee and Lee (2000) also pointed out, however, that addition of moisture to a dry-tomb-type landfill constructed with a single-composite liner (i.e., a minimum Subtitle D landfill) is not appropriate since the moisture added can lead to increased groundwater pollution. However, since all of the Pottstown Landfill constructed since 1984 has the leak detection zone under the composite liner, it is possible that if problems develop with the upper-composite liner during leachate recycle, this could be detected in the leak-detection zone. Leachate recycle could then be stopped and a low permeability cover placed over the landfill, and appropriately maintained, to stop further moisture from entering the landfill.

In the 1980s, under contract with the US Army Construction Engineering Research Laboratory, Drs. Lee and Jones-Lee conducted a comprehensive review of the benefits and problems with leachate recycle. It was concluded that while leachate recycle could shorten the duration of landfill gas formation, it could also lead to groundwater pollution. Lee and Jones-Lee (1993c) published a paper on what they termed "fermentation and leaching" of MSW in double-composite-lined MSW landfills containing shredded waste. A double-composite-lined landfill is constructed with two composite liners with a leak detection system between the two liners. Leachate would be recycled through the shredded waste and collected. When gas production becomes slow, which could occur within five years or so if the waste has been properly shredded, clean-water "washing" of the waste residues would be conducted. The leachate produced from the washing would not be recycled but would be treated at a local POTW. This washing phase is not typically incorporated into bioreactor landfill design and operation of this type. It is necessary, however, to remove readily leachable components that remain associated with the wastes after leachate recycle has effected about as much landfill gas as is going to be produced by the waste.

This fermentation/leaching approach could produce a low-polluting, or even non-polluting, waste residue. There are, however, several aspects of this that need to be considered. One of the most important is that, as discussed above, much of the garbage placed in MSW landfills is bagged in plastic bags. Those plastic bags are made of polyethylene and are resistant to degradation. It is unclear how long it takes for them to degrade, but it could be many decades. Under current landfilling practices, including those at the Pottstown Landfill, the plastic-bagged garbage is crushed. This means that there will be some, and in some cases appreciable, quantities of municipal solid waste in the Pottstown Landfill, as in essentially all MSW landfills, that will be hidden from moisture added to the landfill through infiltration through the cover or through leachate recycle.

Ideally, as discussed by Lee and Jones-Lee (1993c), MSW placed in bioreactor landfills should be shredded to allow all of the wastes to be exposed to the added moisture. Since shredding the waste was not part of the Pottstown Landfill operation, the Committee needs to recognize that there could be a very long period of time during which landfill gas production could occur even under bioreactor operation. In fact, it would be expected that decades after landfill gas and leachate production had ceased after closure, landfill gas and leachate production would resume when the bags decompose and the waste hidden in the buried plastic bags begins to ferment. This resumption of gas production could be at a sufficient rate to require management. It will be important for the Pottstown Landfill Closure Committee to consider this situation in developing a plan for closure and post-closure care of this landfill.

The Conversion of the Pottstown Landfill to a "bioreactor" landfill. It is unclear whether DEP will allow an MSW landfill such as the Pottstown Landfill to be converted from a dry tomb type landfill to a bioreactor landfill. It may take a change in DEP regulations to permit this change in mode of operation for the

Pottstown Landfill. This issue needs further review as a means to better manage a large part of the landfill gas and leachate that can be potentially generated in the Pottstown Landfill.

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